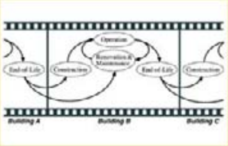

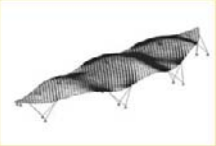

Sustainability Guidelines

FOR THE STRUCTURAL ENGINEER

EDITED BY
Dirk M. Kestner, P.E.
Jennifer Goupil, P.E.
Emily Lorenz, P.E.

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SUSTAINABILITY GUIDELINES FOR THE STRUCTURAL ENGINEER

SPONSORED BY
Sustainability Committee of the
Structural Engineering Institute (SEI) of the
American Society of Civil Engineers

EDITED BY
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Preface

The Sustainability Committee of the American Society of Civil Engineer's Structural Engineering Institute (ASCE SEI) prepared these guidelines to educate and guide structural engineers as they meet the challenge to design and construct a sustainable built environment. The guidelines provide valuable information on a variety of topics of interest to the structural engineering community. The document is intended to fill an obvious gap in the area of useful resources specific to sustainability within structural engineering.

The guidelines are organized into five sections: Sustainable Design and Construction, Sustainable Strategies, Building Materials, Infrastructure, and Case Studies. Although many of the subjects presented are related, each section — and the related subsections — have been written to stand alone. The report does not have to be read through from start to finish, but can be used as a reference for any topic at any given time.

This report was written for structural engineers, but related disciplines will also benefit from the contents. The majority of these guidelines were written by structural engineers involved in building design so the reader will find more references to buildings than to infrastructure. The section on infrastructure has been included to make a broader connection outside of the sustainable building design and construction arena. Many of the concepts and ideas presented will relate to both.

This document does not provide a detailed analysis of climate change, resource depletion, habitat and species destruction, the social or physical effects of pollution, etc. There are many resources available to develop a deeper understanding of the urgency and priority of environmental concerns. The goal of these guidelines is to assist the structural engineer to understand the fundamentals of sustainability as it relates to the practice of structural engineering.

The ASCE SEI Sustainability Committee was formed in 2005 with the following mission: "To advance the understanding of sustainability in the structural community and to incorporate concepts of sustainability into structural engineering standards and practices". The Committee would like to acknowledge the outstanding efforts of the authors, reviewers, and editors. Although each section has been subject to a peer review process, the content is primarily as provided through the research and perspective of the authors listed. In the expanding field of sustainability and the built environment, it is inevitable that a report of this kind will need future updates. The ASCE SEI Committee welcomes your comments.

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Table of Contents

INTRODUCTION....1

SECTION 1: Sustainable Design and Construction....9

1.1 - Design Integration and Synergies....10

1.2 - Metrics: Quantifying Green....17

1.3 - LEED Rating System....29

1.4 - Green Globes Rating System....40

1.5 - Project Delivery and Specification Writing....47

SECTION 2: Sustainable Strategies....71

2.1 - Recycled Content....72

2.2 - Local Sourcing and Local Manufacturing....77

2.3 - Durability and Reduced Maintenance....80

2.4 - Design for Adaptability and Deconstruction....85

2.5 - Reuse of Buildings, Structural Components, and Non-Building Structures....93

2.6 - Life Cycle Assessment (LCA)....117

2.7 - Structural Materials and Toxicity....132

SECTION 3: Building Materials....145

3.1 - Materials Introduction....146

3.2 - Concrete....148

3.3 - Masonry....190

3.4 - Steel....198

3.5 - Wood....212

3.6 - Natural Building Materials and Systems....225

SECTION 4: Infrastructure....243

SECTION 5: Case Studies....257

5.1 - Thin Shell Structures of Felix Candela....258

5.2 - San Francisco Federal Building....263

5.3 - Dalby Forest Visitors Center....273

5.4 - The Nomadic Museum ... 280
5.5 - Bank of America Tower at One Bryant Park ... 285
5.6 - Ithaca College Business School ... 289
5.7 - The David Brower Center ... 295
5.8 - Beddington Zero Energy Development ... 299
5.9 - Crafting Green Specifications ... 302
5.10 - The Savill Building ... 305
INDEX ... 311

INTRODUCTION

Don Allen, P.E.
Carla M. Dhillon, P.E., LEED AP
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"What is sustainability and what is my role in it?"

Maybe you're an idealist who's trying to apply environmental principles important to you to your day-to-day work. Maybe you're a pragmatist who sees changes in the types of projects you're being asked to complete. Or maybe you're simply a professional who sees the need to learn more about an important aspect of the materials and systems you are responsible for specifying. Any of these motivations could lead today's practicing engineer to seek out knowledge about their role in the sustainability of building structures. Over the past few years, new sustainable initiatives and regulations have multiplied quickly, making it difficult to know where to start. The American Society of Civil Engineers/Structural Engineering Institute's (ASCE/SEI) Sustainability Committee has prepared these Guidelines to provide structural engineers with a solid foundation in areas ranging from structural materials to sustainable strategies and green building rating systems.

Structural engineers who seek to contribute to the process of building sustainably must take a global view. We must look beyond the way structural systems and products affect the response of the structure to loads. Beyond this, our choices impact other systems within the building, and the environment beyond the building. It is the understanding of how structural systems integrate with the other building systems that is the foundation of sustainable design. Early integration of disciplines is a basic tenet of sustainable design, but unfortunately, it's often incompatible with our design process.

To contribute to sustainability through this improved process, we must seek to better understand the structural assemblies we specify. This is the foundation of sustainability: first of all, understanding how our structural materials are mined or harvested, processed and transported, and eventually how they are installed. Next, during the life of the structure, asking how they impact air quality, thermal performance, and occupant comfort. Lastly, at the end of the useful life of the structure, how are they removed, and how are they disposed of, or can they be reused? Most of these questions are currently beyond the purview of the typical structural engineer.

The design and construction of sustainable structures does require us to look outside our normal scope: when we optimize a structure, we can consider not only the structural effects and responses to loads, but responses to and interaction with the surrounding environment and ecosystems.

Sustainability — One of the most popular definitions of sustainability comes from the 1987 United Nations Brundtland Commission Report: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." ASCE defines sustainable development in Policy Statement 418 as "the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development." The underlying concept is that our creative focus should be used to find ways to meet current needs without destroying the opportunity for future generations to do the same. Engineers are crucial to this process. Currently, we understand design as the application of mental energy to solve a problem. Sustainability requires that we have the courage and foresight to participate in a design and construction revolution for the sake of future generations.

The Triple Bottom Line

The sustainable business model has focused on what is called "The Triple Bottom Line" such that three factors and incentives — the *environmental*, *social*, and *economic* — are included in business decisions. It has also been called the three "P's" representing people, profit, and the planet. However the discussion is framed, the goal is to pursue business in such a way that all three are maximized at the same time, as opposed to pitting them against each other (Braungart and McDonough 2002).

While many have started to think about the environmental impacts of the built environment, this leaves out the economic and social impacts involved. Creative and effective design in our times should involve optimizing environmental, social, and economic factors. Owners and architects most often hire structural engineers to provide the most effective structure to achieve a first-cost budget. However, the global view prompts us to ask the following questions:

- Are there environmental and social costs related, and can a dollar value be assigned to them?
- Will elements of the structural design improve or degrade productivity or health of the end users?
- What are the long-term energy costs (or savings) due to floor-to-floor heights, how will energy saving strategies affect the cost of structure, or can the structure be integrated with MEP systems?
- As we approach an era where the pricing of carbon emissions is very likely, how will the use of carbon-intensive materials impact a project's bottom line?

Environmental factors

Our work as structural engineers affects the environment in many ways. As practitioners, we need to remain abreast of environmental issues so that in our work we can take steps to reduce the impact of our projects. The following topics are among the most critical environmental issues that face us today.

Climate change — Several recent books have concluded that climate change is today's most serious environmental issue (see Additional Resources at the end of this section). A number of reports issued in 2007 by the United Nations

Intergovernmental Panel on Climate Change (IPCC) have also drawn public attention to climate change. The IPCC asserts that climate change, attributable to the build up of greenhouse gases from human-made sources, is occurring at an unacceptable rate. Further, the IPCC warns that catastrophic changes to the environment will result unless immediate steps are taken to reduce the atmospheric concentration of carbon dioxide (CO_2), and other greenhouse gases. According to the IPCC 4th Assessment Report (2007), the worst effects of global warming may be avoided if annual CO_2 emissions are reduced to the 1990 level within 20 years. To achieve such a drastic cut in carbon emissions worldwide, all major emitters, such as power plants, oil refineries, transportation industry sources, and manufacturers of industrial materials and consumer products, are contemplating what actions to take by the year 2010. In the building construction field, the organization Architecture2030 has issued the 2030 Challenge, calling for all new buildings to be carbon-neutral by 2030. The American Institute of Architects, in addition to many other organizations, has accepted this challenge and is striving to meet it. Carbon dioxide is emitted in the production of all structural materials, for the most part due to fossil fuel consumption and chemical transformations.

Material depletion — Buildings in general, and structural materials specifically, consume both renewable and non-renewable natural resources. Non-renewable resources are those that have taken millions of years to be produced, such as fossil fuels, rocks, and minerals. Once used, they are not replaceable in any human time-frame. Renewable resources, such as wood and agricultural products, are produced within a human lifetime, or several human lifetimes in the case of old growth wood. As long as these resources are not depleted faster than they can be produced, they will be available to future generations. Since a primary goal of sustainability is to ensure that we leave behind the resources needed for future generations to maintain an adequate standard of living, we as structural engineers need to learn to design with reused, recycled, and renewable resources. While some construction resources such as concrete aggregate remain abundant, the search for new sources continues to destroy habitat and increase transportation-related impacts as the sources move further away from centers of growth and construction.

Waste production — According to the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design for Existing Buildings (LEED-EB) Reference Guide (USGBC 2005), a "typical North American commercial construction project generates up to 2.5 pounds of solid waste per square foot of floor space." A U.S. Environmental Protection Agency report estimates that the United States construction industry created 136 million tons of construction and demolition debris in 1996, or 2.8 pounds per person per day (USEPA 1998). The report estimates that only 20 to 30 percent of this waste is recovered for recycling or reuse, with the remaining destined for landfill or incineration. Waste that is landfilled or incinerated can lead to the contamination of air and soil; but perhaps more significant from an environmental standpoint is that many of these materials could be reused or recycled to reduce the extraction of virgin resources (see "Material Depletion" above). The way we design and build can reduce the quantity of building waste. For example, designing for durability, adaptability, and deconstructability can extend the life of buildings and improve the likelihood that building materials will be reused or recycled at the end of a building's life.

Water use and contamination — Water supplies are under increasing pressure as the global population increases. Climate scientists forecast that climate changes could cause more extended droughts and less snowpack in parts of the world. The World Health Organization estimates that water scarcity already affects 40 percent of the world population (WHO 2009). Even in industrialized countries like the United States, aquifers such as the Midwestern Ogallala, the largest in the country, are becoming exhausted and water-rationing is becoming the norm in some communities. Population growth in the arid American southwest is sapping reservoirs such as Lake Mead (Circle of Blue 2008). To add to the problem, human activities can contaminate water. One example was when the fuel additive MTBE started showing up in groundwater supplies. The production of structural materials and process of building construction impacts water supplies. One obvious example is the water we use to produce concrete, which is usually potable. But the production of steel and other structural materials also requires water. Electric arc furnaces and basic oxygen furnaces consume about 2,500 to 4,000 gallons of water per ton of product, and hot-rolling consumes about 7,000 to 9,000 gallons of water per ton of product, 50 percent to 80 percent of which is recycled (USDOE 2003). Strategies such as material efficiency and use of recycled water in concrete can help reduce the impact on water resources of structural materials.

Toxicity — Our natural environment and bodies now contain trace or greater quantities of many toxic chemicals produced by human enterprises. Some of these substances are known or suspected to increase the risk of cancer, allergies, reproductive disorders, and other health problems. One class of chemicals that are especially worrisome is persistent bioaccumulative toxins (PBTs), which accumulate in the bodies of animals, including humans. While the prevalence of some environmental toxins, such as lead, is declining, others, such as PBDEs, a class of chemicals frequently used to provide fire-resistance in consumer products, appear to be on the rise. Toxins are emitted during the production of electricity, such as the mercury released by coal-powered electric plants, so any process that consumes electricity produced by coal (and to a lesser extent other fuels) also produces toxic releases. In our work as structural engineers we specify products such as concrete admixtures and steel coatings that may contain toxic ingredients to a greater or lesser extent. We specify structural materials that are manufactured using processes that release toxic substances to the environment. As part of our effort to reduce the introduction of toxic substances into our natural environment and into our bodies, we must educate ourselves about the toxic consequences of the materials we specify and reduce those consequences where feasible. This topic is discussed in greater detail in Section 2.7 of these guidelines.

Habitat destruction — Habitat destruction can take many forms, from suburban sprawl to poor logging practices to the spread of arboreal diseases due to climate change. Habitat destruction reduces biodiversity and can lead to the extinction of plant and animal species, damaging the natural fabric that sustains all life on our world. Habitat destruction can directly affect human health and well-being by increasing the vulnerability of settled areas to the ravages of natural disaster. Examples include coastal flooding during storms that is exacerbated by the destruction of shoreline mangrove forests, and desertification arising from removing natural flora for agriculture, followed by the loss of topsoil due to poor land management. In addition to the indirect contribution to habitat destruction caused by the production of greenhouse gases during the manufacture of structural materials, direct habitat loss can arise from the use of structural wood products derived from poorly managed forests. In addition to addressing these types of causes of habitat destruction, structural engineers can contribute by avoiding projects such as new roadways, buildings, and other infrastructure projects in undeveloped areas.

The relationship between structural engineering practice and these environmental issues will be addressed throughout this report.

Economic factors

From a business standpoint, achieving economic success is an important part of sustainable design. Listed below are some of the economic benefits of sustainable design (Wilson 2005):

- first cost savings:
    - tax credits and other incentives
    - streamlined permitting and approvals, where available
    - reduced infrastructure costs
    - reduced new material use
    - savings in construction waste disposal
    - savings by downsizing mechanical equipment
- reduced operating costs:
    - lower energy costs
    - lower water costs
    - greater durability and fewer repairs
    - reduced cleaning and maintenance
    - reduced cost of "churn" (reconfiguring office space)
    - lower insurance costs
    - reduced waste generation within the building
- other economic benefits:
    - increased property value
    - more rapid lease-out
    - more rapid sales of homes and condominiums
    - easier employee recruiting
    - reduced employee turnover
    - reduced liability risk
    - staying ahead of regulations
    - positive public image
    - new business opportunities

Social factors

The third component of the triple bottom line is social. Structures are the built environment in which we live, work, and play, and when well designed, can provide nurturing environments and positive social interaction. Poorly designed structures contribute to poor use of time and space, increased sick days, and poor productivity. Social benefits go beyond beauty and aesthetics: sustainable projects support sustainable economies and support organizations with a commitment to social responsibility. Human health and quality of life are intertwined with the economic benefits that business brings to the commons.

Structural engineering and sustainability

It is now common for structural engineers to be included in sustainability design charrettes. Structural engineers are stakeholders in the integrated design process who can suggest innovations and systems that may not be structural in nature, but facilitate the overall sustainability of the project. Our early participation with the rest of the design team will achieve collaborative rather than combative designs. For example, the structural engineer can work with other design disciplines to accommodate a rainwater recovery system through a structural tube, or a heat dissipation system through appropriately and artistically placed fins, or a thermal mass system through properly oriented and colored concrete. All these opportunities become possible when the structural engineer and other designers are well-versed in sustainable construction.

Thomas Jefferson (1789) summed up sustainability eloquently. “Then I say the earth belongs to each… generation during its course, fully and in its own right. The second generation receives it clear of the debts and encumbrances, the third of the second, and so on. For if the first could charge it with a debt, then the earth would belong to the dead and not to the living generation. Then, no generation can contract debts greater than may be paid during the course of its own existence.” As structural engineers, our legacy lies not only in our structures, but in the communities we shape, the values we teach, and the debts and benefits we leave to future generations. When the next generation of structural engineers joins the profession, we want them to inherit a legacy of progress and hope; of cooperation, creativity and sustainability. These Guidelines can be a first step for many in creating that legacy.

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SUSTAINABLE DESIGN AND CONSTRUCTION

Sustainable design and construction techniques have been developed by a variety of project stakeholders. Structural engineers can respond to the demand and contribute to the overall sustainable project goals by familiarizing themselves with what is currently practiced in the industry. This section will discuss the following in more detail:

Section 1.1 — Design Integration and Synergies

Section 1.2 — Metrics

Section 1.3 — LEED Rating System

Section 1.4 — Green Globes Rating System

Section 1.5 — Project Delivery and Specification Writing

1.1

DESIGN INTEGRATION AND SYNERGIES

Ruben Aya-Welland, P.E., LEED AP
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Many structural engineers have experienced coordination difficulties during the building design process. Most structural engineers have encountered untimely and unpredictable changes to column grids, to locations of slab openings, to restrictions in beam depths, or to sizes of shear wall openings, just to mention a few. When conflicts such as these are not identified until very late in the design process, final resolution can become much more cumbersome and costly. How or why do we find ourselves in these situations?

Our professional services typically require us to evaluate fairly developed architectural design schemes, and to then insert the most economical, safe, and durable structural framework that will support the predetermined design intent. This traditional model for structural engineering services typically presents great challenges for the practitioner. If structural engineers don't join design team discussions early in the process, their hands are tied to specific solutions, and their contributions become limited. Structural engineers know that a successful project depends largely on a well-developed and coordinated building design; in essence, success hinges on the timely exchange of information. However, overly focused specialization has often led team members to take too narrow a view of their specific contribution to the design process. This specialized mindset can often limit useful interactions amongst the various disciplines, potentially allowing for major coordination issues to be left unresolved until the end stages of project documentation or even worse, during construction. This process can lead structural engineers to "muscle" solutions into fruition, and even employ excessive levels of conservatism to account for uncertainties in coordination.

How can we as structural engineers become more effective contributors to the building design process? How can we overcome the tedious and even cumbersome design strategies that have invaded our practice? Design integration provides a better framework to proactively address the complexities involved with the building design project. Of course, design integration is not a new concept: it requires the early conceptual involvement of all design team members, regardless of their perceived impact on the initial decision-making process. Over the last several decades, we have seen many examples of successful design integration for unique buildings around the world.

In today's marketplace, we face a great imperative to champion design integration: the critical need for sustainable design. Building design professionals are now confronted with the challenge of re-thinking how we conceptualize our structures. Our goal is to reduce or even eliminate our energy consumption and negative impact on the natural environment. Structural engineers must answer the call to action for promoting a sustainable way of thinking. Design integration is essential for getting sustainable design practices into a project. Sustainable design only reaches its full potential when it is firmly rooted in a deeply integrated approach to design:

the notion that "one idea does many things" reinforces design integration by promoting a more efficient use of energy and materials. The great difficulty for specialists — such as structural engineers — is that the biggest contributions to sustainable integrated design tend to happen outside of the perceived boundaries of our profession. To overcome this obstacle, we must increase our conceptual awareness and knowledge of sustainable design. Understanding holistic building effects — or synergies — will require that structural engineers educate themselves about design work traditionally assigned to other team members such as the architect and MEP engineers. It is critical that structural engineers understand the significance of other team members' design challenges and responsibilities.

Sustainable design integration has led project teams toward adopting innovative ideas that cross inter-disciplinary boundaries. If we are to move towards a truly holistic design philosophy, structural engineers must adapt and think differently about how structures are conceived and built. Ultimately our designs need to satisfy concerns for safety, serviceability, durability, economy, and yes, sustainability.

The extent to which the various sustainable design solutions can be implemented into any project will depend on the level of both passive and active design strategies employed. Passive strategies focus on using the basic elements of building construction to harness nature's energy, while active design strategies tend to focus more on additional overlays of sustainable technologies.

Sun

At the beginning of any design project, it is essential to consider the relationships that exist between project site and the annual sun path. One of the greatest ways in which a building can be more efficient with energy use is to adapt its form, proportions, materials, and construction systems to collect and harness solar benefits, while shielding the building from the sun's less desirable effects.

Building form and proportion — Building orientation and configuration are primary starting points for passive solar design. Although idealized building proportions and site orientations are not always possible, the basic concerns remain the same: how to design the building plan and section to utilize the light and heat of the sun. The goal is to provide a passive way of reducing heating and cooling demands from the very beginning of the building design; before the effects of an HVAC system are even considered.

Two key strategies to be aware of are site orientation and aspect ratios. Building plans that are oriented with their longer sides parallel to the east-west axis tend to be the more efficient plan forms for addressing solar design concerns. During the summer, the harsh afternoon sun exposure is minimized on the shorter west side of the building. In the northern hemisphere, during the winter, the warmest sunlight exposure of the day is maximized on the long south side of the plan. Also, floor plan aspect ratios are important when choosing daylighting strategies. Depending on the plan depth of the building design with respect to relative story height, a variety of daylighting strategies might be appropriate. Buildings with relatively large interior plan dimensions are better suited for skylight or central atrium daylighting, whereas narrower buildings can use perimeter daylighting as an appropriate strategy.

Building enclosure — Exterior enclosure systems are another starting point for sustainable solar design. The overall goal here is to decide whether the enclosure is intended to act as thermal conduit or thermal shield. Thermal mass is a passive design strategy that works by storing solar heat collected by exposure during the day for later release into the cooler evening. A recent article in Structural Engineering International argued that employment of thermal mass is the most effective carbon-reduction strategy available to structural engineers (Anderson and Silman 2009). If solar heat is being used to temper daily temperature differentials, thermal mass strategies will require thick heavy walls. Concrete and masonry walls are effective in this way, and can often be designed as thermal collectors, structural supports, and finished architectural enclosures. Concrete and masonry walls have low R-values, but high thermal mass properties. In order for thermal mass strategies to be most effective, the mass should be in direct contact with the conditioned space, requiring either an exterior insulated system outside of the mass walls or integral insulation typically located between wythes of concrete panels or masonry.

An example of an integral insulation system is pre-manufactured, precast insulated sandwich wall panels. These panels act as thermal shields to the exterior and as thermal storage devices to the interior. Sandwich panels can either be load bearing in nature, or act as non-structural panels that are attached to a back-up structural frame. The inclusion of joints in these walls is directly related to temperature change and should therefore be an important part of the design discussions. Proposed construction methods should be reviewed with the design and construction team to ensure that team members understand and accept the likely appearance of the finished walls. Architecturally, these panels can take on a variety of exterior finished appearances, and the sandwich panel industry is continuing to evolve on this front.

If solar heat needs to be kept out of the building, thermal shield strategies will need to investigate increased levels of building insulation efficiencies. As mentioned above, building insulation can be greatly enhanced by using highly insulated, pre-manufactured sandwich wall panels because these panels act as thermal shields to the exterior. Another design strategy is to use high performance “double-skinned” façade systems. These consist of glazed facades typically separated by 200 mm to 1400 mm of space to allow airflow between the inner and outer glass membranes. The airflow can be either mechanically or naturally vented depending on the type of mechanical strategy incorporated on a project. The double-skin facades advantages consist of the following:

- energy savings,
- sound transmissions reduction,
- increased occupant productivity (GSA 2009), and
- security for operable windows.

In a double skin facade, solar shading devices — blinds — are typically placed between the inner and outer skins. The blinds are usually adjustable and can be raised or lowered as needed. The blinds capture the solar gain and heat the air in the cavity. During cooling season this heat must be removed by the building plant to reduce the temperature. During the heating season, the direct radiation will be desirable and can be used to heat the occupied space.

Structural engineers need to be knowledgeable about these systems because they will need to design the support for this deeper façade system. In some cases, the cavity can be as wide as 1 meter to allow for cleaning and maintenance. An open grating can be used at the floor levels inside the cavity to allow access. The double-skin system can be hung from the main building frame. Depending on the type of double-skin façade system being used, thermal breaks may be needed to prevent thermal-bridging between systems, which can result in more complex connections between the double-skin façade system and the main structural framework.

The double-skin façade will have a greater first cost over most traditional glazing systems. The energy savings over its life must be weighed against its first cost. A study by Buro Happold found that energy payback analyses are usually not sufficient to justify the use of double-skin facades (Stribling and Stigge 2009); other benefits must be considered, such as aesthetics, sound control, and occupant pleasure. Another consideration for this system is the loss of potentially leasable square footage with a deeper façade. As with all design strategies, all the potential advantages and disadvantages will need to be assessed to determine what system is appropriate for a given project.

Daylighting — This design strategy minimizes the need for artificial interior lighting, and therefore reduces daytime electrical energy demands on the building. Building designs can provide for sufficient wall, floor, and roof penetrations to accommodate a certain amount of interior natural lighting throughout the day. During summer months, electrical lighting will add to the cooling load on the building. In addition to energy savings, daylighting also provides exterior views and connections to the outside world that have associated psychological health benefits (GSA 2009).

The architecturally exposed nature of daylighting solutions tends to discourage the use of vertically, solid structural systems that are placed on the building perimeter. Structural systems such as exterior load-bearing walls will create challenges for daylighting strategies, as will braced-frame or shear wall systems around the building perimeter. Although opportunities can exist for integrating these bracing and shear wall solutions with daylighting schemes, these will require early and proactive coordination of lateral load resisting systems by the structural engineer with the design team, in order to maximize the potential of this powerful design strategy. A centralized core wall structural scheme allows architectural freedom around the building perimeter. The alternative use of moment frame systems provides for cleaner architectural solutions; however, additional construction costs and the effect of deeper beams around the perimeter should be investigated.

Daylighting strategies must also be carefully coordinated with building enclosure methods due to the potential conflicts that might arise. For example, a solid wall will provide a certain level of thermal mass or shielding, but these solid walls can also defeat the intent of the specific daylighting strategy. For buildings with large interior plan dimensions, large atriums and mezzanines are often employed as a means of bringing natural light deep into the building. This requires more careful consideration and coordination of floor and roof diaphragm connections as part of the complete lateral load resisting system. The structural engineer's involvement during early concepts and understanding of these basic sustainable design strategies will lead to a more fully integrated design that works optimally as a holistic building system.

Screening — These strategies are intended to provide filtering and shielding during the more undesirable solar exposures related to heat and visibility. Sun shades and canopies are probably the most popular example of this design strategy. Although these elements can sometimes be constructed and function independently from the main building structure, sustainable design integration can inform the selection of the structural system by suggesting modular frames and exposed structural elements. This approach can also make for an interesting and more unified architectural expression. Screening is also a major component of curtain wall design. By integrating louvered elements into high performance double-skinned façade systems, screening can help to cut down on direct solar heat gain within the building interior.

Wind

Structural engineers design structures with both adequate strength and stiffness to withstand the effects of wind loading. However, using the effect of wind on a building can also be a successful sustainable design strategy. Wind works in concert with the heat of the sun to create local microclimates that have an effect on the response of a building structure to its environment. Wind effects can be external, internal, or a combination of both in relation to the building envelope. Under certain site conditions, the relationship between external and internal wind effects can enable passive ventilation through or within the building structure. As with designing for the sun, consideration of wind effects requires the designer to determine the primary design goals. Does the building need to be shielded from the wind? Can the building use the wind to supplement required interior ventilation? Should the building be shaped and sited in response to the prevailing winds?

Site placement and building orientation — The location and shape of a building on its site are important considerations when creating wind-driven sustainable design relationships. Microclimates are created by the interaction between regional prevailing winds, local changes in topography, density of existing trees and ground cover, and density of existing built infrastructure. The more a new building project can adapt itself to the existing wind conditions of a particular site, the less it might be subject to wind-driven weathering effects. This approach to site placement, orientation, form, and proportion can add to long-term building performance and durability.

Natural ventilation — Natural ventilation techniques of cross and stack ventilation can be integrated with the building structure when floor plate depth ratios, floor diaphragm openings, floor framing orientation, and structural wall placement are thoughtfully proposed. Side ventilation introduces air from one side of the building and generally works best when the built-out space width-to-height ratio is less than about 2:1. For a cross-ventilation strategy to work well, the building should have a width-to-story-height ratio no more than about 6:1 to avoid stagnant air in the middle of the building. Higher width-to-height ratios up to about 12:1 can incorporate a central ventilation chase or tower to encourage a buoyancy ventilation system. These towers can even take on a significant structural role.

Convection currents and radiant energy — High performance "double-skinned" curtain wall systems can work in conjunction with solar heat to produce natural convection currents that help to ventilate the curtain wall plenum space and reduce undesirable solar heat gain on the façade. When considering the internal winds of a conditioned building environment, strategies such as displacement ventilation must be structurally coordinated with the air distribution requirements of raised floor systems. Floor slabs can be considered as a strategic base for radiant heating systems. Thermal breaks at exterior balcony structural slabs are important in maintaining an efficient interior heating and cooling system, and structural details at cantilevered slabs must be evaluated in order to help mitigate the unwanted thermal breaks.

Mechanical ventilation — Displacement ventilation is an interior mechanical air ventilation system that works with the natural flow of air. Traditional interior ventilation systems have relied upon a forced air method that supplies cool air from above an occupied space and forcibly blows it to the human occupied space below. This process is inherently inefficient in its use of energy. Displacement ventilation supplies conditioned air from below a finished raised floor and in cooling mode allows undesirable warmer air to rise to the ceiling naturally. The raised floor acts as a plenum space for air flow and is usually 12 to 18 inches deep. A raised floor system provides flexibility for the tenant and boasts some of the following advantages:

- energy savings,
- flexibility of air distribution locations and user control,
- flexibility for changing cabling and electrical systems, and
- opportunity to expose structure and eliminate architectural ceilings.

The structural engineer will need to consider the additional weight of the raised floor system on the structural floor framing. In addition, the supply and return duct penetrations will require coordination through the floors and walls. A centralized concrete core wall system will require careful coordination when shafts are located within the core walls. The structural engineer should be aware that these penetrations may have similar areas for air movement, but different shapes to accomplish it within a raised floor system. For example, wall penetrations are typically long, thin slots at the floor line to stay within the raised floor plenum space.

Screening — Micro climates create site specific wind effects that can be channeled by structural elements such as exterior screen walls. For certain structures, roofs can be sloped or shaped to enhance ventilation with aerodynamic effects. There are times when regional winds will generally be undesirable or harsh in nature and screening methods can be used to shield the building from the natural environment, increasing long-term durability of the exterior enclosure, and possibly reducing the wind loading demand on the building structure. Collaboration and coordination with wind engineering simulation studies can generate wind mitigation and integration solutions that help to define the shape and form of the building design.

Conclusion

While many of the synergies discussed in this section are not entirely within the structural engineer's typical scope or responsibility on most projects, understanding the possible solutions that could lead to project success will benefit not just the engineer, but the whole project. In order for the structural engineer to influence the sustainable design process, they need to interject themselves into the design team discussions on this topic during the early stages of design. This will lead to a more integrated design for the entire building.

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1.2

METRICS: QUANTIFYING GREEN

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Quantifying what is green or sustainable in building design and construction can be a complicated task. There are many measurement tools available with new ones being added at a rapid pace and existing ones undergoing frequent changes. If asked how to measure green buildings, many engineers will mention Leadership in Energy and Environmental Design (LEED), the rating system created by the United States Green Building Council. LEED is currently the most frequently encountered rating system on U.S. projects that require the services of structural engineers. But it is not the only rating system in operation, and rating systems play a limited role in the overall scheme of sustainable measurement.

At the ASTM Symposium in April 2007, on "Common Ground, Consensus Building, and Continual Improvement: International Standards and Sustainable Building," Todd presented the following questions related to sustainable measurement:

- Why do we measure?
- Where do we measure?
- What do we measure (or not measure)?
- How do we measure?
- What do we do with all this information?

An attempt to deeply discuss all of these questions is beyond the scope of this report, but some ideas are presented because it is important for structural engineers to develop a sustainable mindset when working with rating systems and other measurement tools.

Why do we measure?

This question relates to the purpose of our metrics and the goals and objectives we seek in sustainable structures. There are multiple objective levels currently in use within the building industry. The following various objectives are not equally beneficial to achieving sustainable goals, nor are they equally achievable on a broad scale in the near future.

Mitigation — A mitigation approach looks to make the built environment less bad. This is an important first step in our industry's thought process as we begin to reduce negative environmental impacts. The majority of green building practice today understands mitigation as their project objective.

High-performance design – High-performance buildings focus on the structure and the systems as a whole, often using newer technologies to achieve energy efficiency, energy savings, and efficient building operations. An emphasis may be placed on superior occupant comfort and smart building automation systems.

Although high performance design may integrate passive and bioclimatic design considerations, the emphasis is on advanced building performance that frequently involves advanced technologies.

Net-zero — Net-zero goals typically mean that buildings and sites produce and manage what they need. Such buildings, by the nature of their very existence, cannot be said to have no impact per se. But this goal involves the building and site generating what they need, including on-site renewable energy and closed-loop hydrologic systems which require rainwater catchment and storage. The building and site also manage their own waste, usually in the form of a Living Machine™ or other wetlands. Living machines process human waste through nutrient reservoirs, microbial processes of organic plant and animal life, and photosynthesis (Todd 1999). They can be building integrated, as used at the Oberlin College Lewis Center, or placed on wetlands like those at Islandwood on Bainbridge Island in the state of Washington. Net-zero targets are gaining momentum, partly due to the Living Building Challenge. For more information on the Living Building Challenge, reference the Metrics Glossary at the end of this section.

Restorative and regenerative — The goal of restorative and regenerative design is to build in ways that improve the environment and sustain life in the long term. The basis of this approach is to engage the entire building, site and surrounding region so that energy and nutrient flows are in balance. This restores and creates health where there may have been past damage. It is place-based design stemming from an understanding of the local climate, eco-system and history of the site. This is the next step in integrated or whole-systems thinking that requires a melding of ecology and the natural and technological sciences. A relevant case study project is the Loreto Bay Resort in Baja, Mexico (Reed 2006).

This broader understanding of the goals related to sustainable buildings can aid structural engineers to make better choices, as well as inform our involvement in achieving a long-term sustainable future. It is not known how quickly and in what ways industry objectives will change, although the general trend has been toward greater inclusion of sustainable goals. The changing of building industry targets will depend upon many factors such as government regulation (incentives and/or policy), energy costs, fossil fuel depletion, public opinion, the world water crisis, non-renewable material depletion, environmental disasters, and links between human health/natural disasters with environmental factors. Sustainable measurement illustrates achievements and provides direction on what is yet to be done.

Where do we measure?

This question asks: in what context are we measuring (environmental, economic, social, cultural)? Can we measure in all of these contexts at the same time? What are the priorities of government, society, and building owners? Are we interested in green regulatory codes or in voluntary practices?

In the current market, ecological, economic, social, and cultural factors are increasingly interconnected. The transforming business model that incorporates a triple bottom line (equally valuing people, profit and the planet) is no longer merely an ethical construct. It is becoming a necessary paradigm shift as business responds to changing patterns of scarcity, population, and public sentiment (Hawken et al. 1999). The idea is not to pit business against the environment, but to create real value in all three sectors simultaneously (ecology, equity, and economy) so that economic wealth does not come at the expense of the community or the natural world (Braungart and McDonough 2002).

As engineers this requires us to think critically about how our project and business choices affect the environment and the commons. Recommended references to enable further thought and dialogue are presented in the books *Cradle to Cradle* (Braungart and McDonough 2002), *The Ecology of Commerce* (Hawken 1993) and *Natural Capitalism* (Hawken et al. 1999). For information on greening internal business operations through leadership, management, and a shared mental model refer to the BuildingGreen report “Expanding Our Approach to Sustainable Design-An Invitation” and “Appendix-Real World Examples” by Reed et al. (2005).

What do we measure (or not measure)?

This question deals with the scope of what is measured, or what is intentionally or unintentionally left out of the measuring. What should rating systems address? Should we measure based upon a building’s entire life cycle, or only what occurs during the design and construction phases? Do we measure design intent or actual building performance? Do we measure neighborhoods and communities, or individual project sites?

Rating systems are evolving to address a larger scope: more building types and whole neighborhoods instead of individual structures in isolation from their context. Rating systems are also expanding to include building material, system, and overall structure life-cycle analyses. As structural engineers this means a better understanding is needed not just of material specific sustainability strategies, but also of designing for durability, disassembly, and the building end-of-life. Engineers optimize multiple design factors such as code requirements, cost and constructability; so including additional factors related to sustainability is not a big intellectual stretch (Addis 2001).

It is important to understand that a sustainable choice for one project may not be the best choice for another. Is it best to design for durable structures, even if those structures cannot be dissembled in a useful way and do not safely biodegrade at the end of life? How do the site climate and energy optimization strategies play into material selection? A solid understanding of the issues involved and what influence our profession has over them is important. Context specific assessments must be made that consider the project scope, sustainable goals, climate, projected life span, integration with architectural and mechanical strategies, and many other factors. What is included in, or left out of, the optimization and measurement process will affect the ultimate decisions.

The list below contains items that are or might be measured as part of sustainable metrics.

Site design
- building orientation
- development density
- habitat protection and site disturbance
- green space and corridors
- stormwater management
- heat islands
- light pollution
- erosion
- soil depletion/quality
- native/adapted species use

Energy
- energy optimization
- use of renewable energy sources
- daylighting
- natural ventilation
- thermal massing
- commissioning
- refrigerants/ ozone depletion
- measurement and verification of systems
- passive design and reduction of artificial systems

Materials
- sustainable harvesting
- recycled content
- recyclability/disassembly
- toxicity
- local sourcing
- material reuse/salvage
- existing building reuse/renovation
- design for disassembly
- construction waste
- local/regional materials
- bio-based materials
- durability
- certified materials and products

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Water
- efficient use of building and landscaping
- rainwater catchment
- greywater system
- wastewater processing
- water equity

Indoor environmental quality
- air quality (ventilation, toxicity)
- construction air quality
- views to the outside
- occupant thermal comfort
- light quality and natural lighting
- carbon dioxide monitoring

Inspiration
- beauty
- essence of place
- historical/cultural

Neighborhoods
- mixed-use
- proximity to public transit
- walkability
- bicycle friendly
- cultural amenities

How do we measure?

How we measure relates to the technical metrics behind the rating systems. There are multiple green building rating systems in use, as well as green product evaluation methods. The Metrics Glossary at the end of this section provides a brief definition and internet links for various rating systems currently in use.

What do we do with all this information?

How do we integrate what we know needs to happen into our organizations, procedures, industry standards, and building structures? Delivery of sustainable buildings involves measurement, verification, and documentation of what we are achieving and what we are aiming for. Rating systems, although in flux, provide some framework for this task. Also important is active training and support in these topics for structural engineers and other design professionals. It will be some time before industry environmental standards can provide a clearly marked road map for broad scale change. What will remain voluntary and what will become codified is yet to be determined on the national and international scale.

The individuals and companies that begin to consider the environment as the silent stakeholder in their projects will take the lead. An integrated design process reconnects all the stakeholders for a given project: the owner, the builder, occupants, and each discipline on the design team, the site eco-system, and surrounding sites. Feedback loops within the industry can communicate performance and aid deeper understanding of how design intent and goals compare with actual results. Success in sustainable design requires thinking intentionally about measurement and expanding the scope of structural engineers' dialogue to include not only material considerations, but also building science, ecology, and ethics.

Glossary

Several terms, organizations, and programs are dedicated to various aspects of sustainability in buildings. Many are explained briefly below, and websites are provided for additional resources.

Rating systems

Understanding each of the rating systems will shed light on the variety of needs of project stakeholders.

Collaborative for High Performance Schools (CHPS) (www.chps.net) — CHPS is a green building rating system designed specifically for K-12 schools. It was originally developed for California schools in 1999 to reduce school energy use, but has since expanded into a national program with similar credit categories as that of the LEED rating system. CHPS has developed and maintains a six-volume, technical best practices manual for high performance schools. The manual covers planning, design, high performance benchmarks, maintenance and operations, commissioning and relocatable classrooms. Schools can self-certify through the free "CHPS Designed" program or seek third party verification through the "CHPS Verified" program. There are similarities and differences between CHPS and the USGBC LEED for Schools rating system. Some of the differences stem from how the CHPS program priorities differ from those of the USGBC. The USGBC's goal is to transform the building marketplace by targeting the top 25 percent of buildings. CHPS's goal is to create a "new generation of green, healthy schools" by targeting all schools. The focus is to impact all schools by reducing school district energy costs and improving student and teacher performance and health through a greater emphasis on the indoor environment. The CHPS materials credits are very similar to LEED, although they incorporate additional credits related to organically grown rapidly renewable materials and the use of Environmentally Preferable Products. CHPS 2009 is slated to include a credit that addresses designing for adaptability, durability, and disassembly.

Energy Star Program (www.energystar.gov) — Energy Star is a joint program by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy to promote energy efficient products and practices. The system involves individual consumer product ratings, programs for energy saving home improvement, as well as qualification of new homes and commercial/industrial construction. The EPA, through Energy Star, provides strategies, tools, professional assistance, and recognition opportunities to improve energy efficiency. The Residential Energy Services Network (RESNET) home energy rating system (HERS) is becoming a standard for home energy efficiency and includes a plan review and on-site inspections for energy audit concerns such as leaking ducts and home weatherization. RESNET's standards provide verification of a home's energy performance for the Energy Star Homes program.

Green Globes Program and the Green Building Initiative (GBI) (www.greenglobes.com) — Green Globes is an environmental assessment and rating system that was developed by the Green Building Initiative (www.thegbi.org) and grew out of a Canadian system that is based on the UK's Building Research Establishment's Environmental Assessment Method (BREEAM). Green Globes was introduced in the United States in 2004, and was developed into a proposed American National Standard for Green Building Assessment (GBI ANSI 01-200XP) that is currently in a public comment period. It uses a web-based interface where users complete a series of questionnaires at various project stages. Following completion of the questionnaire, a report discussing the environmental benefits of each design strategy is automatically generated. If a rating is desired and a minimum threshold score is achieved, the building project is eligible to schedule an independent third party review and site assessment that leads to a formal Green Globes rating. Green Globes contains features of interest to the structural engineer, some of which are not included in LEED. It awards points for using an integrated design process as well as for commissioning of structural systems in accordance with ASHRAE Guideline 0-2005, *The Commissioning Process*. Additional points are awarded for designing for adaptability and disassembly. Green Globes also awards materials points if the selection of the structural system is informed by life cycle assessment (LCA). Refer to Section 1.4 Green Globes for additional information.

Green Guide for Healthcare (GGHC) (www.gghc.org) — GGHC is a voluntary sustainable design toolkit addressing issues unique to healthcare facilities. It is not an official rating system or a LEED product, but has worked in partnership with the USGBC and borrowed much, by mutual agreement, from LEED during its development. The GGHC is self-certifying and does not contain threshold levels. It is not intended to be a minimum standard, but to serve as an educational guide for the sustainable design, construction, and operations of high-performance healing environments and to encourage continuous improvement in the health care sector. The GGHC contains integrated design, design for flexibility, and design for durability credits.

LEED and the United States Green Building Council (www.usgbc.org) — Leadership in Energy and Environmental Design (LEED) is a national green building rating system for the design, construction and operation of high-performance green buildings. LEED was introduced in 1998 and was the first widely accepted tool in the

United States to establish and award sustainability ranking based upon third-party verification. While initially only applicable to new construction, a number of variations have since launched to address renovations and building operations, as well as subsets of new construction. The LEED system is the most frequently used rating system for U.S. commercial and institutional markets, and therefore it is the rating system most often encountered by structural engineers. Refer to the Section 1.3 LEED Rating System for additional information.

Living Building Challenge (www.cascadiagbc.org/lbc) — The Living Building Challenge is a program developed by Jason McLennan of the Cascadia Region Green Building Council that seeks to move targets beyond the LEED platinum level. It is a guideline that begins to lay a framework for net-zero buildings. The program has no credits, just 16 pre-requisites that must be achieved. Compliance with the standard is based on actual, not intended or modeled performance. The prerequisites include goals such as the following:

- 100 percent on-site renewable energy,
- 80 to 100 percent of construction waste diverted, depending upon type of material,
- closed loop hydrologic cycles for water source and wastewater,
- building only on previously developed sites,
- zero use of off-limits materials, called the "Materials Red List",
- only Forest Stewardship Council (FSC) or salvaged wood, and
- a materials/services radius list that defines how far a material can travel based upon its weight.

The Living Building Challenge at this time does not address the issues surrounding closed loop material cycles such as addressing the building's end-of-life (disassembly, recyclability, safe non-toxic disposal, etc.).

National Association of Home Builders' (NAHB) Green Homebuilding Guidelines (www.nahbgreen.org) — The NAHB has developed a voluntary model standard for the mainstream home builder to incorporate green practices into their building methods. These guidelines, available since 2005, cover seven areas: Lot Preparation and Design, Resource Efficiency, Energy Efficiency, Water Efficiency/Conservation, Occupant Comfort and Indoor Environmental Quality, Operation and Maintenance, and Homeowner Education. The guidelines have three certifying levels: bronze, silver, and gold.

The program can be used as a self-certifying tool or a local accredited verifier can provide a report so that a Certified Green Home certificate may be issued. Local green home building programs have also developed in various parts of the country including Built Green (www.builtgreen.net) in the Northwest and Built It Green (www.builditgreen.org) in California. These local programs sometimes partner with the NAHB, while others have their own rating systems, certified professionals, and verification process. An ANSI approved green residential standard is under development by the NAHB and the International Code Council.

Environmental standards and guidelines

Various environmental standards and guidelines are listed below. In some cases, there is overlap between standards and the sections below on life cycle assessment and product based rating methods. Each listing in this glossary was placed according to where it appeared to best fit within these categories.

Advanced Energy Design Guides (www.ashrae.org) — These energy design guidelines were developed by ASHRAE, AIA, IESNA, USGBC, and the Department of Energy. They provide a sensible approach to achieve energy reductions using practical products and off-the-shelf technology. The guidelines are available for free download at the website above and are generally geared toward smaller projects. Of particular interest to structural engineers will be the sections on the building envelope.

American National Standards Institute (ANSI) (www.ansi.org) — ANSI facilitates the development of standards by accredited organizations. Accreditation by ANSI signifies that the procedures used in standard development and certification programs meet the requirements for openness, balance, consensus, and due process. ANSI partners with multitudes of environmental standards developers and product certification agencies. Refer to their website for more information.

ASTM International (www.astm.org) — ASTM is a standards development organization and has a sustainability subcommittee. Engineers and green building practitioners use many of their standards on subjects ranging from materials to remediation to solar reflective index. A list of their standards related to sustainability is available on the website above.

International Organization for Standardization (ISO) (www.iso.org) — ISO has over 350 standards for monitoring of air, water and soil quality. The ISO 14000 series deals with environmental management standards that can be implemented within organizations. Additional ISO 14000 family standards, some still in progress, deal with life cycle assessment, product design and development, eco-design and greenhouse gases.

State of California Special Environmental Requirements Specification Section 01350 (www.ciwmb.ca.gov/greenbuilding) — This specification establishes goals and provides an overview of environmental requirements in areas similar to other green building rating systems but with key elements related to indoor air quality to protect human health. This part of the specification includes product selection guidelines and emission-testing protocols to distinguish low-emitting materials. Section 01350 has been incorporated into the California Department of General Services standard agreement for engineering and architectural services.

Life-cycle assessment (LCA)

LCA uses inventory analyses from all stages of a product or system's life cycle to perform quantitative comparisons of multiple environmental impacts and cost information. Because of the large amount of product data analyzed in LCA, tools are available to facilitate the process. Some methods allow weighting across impact categories, so that impact (or damage) results are given weights in a total score. Refer to Section 2.6 of these guidelines for more information on the various LCA metrics and tools.

Product-based rating methods and programs

There are numerous product-based rating methods and programs. Many deal with raw materials, interior and exterior finishes, carpets, paints, adhesives, recycled content, responsible sourcing, and more. Following is a sampling of such methods, although a detailed explanation of each is beyond the scope of this report. Since structural engineers do not typically specify finish materials, this list is provided as a starting point.

Architectural Record **Green Product Guide** (www.archrecord.construction.com) — Listing of green products, by specification section, based upon interpretation of the *Architectural Record* staff.

BuildingGreen GreenSpec™ Directory (www.buildinggreen.com) — Lists product descriptions for environmentally preferable products based upon independent research.

California Integrated Waste Management Board (CIWMB) Recycled Content Product Database (www.ciwmb.ca.gov/rcp) — Directory to aid in purchasing of recycled content products. This program lists recycled materials and provides information on manufacturers, distributors, and re-processors of these products.

Carpet and Rug Institute Green Label™ and Green Label Plus™ (www.carpet-rug.org) — This group maintains standards for carpet, cushions, and adhesives.

Cradle to Cradle™ Certification (www.mbdc.com/c2c) — Certification by McDonough Braungart Design Chemistry for products that employ cradle to cradle concepts. The measurement system involves: safe and healthy materials, design for material reutilization, use of renewable energy, efficient use of water, and strategies for social responsibility.

Ecologo™ (www.ecologo.org) — Multiple attribute environmental standard and certification evaluation that compares products and services with others in the same category using scientifically relevant criteria.

Environmentally Preferable Products/Purchasing (EPP) — There are various definitions and standards for EPP, one being the EPA program for federal government purchasing (www.epa.gov/epp) and another being the State of California EPP Best Practices Manual (www.green.ca.gov/EPP/Introduction).

Greenguard™ (www.greenguard.org) — Product and building certifications based on testing for indoor air quality, with a unique set of criteria for children and schools based upon State of California specification section 01350.

Green Seal™ (www.greenseal.org) — A non-profit organization that sets environmental standards and then certifies products according to those standards. Examples of standards include paints and coatings, food service packaging, and household cleaners.

National Institute of Standards Technology (NIST) Building for Environmental and Economic Sustainability (BEES) (www.bfrl.nist.gov/oae/software/bees/) — BEES is public domain software that performs LCA for individual building products, although not entire buildings. It is based on applicable ISO and ASTM standards. BEES includes many environmental impact categories as well as consideration of economic factors. Refer to Section 2.6 on LCA for more information.

Pharos Project™ (www.pharoslens.net) — Project by the Healthy Building Network, the Center for Clean Products and Technologies, and the Cascadia Region Green Building Council. The initiative covers health, resource sustainability and social justice.

Resilient Floor Coverings Institute (RFCI) Floorscore™ (www.rfci.com) — Flooring product certification developed in partnership with SCS.

Scientific Certification Systems (SCS) (www.scscertified.com/ecoproducts) — SCS develops standards and provides third-party certification on a variety of products including office furniture systems, carpet, flooring, paints and finishes. SCS is also working in partnership with ANSI to develop ANSI SCS-002, *Type III Life-Cycle Impact Profile Declarations for Products and Services*.

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1.3

LEED RATING SYSTEM

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Created by the United States Green Building Council, the Leadership in Energy and Environmental Design (LEED) Rating System was introduced in 1999, and is the most popular green building rating system now in use in the United States. If practicing structural engineers have not worked on a LEED project yet, they will likely work on one soon. In this section, we introduce LEED, describe how it works, and explain how structural engineers can contribute to the achievement of LEED certification.

Development and objectives of the LEED Rating System

The LEED Rating System is a product of the United States Green Building Council (USGBC), a non-profit organization founded in 1993. The USGBC membership is made up of all building stake-holders, including owners, architects, engineers, and regulators. The USGBC's mission is "to transform the way buildings and communities are designed, built and operated, enabling an environmentally and socially responsible, healthy, and prosperous environment that improves the quality of life." LEED products are developed by committees and issued for comment to membership and stakeholders. Following response to comments, the final products are voted on by membership, and if approved, released for use.

The USGBC's core rating system is LEED-NC (LEED for New Construction). The USGBC issued LEED in a pilot version in 1999. Based on experience with the pilot, the USGBC released LEED Version 2.0 in March, 2000, and subsequently released updated Versions 2.1 and 2.2. In November 2008, the USGBC membership voted to approve LEED 2009, which took effect in April, 2009. Projects registered under LEED 2009's predecessor, Version 2.2, will continue under this earlier version.

The USGBC now has a range of LEED products that are targeted towards certain building types. Table 1.3-1, summarizes the status of the various LEED rating systems as of 2009.

The LEED Rating System has been criticized in some quarters for weaknesses. Some LEED-certified buildings, for example, have not met predicted energy performance, and the environmental benefits the credits provide vary widely. The USGBC is working to improve LEED so that it will more consistently deliver buildings with superior environmental performance. While LEED is a good starting point, practitioners need to realize that no rating system can guarantee excellent environmental performance. For the structural engineer, it is ultimately more valuable to address the environmental impacts of structural materials and systems using the rational approaches and knowledge base provided by these guidelines than to merely seek LEED credits.

Table 1.3-1. Summary of the LEED rating systems

Name	**Current version**	**Date released**	**Description**
LEED-NC	3.0	2009	For new buildings and major renovations
LEED-EB	3.0	2009	For existing buildings
LEED-CI	3.0	2009	For commercial interiors; may be used with LEED-CS
LEED-CS	3.0	2009	For core and shell developments; may be used with LEED-CI
LEED for Schools	3.0	2009	For new construction and major renovations of K-12 school facilities
LEED for Retail	Pilot	2007	Two versions in pilot, one for new construction and one for commercial interiors; expected release 2009
LEED for Healthcare	Comment Period	N/A	For new construction and major renovations of health care facilities; expected release 2009
LEED-Homes	none	2008	For new construction of one- and multi-family homes. New version slated in 2011
LEED-ND	Comment Period	N/A	For neighborhood development (multiple buildings); expected release 2009

LEED structure

LEED is a point-based rating system. The points are achieved by satisfying credit requirements. The project's LEED rating depends on how many points the project achieves. The levels of achievement (from easiest to hardest) are: Certified, Silver, Gold, and Platinum. The required thresholds vary with the rating system. For LEED NC v. 2.2, 69 points are available, exclusive of the Innovation & Design Process category (discussed below). The thresholds for certification are as follows:

- Certified: 26 to 32 points
- Silver: 33 to 38 points
- Gold: 39 to 51 points
- Platinum: 52 to 69 points

New LEED rating systems for 2009 all have a total of 100 available points to make achievement thresholds more uniform between systems.

All LEED rating systems have six categories of credits. The categories and associated points for LEED NC v. 2.2 and v. 2009 are shown in Table 1.3-2.

Table 1.3-2. Comparison of LEED NC v. 2.2 and v. 2009

LEED Category	**v. 2.2**	**v. 2009**
Sustainable Sites	14	26
Water Efficiency	5	10
Energy & Atmosphere	17	35
Materials & Resources	13	14
Indoor Environmental Quality	15	15
Innovation & Design Process	5	15
Regional Priority Credits	N/A	4

LEED credits of particular interest to structural engineers

Structural Engineers have the most influence over the Materials and Resources (MR) credits, which are summarized for LEED-NC below. Refer to the LEED-NC Rating System and Reference Guide (USGBC 2007a) for more information.

MR Credit 1 (3 points available in v. 2.2, 4 points available in v. 2009): Building Reuse — LEED gives credit for reusing existing building stock. In v. 2.2, the following thresholds apply: one point is given for maintaining at least 75 percent of existing building structure and envelope; two points are given for maintaining at least 95 percent of existing building structure and envelope; an additional point may be earned for reusing at least 50 percent of existing non-structural elements (interior partitions, doors, floor finishes, ceiling systems). In the 2009 version, an additional point is available at the 55 percent threshold for structure and envelope. Calculations are based on surface area of reused floors, roofs, and walls. This credit currently has a very low achievement rate (most LEED projects are new construction, not renovation). Structural engineers have an opportunity to influence the achievement of this credit when they are engaged to perform feasibility studies on building reuse. In many cases, however, the decision to renovate or build new is made by the project owner before the engineer becomes involved.

MR Credit 2 (2 points available): Construction Waste Management — LEED gives credit for diverting construction and demolition waste from disposal to landfill and incinerators. One point is given for recycling or salvaging at least 50 percent of the non-hazardous construction and demolition (C&D) waste, and two points for diverting at least 75 percent of this waste. This credit has a very high achievement rate. Structural engineers do not have much influence over the achievement of this credit. Engineers can reduce project waste by using shop-fabricated assemblies, but waste that never reaches the site is not counted in the calculation.

MR Credit 3 (2 points available): Materials Reuse — LEED gives credit for using salvaged materials. One point is given for using salvaged materials for at least 5 percent of the project materials by cost, and two points for 10 percent. The cost basis of the salvaged materials may be actual cost paid or the cost of equivalent new materials. This credit has a very low achievement rate. Engineers can encourage and facilitate the use of salvaged structural materials. See Section 2.5 — Reuse for more information.

MR Credit 4 (2 points available): Recycled Content— LEED gives credit for using materials with recycled content. One point is given when 10 percent by cost of the project materials are recycled, and two points for 20 percent. If a material or product has only partial recycled content, only the percentage by weight of the recycled portion of the product or material counts towards the calculation. Post-consumer recycled content is given full value in the calculation and pre-consumer recycled content is given half value. Post-consumer waste is defined as "material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose." Pre-consumer waste is defined as "material diverted from the waste stream during the manufacturing process."

The default recycled content offered for steel products is 25 percent post-consumer. Most structural steel has much higher recycled content, and the project team may submit actual recycled content obtained from the steel producer if it wishes to receive full credit. SCMs in concrete, such as fly ash and slag, are counted as pre-consumer recycled content. Recycled content for SCMs may be calculated as a percentage of cementitious materials rather than as a percentage of the entire concrete mix. An example calculation is provided later in this section. Other structural materials may also be eligible for this credit, such as steel reinforcement, cold-formed steel, masonry, and structural fill/sub-grade materials. See the Building Materials section of this guideline (Section 3) for additional information. This credit has a very high achievement rate.

MR Credit 5 (2 points available): Regional Materials— LEED gives credit for using materials that are sourced from within a 500-mile radius of the project site. The material must be extracted, processed, and manufactured within the given radius. One point is given when 10 percent of the project materials by cost are sourced regionally, and two points for 20 percent. If only a fraction of a product or material complies, then only that percentage, by weight, can contribute to this credit. An innovation in design exemplary performance credit is awarded at 40 percent. This credit has a very high achievement rate.

Concrete and masonry products often meet these requirements. Steel seldom meets the requirement, since the scrap steel must be sourced within the 500-mile radius to count, and the steel must be produced and fabricated within the 500-mile radius as well. Reused and salvaged materials that qualify for LEED MR Credit 3 also are eligible for Credit 5. The location from which materials were salvaged is to be used as the point of extraction, and the location of the salvaged goods vendor is to be used as the point of manufacture. On-site salvaged materials automatically qualify.

MR Credit 6 (1 point available): Rapidly Renewable Materials — LEED gives credit for using "rapidly renewable" materials. LEED defines rapidly renewable as "made from plants that are typically harvested within a ten-year cycle or shorter." One point is given for using rapidly renewable materials for at least 2.5 percent of the project materials by cost. Few structural materials are rapidly renewable. Examples of rapidly renewable materials are bamboo, agrifiber, wheatboard, and strawboard. Bamboo is occasionally used structurally, particularly overseas. This credit in its current form has a very low achievement rate.

MR Credit 7 (1 point available): Certified Wood — LEED gives credit for using certified wood. LEED presently only recognizes wood certified by the Forest Stewardship Council (FSC). One point is given for using a minimum of 50 percent certified wood, by cost, as a percentage of all wood used on the project. At its discretion, a project team may include wood products purchased for temporary use on the project, such as formwork, shoring, and bracing, in the calculation, so long as all such wood is included in the calculation denominator. Credit for wood products purchased for temporary use is only allowed for one project in cases where the wood is used for multiple projects. In late 2008, a proposal to open MR Credit 7 to any certification system that meets pre-defined benchmarks is in a comment period. This credit in its current form has a low achievement rate.

Credit Interpretation Requests (CIRs) — Project teams sometimes submit CIRs to the USGBC to determine whether particular strategies for achieving credits are acceptable. The USGBC maintains a list of these CIRs and responses on its website. Reviewing the CIRs related to a credit can help a project team achieve the credit.

Innovation and regional credits

The LEED Rating System v. 2.2 has up to 4 points (6 points in v. 2009) available for "Innovation in Design" in the Innovation and Design Process (ID) section. These points may be awarded for exceptional achievement of the standard credits, or for using design strategies that are not recognized elsewhere in LEED.

Exceptional achievement in the standard credits means that the project team has surpassed the minimum requirements for achievement by an additional factor. For example, MR Credit 6 awards a point for using 2.5 percent rapidly renewable materials. If the project team can double this achievement to 5 percent, it will be eligible for an innovation credit. Similarly, MR Credit 5 awards one point for using 10 percent regional materials, and two points for 20 percent. If the project team can increase the quantity of regional materials to 40 percent, it will be eligible for an innovation credit.

Sometimes innovation credits may be achieved through precedent. For example, LEED has a standing innovation point for 40 percent replacement of cement with supplementary cementitious materials (SCMs) such as fly ash and slag. This innovation credit is billed as a carbon-reduction credit, in that it reduces the CO_2 emissions that cause global warming. The credit requires the following:

- A minimum 40 percent reduction in CO_2 by weight for all cast-in-place concrete, compared to standard baseline mixes.
- The cast-in-place concrete work must make up a significant proportion of the project work.
- To demonstrate that the requirements are met, the following instructions are provided:
- One pound of cement is equivalent to one pound of CO_2.
- Baseline mixtures are standard 28-day mixtures in the project region.
- Temperature effects must be considered (this goes without saying!) and documented. This requirement may be for educational purposes.
- SCMs may be fly ash, slag, silica fume, and rice hull ash.

Other innovative design strategies may also qualify for ID credits. For example:

- A design team could use life-cycle assessment (LCA) to optimize its building design and demonstrate quantified benefits compared to a "typical" building design.
- A design team could attempt to obtain a point by demonstrating high efficiency in the use of materials compared to a "typical" building design. The use of LCA could help make such an argument.
- A design team could incorporate Design for Deconstruction and Adaptability into the project, demonstrating that its proposed design simplifies future adaptation and deconstruction of the building, compared to a "typical" building design. It is this author's understanding that at least one LEED project has successfully obtained an ID point using this strategy.

The USGBC published a list of all the innovation credits granted in 2007 (USGBC 2007b). Project teams may refer to this list to brainstorm ideas for innovation credits on their own projects. Circumstances vary from project to project, and over time, so the USGBC does not guarantee that a credit granted in the past will be granted to other projects.

LEED 2009 adds regional credits to the rating system. Regional credits address regional environmental priorities. Local USGBC chapters determined which existing LEED credits should receive extra credit in their regions and prepared lists of these credits organized by project zip code. Projects that achieve the designated credit requirements receive an additional point, up to four points per project.

Achieving credits

Credits must be achieved as a team. Most of the Materials & Resources credits apply to all the materials in a project except for mechanical systems and furniture, although in some cases certain mechanical systems and furniture may be included at the project team's discretion. The materials credits are evaluated with respect to all the materials on the project – for example, the cost of all the materials with recycled content is compared to the total materials cost for the project (i.e. not all materials have to have recycled content to achieve the credit). The team must decide which credits it will seek, and then work together to achieve them. If the team decides to go after the recycled content credit, for example, the structural engineer can help by specifying materials with high recycled content, such as structural steel, and furthermore by selecting steel products with the highest recycled content. All major structural materials can contribute to LEED credits (Table 1.3-3).

Table 1.3-3. How major structural materials can contribute to LEED credits

Material	**Most relevant LEED credits**
Concrete	*Recycled Content*: Maximize SCMs; reinforcement usually high recycled content *Regional Materials*: Raw materials and manufacturing often within 500 mile radius *Heat Island Effect*: LEED-NC Sustainable Sites Credit 7.1 offers credit for the use of light-colored pavements such as white concrete. Light-colored pavements in combination with other strategies such as shading and open-grid pavements must be used for at least 50 percent of the site hardscapes to achieve the credit. *Energy Use*: LEED-NC Energy & Atmosphere Credit 1 offers points for building energy efficiency. Careful application of exposed concrete and masonry surfaces can help achieve this credit, since the thermal mass of these materials can help reduce daily temperature swings and capture solar heat during the heating season.
Masonry	*Recycled Content*: CMU, mortar, and grout with SCMs; steel reinforcement *Regional Materials*: Raw materials and manufacturing often within 500 mile radius *Energy Use*: See Concrete section above in this table.
Steel	*Recycled Content*: Structural steel can be a dominant contributor to this credit
Wood	*Certified Wood*: Specify FSC-certified structural lumber *VOCs*: LEED-NC Indoor Environmental Quality Credit 4.1 awards one point for the use of low-VOC adhesives, including structural wood adhesives with a VOC content of less than 140 g/L.

The structural engineer can help the project team by including LEED submittal requirements in the structural specifications. Although project teams are no longer required to submit all the supporting documentation with their LEED submittals, the USGBC audits selected credits in each application and requests full documentation. The project team should be prepared to provide the documentation if requested, especially since it can be difficult or impossible to collect after the fact. Documentation requirements for the Materials & Resources credits most likely to affect the structural engineer are summarized in the Table 1.3-4.

Table 1.3-4. Documentation requirements for the Materials & Resources credits most likely to affect the structural engineer

Credit	**Documentation requirements**
Credit 3: Salvaged Materials	• Total project materials cost. • Tabulation of each salvaged material, including description, source, and cost. • Narrative describing material reuse strategy for the project.
Credit 4: Recycled Content	• Total project materials cost. • Tabulation of each material with recycled content, including description, manufacturer, cost, pre-consumer and/or post-consumer recycled content, and the source of the recycled content data. • Optional narrative describing any special project circumstances.
Credit 5: Regional Materials.	• Total project materials cost. • Tabulation of each regional material, including product name, material manufacturer, product cost, percentage of product meeting extraction and manufacturing requirements, distance from extraction location to project site, and distance from manufacturing location to project site. • Optional narrative describing any special project circumstances.
Credit 7: Certified Wood	• Tabulation of each FSC-certified wood product, including product type, manufacturer, and chain-of-custody number. • Optional narrative describing any special project circumstances.

In addition to the Materials & Resources credits, structural engineers can help achieve Energy & Atmosphere credits if the thermal mass of structural systems is used to reduce building energy use. Materials such as concrete and masonry are good thermal reservoirs and can help reduce temperature swings, particularly in regions where night-cooling is an effective energy-reduction strategy, or in envelope-dominated buildings in cold climates where passive solar heating strategies are effective. Use of shallow floor systems can also help reduce building energy use, particularly for mid- to high-rise buildings. For example, post-tensioned concrete floor systems can be significantly shallower than conventionally reinforced and structural steel floor systems. Shallow floor systems reduce the story-to-story height and the volume of interior space that requires heating and cooling.

Calculations — For illustrative purposes, the calculations for the recycled material credit (MR Credit 4), which is commonly achieved with the help of structural materials, are outlined below for a project using both fly ash and structural steel. The following two steps outline how to calculate recycled material content:

Step 1: Calculate the Recycled Content Value of each applicable material: Recycled Content Value ($) = (percent post-consumer recycled content x material cost) + 0.5 x (percent pre-consumer recycled content x material cost).

LEED permits the Recycled Content Value of concrete with SCMs to be calculated in two ways. The first way is to treat the concrete as an assembly. In an assembly, only the percent by weight of the components containing recycled material is in included in the calculation. For this example, assume that the concrete cementitious materials are 40 percent fly ash, that the cementitious materials make up 10 percent of the mix by weight, and that the value of the concrete (material only) in the project is $100,000. Then the recycled content value of the concrete is 0.5 x 0.4 x 0.1 x $100,000 = $2,000 (SCMs are pre-consumer so are subject to the 50 percent reduction factor).

The alternate calculation path developed specifically for the use of SCMs is to base the SCM percentage on value of the cementitious materials only. In the case of our example, assume that the value of the cementitious material is $30,000. Then the recycled content value is 0.5 x 0.4 x $30,000 = $6,000. The second calculation path generally gives more favorable results, but requires the ready-mix company to break out the cost of the cementitious materials. Table 1.3-5 is based upon the second path.

Step 2: Calculate the project percent recycled content: Percent Recycled Content = Total Recycled Content Value ($) / Total Materials Cost ($)

Assume the total project materials cost is $2,500,000. Then the Percent Recycled Content is 24 percent. The thresholds for recycled content are 10 percent for one point and 20 percent for two points. This project would therefore be eligible for two points under MR Credit 4.

Table 1.3-5. Alternate path for calculating recycled content.

Material	**Post-consumer recycled content**	**Pre-consumer recycled content**	**Material value**	**Recycled content value**
Cementitious materials		40%	$30,000	$6,000
Concrete reinforcement	55%	30%	$50,000	$35,000
Structural steel	45%	30%	$250,000	$150,000
Total Structural				**$191,000**
Non-structural materials				$400,000
Project Total (all materials)				**$591,000**

Improving LEED

Certain changes to LEED could allow structural engineers to contribute more significantly to the LEED process. Suggestions that would give the structural engineer a greater role include the following:

- Add a credit for design for deconstruction (DfD). Most of the building's mass is in the building structure. Encouraging DfD would make the future salvage of structural components more likely.
- Add a credit for durability. The structural system is the most permanent part of a building. Other systems, such as mechanical systems and the envelope, are often replaced during the life of a building, but the structural system remains intact. A credit for durability could lead to system designs that extend the life of the building by reducing the chances of premature deterioration and failure. LEED-NC Canada already offers a durability credit that requires the project team to design selected building systems to meet or exceed service life targets set by the Canadian Standards Association S478-95, *Guideline on Durability in Buildings* (CSA 1995).
- Increase the number of innovation credits. Innovation credits have been achieved for strategies such as structural system efficiency and design for deconstruction. However, many LEED projects use up all their innovation credits on other strategies, leaving none for the strategies that structural engineers may propose. Increasing the number of available innovation credits would increase the opportunities available to structural engineers to contribute to achieving LEED certification.

The LEED Green Building Rating System is a work in progress. The USGBC, through its paid staff, volunteer committees, and public comment process, is continuously working to improve LEED. In late 2008, the USGBC is working on improvements to the bio-based materials credits (MR Credits 6 and 7) and introducing life-cycle assessment (LCA) options to achieve credits. During 2009, the USGBC will discuss what will likely be major changes for the next version of LEED, scheduled for 2011. Structural engineers have a stake in this process and need to become involved in LEED committee work and the public comment process.

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1.4

GREEN GLOBES RATING SYSTEM

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The Green Globes Rating System is a product of the Green Building Initiative™ (GBI), a non-profit organization. It is used in both the United States and Canada. The development of Green Globes was originally influenced by Canada's adaptation of the UK Building Research Establishment Environmental Assessment Method (BREEAM) in 1996. That standard has been refined several times and spawned the development of a draft American National Standard for Green Building Assessment (GBI 2009), on track for approval in late-2009. The GBI's mission is "to accelerate the adoption of building practices that result in energy-efficient, healthier and environmentally sustainable buildings by promoting credible and practical green building approaches for residential and commercial construction." The following discussion provides an overview of the Green Globes system for those unfamiliar with its features.

In addition to an assessment protocol based on the proposed standard (GBI 2008) and a web-based rating system (www.thegbi.org), Green Globes for New Construction serves as a design tool, suggesting improvements and guiding the integration of green principles throughout the design process. This is accomplished through use of software tools designed for Green Globes and provided to the design team. Examples of these tools are the Green Globes™ LCA Credit Calculator for Building Assemblies and the Green Globes™ Water Consumption Calculator. Green Globes allows users to change inputs for up to a year so they may keep assessments up-to-date, and to compare multiple buildings within a portfolio. As more buildings are Green Globes rated, point scores will be aggregated in an anonymous database (maintained by GBI), enabling users to analyze how their designs perform in relation both to the median and to buildings that are similar in terms of size, type, and region.

What does the Green Globes System measure?

As in other rating systems such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED), there are four "achievement levels" (based on a percentage of 1,000 total points) as follows:

• One Green Globe:	35 to 54 percent
• Two Green Globes:	55 to 69 percent
• Three Green Globes:	70 to 84 percent
• Four Green Globes:	85 to 100 percent

Although the architect may be the coordinator of the entire construction document set, specific performance of the building is directly related to the building sub-systems, choice of materials and monitoring/control systems. Green Globes evaluates a sustainable project in the following areas: project management, site, energy, water, resources/materials, emissions and storage of hazardous materials, and indoor environment (Table 1.4-1).

Table 1.4-1. Point structure for the Green Globes rating program

Environmental assessment area	**Total points available**	**Minimum number of points required for compliance**
Project Management	100	50
Site	120	24 (0 for *major renovations*)
Energy	300	Performance Path A: 150
		Prescriptive Path B: 100
Water	130	26
Resources/Materials	145	29
Emissions and Storage of Hazardous Materials	45	9
Indoor Environment	160	32

Assessment and certification processes

Green Globes tools are typically initially used for web-based self-assessment during the conceptual and design phases, providing the design team with immediate feedback on the sustainability implications of specific project design decisions. Once the self-assessment is completed, and if the assessment indicates a minimum threshold score of 35 percent of the 1,000 available points, the building project is eligible to schedule an independent third party review and site assessment that leads to a formal Green Globes rating. Depending on the points scored after the independent assessment, buildings are assigned a rating of one to four Green Globes.

Green Globes assessment for structural engineers

Within each assessment area, there are several criteria and practices that must be met during the design and operation of the building. The aspects of a building project where the structural engineer plays a key role are listed below. The first 5 sections of Green Globes address general issues and definitions. Specific criteria for compliance begin in section 6 of the documents. Although some of the topic areas in Green Globes are the primary responsibility of another member of the design team, such as the architect or the mechanical engineer, a brief overview of each section is provided herein to provide a broader context on Green Globes for structural engineers. For those areas of primary interest to structural engineers (such as Section 10, Materials and Resources), significantly more information is provided.

Brief overview of specific Green Globes sections

The following sections, while not the primary responsibility of the structural engineer, will impact building design decisions. This brief overview provides a broader perspective of the Green Globes provisions. The following discussion is based on the GBI Proposed National Standard 01-2008P, Public Review Draft dated 24 October 2008. This standard is not yet ready for public use, but is similar to the web-based version of Green Globes that is presently available. In the future, GBI intends to align the web-based version of Green Globes with the final ANSI standard.

Project Management (GG Section 6) — All systems, including electrical supply, lighting, HVAC, structural, mechanical, plumbing, fire protection ,interior systems, and conveying systems, require commissioning in the pre-design, design, and construction phase per American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Guideline 0-2005. Points are awarded for various levels of pre-design team meetings specifically dedicated to discussion of green topics.

Green Globes offers four points for commissioning of the structural system. Structural systems commissioning is not widely practiced, so some of the commissioning requirements, as outlined in the ASHRAE guideline, are explained here.

Pre-design phase: Tasks for this phase include the following:

- Form a Commissioning Team to develop and administer the Commissioning Plan. The Commissioning Team is responsible for all project system commissioning requirements, including structural, so should include an independent structural engineer.
- Develop the Owner's Project Requirements.
- Develop the commissioning scope and budget and prepare the Commissioning Plan.
- Define Issues Log procedures and periodically prepare an Issues Report. The Issues Log lists all design, installation, and performance issues that do not meet the Owner's Project Requirements.
- Periodically Prepare Commissioning Process Progress Reports.

Design phase: Tasks for this phase include the following:

- Prepare the Basis of Design. Some structural engineering firms routinely prepare such documents for their design work.
- Update Commissioning Plan as needed.
- Ensure commissioning requirements are included in the Contract Documents.
- Prepare Construction Checklists, Systems Manual, and Training Requirements (may not be needed). The training requirements should include information about proper maintenance of the structural system, if required.
- Review design professional's submittals.

Construction phase: Tasks for this phase include the following:

- Verify installed systems and assemblies meet the Owner's Project Requirements.
- Explain commissioning requirements during Pre-Bid Conference.
- Update Owner's Project Requirements and Commissioning Plan as required.
- Conduct pre-construction Commissioning Process meeting with the commissioning team.
- Verify representative sampling of project submittals.
- Define, develop, and monitor field test procedures. In the case of structural systems, the Structural Engineer of Record would likely define the required structural tests, but these could be reviewed and approved by the Commissioning Team.
- Develop test data records. In the case of the structural systems, this work might be out-sourced to the testing agency; alternatively, the testing agency might be a member of the

Commissioning team: Tasks for this phase include the following:

- Conduct periodic Commissioning Team meetings.
- Conduct periodic site visits.
- Prepare a Construction Phase Commissioning Report.

Structural commissioning is an interesting proposal, and, if well-implemented, could lead to improvements in the structural design, and perhaps more importantly, improved field monitoring of structural system construction, which is often limited in standard practice by cost constraints. Ultimately, the project owner will need to determine whether the potential improvement in the structural system design and performance is worth the additional cost of structural commissioning. The four-point incentive in the Green Globes system may be enough to tip the balance in favor of structural commissioning on some projects, and structural engineers working on Green Globes projects should be sure to mention the commissioning option to their clients.

Site (GG Section 7) — Site development utilizes engineering expertise to evaluate and design for the physical layout and performance of the land. Assessment in this section requires the design team to develop specific designs and document criteria related to greenfield versus brownfield sites, flood plain areas, erosion, irrigation, stormwater, and exterior lighting issues

Energy (GG Section 8) — As in LEED, energy considerations are a major part of the Green Globes rating system. Design considerations include energy efficiency and verification, greenhouse gas emissions, daylighting, renewable energy, and other related issues.

Water (GG Section 9) — This section requires the use of the *Green Globes™ Water Consumption Calculator*, a software tool (available online) that calculates the baseline water use, projected water use, and percentage reduction in water use for purposes of designing to the GBI (2008) ANSI standard.

Green Globes sections

The following sections are of particular interest to structural engineers.

Resources and Materials (GG Section 10) — The architect, engineer and contractor generally have input into the design decisions related to this topic area. Points related to materials are generally awarded based on the percentage used. The calculation is permitted to be on either a cost or weight basis – provided that either cost or weight is used consistently throughout the calculations. Points of particular interest to structural engineers include:

Structural and envelope assemblies: The structural engineer is a key decision maker in material selection for structural assemblies. Green Globes allows the design team to opt for a performance path (maximum of 33 points, as assigned by the *Green Globes™ LCA Credit Calculator for Building Assemblies*) or a prescriptive path (maximum of 22 points). The Credit Calculator is a software tool (available online) that evaluates environmental impacts for common building structural and envelope assemblies.

Within the prescriptive path, points can be achieved by using products that meet the following targets (as a percentage of the total building materials):

- With recycled content (1 to 20 percent, maximum = 8 points). Recycled content may be pre- or post-consumer. Although not clearly stated in the rating system language, it is our understanding based on communication with individuals who participated in the rating system development that the recycled product contribution is in proportion to the product's recycled content. In other words, if 50 percent of the entire building's materials have 20 percent recycled content, then the overall contribution is 10 percent, not 50 percent, which would be good for 3 points.
- That are bio-based (1 to 20 percent, maximum = 6 points). Bio-based materials must contain at least 50 percent bio-based content in order to qualify. No additional weighting is required, in contrast to the approach taken for recycled content.
- That are regionally harvested, recovered, salvaged, or extracted (1 to 20 percent, maximum = 4 points)
- That are regionally processed or manufactured (1 to 20 percent, maximum = 4 points)

The definition of "regional" is within 500 miles of the jobsite unless shipped by rail or water, which increases the distance to 1,500 miles.

Other material properties: The structural engineer will participate in decisions related to material selection in this area. Points can be achieved by using products:

- That are off-site salvaged materials (1 to 9 percent, maximum = 6 points)
- That are made from certified wood materials (10 to 60 percent of all wood-based materials, maximum = 6 points)

The definition of certified wood includes material certified in accordance with sustainable forestry programs of the American Tree Farm System (ATFS), Canadian Standards Association (CSA), Forest Stewardship Council (FSC) or Sustainable Forestry Initiative (SFI).

Re-use of existing structure: The structural engineer may be invited to participate in decisions related to material selection in this area. Points can be achieved by re-using various percentages of the existing structure, as follows:

- Building facades (reuse 10 to 75 percent of facade based on area, maximum = 6 points)
- Structural systems (10 to 95 percent of gross building volume, maximum = 6 points)
- Nonstructural elements (10 to 95 percent of component area, maximum = 6 points)

Reduction, re-use, and recycling of waste: The structural engineer may be invited to participate in decisions related to material selection in this area. Points can be achieved as follows:

- Divert 25 to 75 percent of demolition and construction waste from landfill (maximum = 6 points)
- Re-use existing materials for site development and landscaping (1 point). This credit is educational, and therefore has no threshold; re-using any quantity of existing materials will qualify the project.
- Address building operational recycling program needs (2 points)

Resource conservation through design: Points can be achieved by design team documentation of the following design attributes:

- Detailed building service life plan (7 points)
- Design for reconfiguration, demounting, and disassembly (maximum = 4 points for accommodating interior fit-out changes, and 3 points for designs allowing the removal of reusable materials without substantially damaging the materials or their surroundings)

Building envelope: The structural engineer may be involved in design and detailing of various portions of the building envelope. Since envelope design is key to structural durability, Green Globes awards points when various subsystems are designed and detailed in accordance with key reference standards and procedures, as follows:

- Roofing membrane (per ARMA, NRCA, and SPRI recommendations, 5 points)
- Flashings (per SMACNA recommendations, 5 points)
- Roof, wall openings (per AAMA, WDMA, and CSA recommendations, 5 points)
- Foundation system vapor barriers and damp-proofing (per ASTM and NIBS recommendations, maximum = 4 points)
- Waterproofing of below grade walls, slabs, and above grade horizontal assemblies (per NIBS and ASTM recommendations, 4 points)
- Exterior wall cladding (per NIBS recommendations, 5 points)
- Rainscreen wall cladding (per AAMA recommendations, 2 points)
- Continuous air barrier (per ASTM recommendations, maximum = 6 points)
- Vapor retarder (per IECC recommendations, maximum = 6 points)

Indoor Environment (GG Section 11) — The primary area of interest to structural engineers in this section relates to VOC emissions. Levels of VOC content and emissions necessary for compliance with Green Globes exceed typical standards published for many materials used throughout the interior and exterior of the building. The structural engineer will be directly involved in those aspects of indoor environment related to the structural building materials. Points are available for selection of low VOC adhesives and sealants used within the materials themselves or to attach one material to another (maximum = 8 points).

Summary

Green Globes provides the design team with an alternative to the LEED series of rating systems. It was developed as an online interactive system that assists the design team to optimize green attributes of a building. It is ANSI consensus-based (which is required in some jurisdictions). Additionally, while the primary focus of many engineers will be commercial buildings, there will be occasions where engineers wish to design residential buildings under a consensus-developed green building rating system. The ICC-NAHB National Green Building Standard, approved by ANSI in January 2009, provides guidance for those applications (more information is available at www.thegbi.org or www.nahbrc.org).

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1.5

PROJECT DELIVERY AND SPECIFICATION WRITING

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This section will address the very practical aspect of project delivery and specification writing as they relate to structural engineers and their workflow processes.

Project delivery

The role of the structural engineer is somewhat more involved in a project that is pursuing sustainable principles. Depending on the size of the project and the systems required to be supported by the structural engineering team, the work can be easily rolled into the basic services fee, or the fee may need to be slightly increased to account for additional work. This Guideline is intended to acquaint the reader with the range of scope that could be required for a project. Armed with this information, the response to the proposal can address whether or not an additional fee is warranted. Owners pursue sustainable designs for various reasons, and should be made aware that there are additional design considerations and work — such as documentation — to meet the project goals. As design professionals, we should be paid for the services we provide to the owner.

The structural engineer participates with the design team in defining and possibly ranking project goals. For example, a certain project may include reducing carbon footprint as the priority. The structural engineer must be able to provide the narrative describing how this goal is (or is not) realized by the structural choices in the final design. Another example is prioritizing improved indoor air quality, such as by limiting VOC content in specified products used in the project.

The structural engineer will likely incorporate sustainable design into the structural construction drawings and specifications and will evaluate the construction documents' stated goals during the construction administration phase of the project

Examples of green building features that may affect the design loads are green roofs, double curtain walls, and design for future flexibility. Drawings should reflect loading conditions due to green roofs. The loading is very different for extensive versus intensive green roofs and must be coordinated with the Architect from the onset.

If there is a cost estimate during the schematic design and/or design development phase — and before full specifications are issued — it is important to include notes on the drawings indicating that the contractor will be required to track materials and submit proof of quantities to substantiate the sustainable goals for the project. These activities are additional work to the construction team's efforts and the owner needs to understand this cost, as well as any other cost, from the onset of the project.

The structural engineer's role in the project specifications can have a significant impact in achieving project goals for sustainability because all material specifications are generally affected. Additionally, the structural engineer needs to carefully coordinate any Division 1 requirements with the materials divisions so there are no gaps or contradictions. An in-depth description follows in subsequent paragraphs of this section.

During the construction administration phase the contractors will submit documentation per the project specifications. For example, if the steel submittal specification section stated the following:

1. Indicate recycled content: indicate percentage of pre-consumer and post-consumer recycled content per unit of product.
2. Local/Regional Materials:
    A. Manufacturing (fabrication) location(s): Indicate location of manufacturing (fabrication) facility: indicate distance between manufacturing facility and the project site.
    B. Product value: Indicate dollar value of product containing local/regional materials; include materials cost only.

The structural engineer would expect to get documentation, such as a letter stating, verifying that the specification (in the example above) has been satisfied. Following is an example of such documentation:

> The attached letter from contractor "x" provides the pre-consumer and post-consumer recycled content of the structural steel and also confirms the plant location is within 500 miles of the project location. The estimated value of the material for this project is $500,000.

This is one example of how the requirements for achieving the stated sustainable project goals could require additional work for the project team. This type of documentation and information may or may not be easily produced by the contractor, but the need for it must be acknowledged in advance.

Specification writing

For every project, specifications are a critical component of the contract documents. Specifications take on a new level of importance when the project includes additional requirements of meeting environmental criteria. While achieving certification for improved environmental performance is a worthy goal that supports more sustainable design, these principles should simply be considered good practice. These strategies, often referred to as "green" design, are rapidly becoming an industry standard; therefore, the master specifications for a structural engineering firm ought to embrace the intentions and suggestions presented in this Guideline as a minimum. Currently, however, many offices must maintain two specifications. As this guide is being written, U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program is the primary rating system used in the United States. As a result, this section will assume that an office master specification will be modified for projects pursuing green design and/or LEED certification. There are other systems gaining some prominence; please refer to the section titled "Metrics: Quantifying Green" for information on the variety of ratings systems. For brevity, this section will refer to "LEED" as a stand-in for all certification systems that might apply. Although the particulars of each program may vary, the overall themes of coordination that are presented here are universal.

Some of the differences between green specifications, certification (LEED) specifications, and conventional specifications are as follows:

- Green and LEED specifications yield improved specifications, with regard to material efficiency, durability, and waste management.
- Green specifications can be cost-neutral. Philosophically a green specification includes methods of construction and choices of materials that will lessen the environmental burden associated with the construction of the project. A green specification need not include a certification process; however an embedded metric is essential for nearly every project of substantial scale as a way to measure that goals have been achieved.
- A LEED specification may be cost neutral with respect to construction costs, but there is an additional cost associated with the administration of certification. As the experience of architects, engineers, and contractors becomes more common place, the additional effort should become very straight-forward.
- Unlike a conventional specification, first-rate green and LEED specifications will include informative sections to educate all stakeholders. It is important for these sections to be written in an engaging style, such that they stand out from the prescriptive sections and invite attentive readership. Generally, the project's broad environmental goals will be covered in Division 1. It is critical that the environmental issues related to each division appear in each division so that the sub-contractor reviewing a particular division will be made familiar with the reasoning behind new expectations for his/her contract.

Some aspects of the green requirements do not increase the cost of the project, such as specifying that structural steel components satisfy the American Institute of Steel Construction specifications. Other choices can decrease material costs, such as specifying fly ash to replace portland cement, or instituting a waste management program. It is worth noting that for every material tracked to meet certification requirements, there is a small administrative cost associated with seeking, organizing, and submitting documentation. These duties are normally split between the contractor, architect, and structural engineer. Most experienced contractors can perform a cost estimate during a schematic design or design development phase without having full project specifications. As specifications for green/LEED projects include new obligations for contractors, it is imperative that any submittal reviewed for cost estimating purposes, incorporate notes clearly identifying the expectations for sustainable design.

Green specifications will provide contract bidders with a framework for achieving the environmental goals of the project. The framework is broken down into the usual divisions. This is where the information is located that is necessary to complete the project with green goals intact. The information must be current, clear, and include all instructions necessary to perform any, and all, unfamiliar tasks. The structural engineer must pay particular attention to the following tasks:

- Confirm that material suppliers are still active and reasonably capable of delivering the product on schedule.
- Confirm that explicit instructions are given to the contractor regarding how each metric will be documented. In the case of a LEED certification an instruction might require the contractor to submit the documents detailing the source location of a material.
- Confirm that methods with or needlessly negative environmental impacts are explicitly prohibited and viable practical alternatives are clearly explained. While "means and methods" is classically under the contractors' purview, these method prescriptions should follow from the same logic that allows for similar instructions where personal safety or historic preservation are at issue. For example, instructions on material storage could instruct the contractor to use cribbing to minimize site disturbances such as densification of topsoil.

Coordination — As with any project, it is imperative to coordinate with the Division 1 specifications. The content of the materials specification must not contradict the intent of the instructions noted in the Division 1 specifications.

During the schematic design and/or design development phases, it is important to get at least an outline specification of the green requirements to identify the most achievable aspects of the environmental criteria. Thoughtfully edited outline specifications will be required for the pricing documents at early stages. In addition, a well-thought-out outline specification can help shape the direction of the project design. Each project is unique, and must be evaluated for the requirements as stated in the specifications.

Sometimes the structural engineer's bid documents are issued before the rest of the design team. The structural engineer may need to take the lead with the architect of record regarding the Division 1 specification; but the architect should commit to providing the Division 1 specifications at the same time. Topics covered in the Division 1 specifications need to be carefully coordinated with information to be repeated in other divisions. For example, each division should contain a construction waste management section particular to the work covered in that division. It is extremely important that information contained in the Division 1 does not conflict with the work instructions.

Lastly, if the architect of record is not forthcoming with the Division 1 specifications at the time a foundation bid packaged is released, the structural engineer must incorporate the proper language at the front end of the structural materials specifications. Examples of the language used in the Division 1 section can be found at the end of this section.

Through the content of the specifications, the structural engineer will direct the contractor to consider product selections that fit with the sustainable principles of the project. Most structural specifications list products that are acceptable for the project, thus the structural engineer should proactively achieve the following:

- Consider how the requirements will impact, or possibly eliminate certain bidders. As an example, single-sourcing a particularly green product, may be in conflict with standard project requirements. This is probably more of a challenge in public sector work and should be addressed with the owner from the beginning. Where the use of a green structural material or related product is a critical component to the green strategy, the structural engineer should assist the architect in seeking an exception to the single bidder rule from the governing authority.

- Research and understand new materials and products and any possible issues associated with their uses. A thorough knowledge of the materials properties and issues means the structural engineer can more readily support the contractors' selection and use of the product.
- Make contact with material suppliers to ensure availability. Especially for new products and emerging technologies, sources must be checked for each issuing of the specification.
- Coordinate Divisions 2, 3, 4, 5, 6, and 9 to adhere to the project goals and LEED principles.
- Coordinate certification (or other metric) language with the architect of record. Ensure that each instance of measurable effect is properly identified within the specification sections with correct references back to a "certification requirements" section that clearly describes the procedure for collecting, organizing, and reporting data. For example, a materials section specifies a percentage of rough framing lumber to be sourced from reclaimed lumber. The paragraph tells the contractor three things: this is a "tracked issue," what needs to be measured, and the contactor is referred to a section that details how to measure and process this information — some material will be tracked by quantity (tonnage) while others are by cost.
- Assist in scope meetings with the bidders to be sure they understand the specification expectations, especially for the following purposes:
    - "tallying" the quantities of certain specified materials,
    - separately tracking post-consumer and post-industrial recycled contents, and
    - understanding limitations on emissions, such as VOCs, and in some cases construction equipment exhaust.
- Assist the architect in ensuring the owner understands the pros and cons of the green aspects of the design, with or without certification. It is possible to allow bidders to include an allowance for LEED certification if the Owner is considering it, but is not quite sure if the project can afford the cost.
- Public bids may be particularly sensitive to the cost and logistics of LEED certification. Often public bids set aside a percentage of work to attract minority/women/disadvantage business enterprises. As LEED is still developing in the construction industry, some of these business enterprises may not have the financial capacity to absorb or understand the LEED requirements. Knowing the climate of your project, the structural engineer should work with the owner to develop a bidders list that would not be in conflict with other project goals.

Topics to consider in each section — This section of the Guideline is not intended to be an all-encompassing list of specifications, but rather a list of the issues to be considered and coordinated within each section. Examples are given to help the reader understand the thought process that links green design issues to contract documents.

If a structural engineering firm executes its own in-house specification, the firm should consider adding contractor notes encouraging the use of green principles reflecting the intent of the design, but which are not explicitly stated in the specifications. These notes could further explain the project goals as they relate to a sustainable design. The engineer should place these notes at the beginning of each section and clearly indicate that the notes are suggestions rather than directives to the contractor. Secondly, to aid the structural engineer unfamiliar with green specifications, the firm could include notes to engineers in their specifications. These notes could elaborate on the intentions of the green specifications and help the editor to understand the basis of the mandated specification notes.

Each project, as well as each firm, is unique with the approach to specification writing, as well as the inclusion of sustainable considerations. In some cases the team may have a green specification consultant whose scope could include everything from specification writing to processing submittals. At the opposite end of the spectrum, the team may be responsible for everything. This scenario will require the structural engineer to be very involved in the material sections of the project specification and with coordinating Division 1 with the material sections, as well as processing any submittals if the project goal includes LEED certification. The premise of this section is the latter scenario; the structural engineer is responsible for providing a unique set of specifications, integrating green principles into the material divisions, and coordinating Division 1 statements throughout the entire document.

Specifications example — Note that the following are not intended to be a comprehensive specification. On the contrary, the following are examples of where structural engineers could add to conventional specifications to support sustainable project goals. Sample specification language is shown throughout this section with a different font for clarity.

General, Site, and Foundation divisions: Several aspects of these sections should be addressed when adding sustainable project goals; see the example below.

Division 1: General

The Structural Engineer provides the Architect of Record with sections relevant to structural materials to address the environmental impact of the materials and construction methods for the project.

Construction Waste Management should be addressed in details related to overall project goals and cost benefits in this Division. Each Division will include a waste management section, which is solely applicable to the work of that division. All sections should be coordinated so the same general statements are used in each section.

If the project is seeking LEED certification, the Division 1 specification will likely state the points that are required to meet the requirements of the certification. Division 1 typically describes the submittal process for the project. Special instructions for tracking, organizing and reporting data must be described to the contractor in order to provide the required documentation to achieve LEED points. During the construction administration phase, the Structural Engineer will verify the Contractor's submittals for LEED requirements for structural materials. Thus, it is in the interest of the Structural Engineer to prescribe or at least approve the format in which this data is submitted.

Division 1/2: Site/Foundation

The Structural Engineer should consider noting Site Management construction issues such as:

1. Storage of heavy materials and semi-permanent equipment. For example, soil compaction can negatively impact landscaping and storm water flows.
2. Designated areas to safely store hazardous materials and retain contaminated water, such as wash-out areas.
3. Noise reduction. For example, if noise is recognized as an issue during design development the Structural Engineer should consider alternatives to foundation systems that require the driving of piles.
4. Emissions due to construction vehicle exhaust. Provisions could include "No Idling" restrictions and the use of bio-fuels in place of diesel.

For foundation elements such as drilled caissons, the specification should note:

1. The use of local materials, such as coarse and fine aggregates.
2. Locally sourced recycled aggregate; all sub-base material should be locally sourced recycled concrete aggregate.
3. Recycled content if permanent steel casings are required.
4. Construction waste should be reused on site wherever possible. Remaining waste should be sorted by type for direction to appropriate facility.
5. Coordinate the site management section from Division 1 for foundation specifications. Repeat site management section information for site preparation specification or in foundation specification if no site prep specification is to be issued.

Concrete division: Several aspects of this section should be addressed when adding sustainable project goals; see the example below.

There is considerable opportunity to implement sustainable principles in the Division 3 Specification. Listed below are a variety of issues the structural engineer should consider for each project. Under Part 1, General Requirements, it is important to lay out the big picture in informational paragraphs. This helps educate the subcontractor in charge and gives them a value as a stakeholder in the successful achievement of the green goals. It is important to make the informational paragraphs distinct from the prescriptive/mandated sections that follow. This can be done through writing style, formatting, or both. Below is a suggested format wherein both environmental problems and generic solutions are outlined. An in-depth discussion of the environmental issues as well as a summary of strategies to lessen the impacts of concrete are included in this Guideline in Section 3.2—Concrete.

Division 3: Concrete (Reprinted with permission, Robert Silman Associates)

ENVIRONMENTAL ISSUES
(This section is for *educational purposes only. For requirements related to meeting environmental goals, see instructions in the body of this specification following this section).*

Problems associated with the production and use of concrete

- *Production of Portland cement is energy intensive. Related emissions include over 6% of global carbon dioxide (CO2) (IPCC 2007), as well as significant amounts of particulates to the atmosphere.*
- *Mining of coarse and fine aggregate causes local pollution and damage to natural habitats.*
- *Discarded formwork generates waste.*
- *Some curing compounds, release agents and sealers emit VOCs especially during the curing process, compromising indoor air quality and contributing to ground level ozone, also known as "smog."*
- *Residual water generated by wash-out of transit mix truck drums can cause localized pollution.*

Solutions:

- *Use byproducts from other processes (fly ash, slag, silica fume, rice hull ash) as supplementary cementitious materials added to the concrete as a "blended cement" or as a separately batched ingredient proportioned for the performance requirements of the Project. Use of byproducts diverts this material from landfills while reducing portland cement requirements.*
- *Use gray water in production of ready mixed concrete. See ASTM C94 (2009) for guidelines and requirements.*
- *Demolition concrete can be a great source of aggregate. Using recycled aggregate in place of virgin aggregate reduces mining and diverts waste material from landfills. Uses range from sub-base material to coarse aggregate in structural concrete. Recycle, reuse, or use alternative formwork systems.*
- *Specify low-VOC or water- or vegetable-based curing compounds, form release agents, and sealers.*

The sections below outline the specific areas in a green concrete specification that will require attention.

1. Formwork:
    A. Specify % recycled content, % re-use, % FSC Certified Wood.

    B. Specify vegetable-based zero VOC (volatile organic compounds) form release agent.

    C. When the project requires documentation, track the amounts of aforementioned materials above, the MSDS (Material Safety Data Sheets) for VOC emissions, and the local materials (specify miles from project). Refer to appropriate section in Division 1 for documentation instructions.

2. Reinforcement:
   A. Typically, rebar, welded wire mesh, and supports for setting rebar have a high percentage of recycled content. Avoid using epoxy coated rebar unless rigorous Quality Control measures are followed during the rebar placement to ensure no nicks are left in the coating; nicks act as host sites for rapid corrosion. As an alternative, consider specifying above-code clear cover, or stainless steel rebar for critical applications.

   B. When the project requires documentation, track the amounts of aforementioned materials, the recycled content (specified percentage of post-industrial and post-consumer), the local fabrication (specify miles from project), and the amount of construction waste diverted from landfill. Documenting the recycled content of all metal elements. For LEED certification, industry letters stating average recycled contents will not suffice. For recycled material credit, the actual recycled content used in the process (EAF vs. BOF furnace) to make the steel reinforcement used on the project must be quantified and submitted by the supplier. A chain-of-custody statement may be required. If the project is not seeking certification the tracking of recycled steel content is not critical, but will add to the projects administrative cost. Refer to appropriate section in Division 1 for documentation instructions.

3. Cementitious Materials:
   A. Portland Cement: use Type appropriate to projects overall goals and that will facilitate the use of waste materials (e.g. early strength, improved durability).
      i. ASTM C595 (2008) provides the standard for blended cements incorporating fly ashes (Type-IP) and slags (Type-IS)

   B. Reducing portland cement content is the most effective way to reduce the carbon footprint associated with concrete construction.
      i. The judicious use of mineral admixtures can reduce cement required and improve quality and workability. Pozzolans such as class F fly ash and rice hull ash increase long-term strength and durability. Class F fly ash is slower to gain strength. This can be offset by the inclusion of inert filler material with high specific surface areas, or with silica fume, see mineral admixtures in this section. *(Note to the readers: see Section 3.2—Concrete for more information on this topic.)*
      ii. The concrete mix used should be specific to the building element and the specification may consider presenting mix performance and admixture requirements in tabular form. For example, it is easy to incorporate large volumes of complementary cementing materials into foundations and shearwalls that do not see significant loading at early ages. The specification should clearly state for which elements 56-day or 90-day strengths are to be used in lieu of the conventional 28-day target. Conversely, beams and slabs in high-rise construction will usually have low percentages of fly ash.

   C. Water/Binder ratio: The water/binder ratio and mineral admixture content are the main factors influencing strength and durability.
      i. The Structural Engineer should note that use of fly ash increases workability, thus the water/binder ratio (which includes cement plus fly ash or other mineral admixture) can be reduced

accordingly.*(Note to the readers: see Section 3.2—Concrete for more information on this topic.)*

D. ASTM C1157 (2008) provides a standard for performance-based specification of blended cements (including batch mix blending). This approach gives the Structural Engineer considerably more leeway in designing a mix for high durability and reduced CO_2 emissions. See www.nrmca.org/P2P website for additional guidance and case studies.

4. Complementary Cementing Materials and Mineral Admixtures: *(Note to the readers: see Section 3.2—Concrete for more information on this topic.)* A LEED Credit Interpretation Request (CIR) grants an innovation credit for projects using an average of at least 40% fly ash as a cement replacement. This credit will likely also apply to mixes that incorporate other materials such as slag, rice hull ash, and by-product ultra-fines to achieve the required cement reduction.
   A. Pozzolans (ASTM C618 [2008], unless noted otherwise)
      i. % Fly Ash: specify class, mean fineness, max % LOI *(LEED note: check transportation method for regional material credit. Most fly ash is transported by rail)*
      ii. % Rice Hull Ash: specify specific surface area, mean fineness, % amorphous SiO_2, max % LOI
      iii. % Silica Fume (ASTM C1240 [2005])

   B. Slags (ASTM C989 [2009])
      i. % Slag: specify grade.

   C. Inert Fillers (such as reclaimed quartz, dolomite or limestone powders – refer to ASTM C1240 [2005] for guidance).
      i. % filler:, specify specific surface area, source locally/regionally

   D. When the project requires documentation, track the amounts of aforementioned materials (including portland cement replaced), the recycled content (specified percentage of post-industrial and post-consumer), the local source (specify miles from project, transportation method). Refer to appropriate section in Division 1 for documentation instructions.

5. Aggregates:
   A. Coarse aggregate: To minimize paste volume (and cement), specify the largest maximum aggregate that will satisfy construction requirements.
      i. Recycled Aggregate Concrete: *(Note to the readers: see Section 3.2—Concrete for more information on this topic and for percentages and procedures related to using recycled coarse aggregate in structural concrete).* The Structural Engineer must confirm that the source of recycled coarse aggregate was
         a. not exposed to de-icing salts
         b. does not contain calcium chloride
      ii. Natural (virgin) Aggregate
         a. Specify locally available suitable aggregate

   B. Use 100% locally available recycled aggregate for sub-base applications. If the project is located where noise pollution is not an issue and demolition concrete will be available on site, consider specifying that material crushed on site for reuse. Include provisions for dust control.

C. Fine Aggregates: When good quality well-graded coarse sands are not locally available, explore using a gap graded mix design with complementary cementing materials used to offset the increase in binder required for a larger paste volume. Recycled aggregate fines are not recommended at this time without special mix design considerations and thorough testing.

D. When the project requires documentation, track the aforementioned amounts of materials above, the recycled content (the specified percentage of post-industrial and post-consumer), the local source (specify miles from project, transportation method). Refer to appropriate section in Division 1 for documentation instructions.

6. Sealants and Adhesives:
   A. Use compounds with low VOC emissions. Generally the Division 1 specification will note the maximum limit for a project. Ensure that sealants and flooring underlayment adhesives are compatible. These compounds can be reactive when in contact with the alkalinity of concrete; this releases toxic emissions and reduces the effectiveness of the adhesive.

   B. When the project requires documentation, track the amounts of aforementioned materials and require Contractor to provide an MSDS submittal. Refer to appropriate section in Division 1 for documentation instructions.

7. Curing Compounds and Curing Methods:
   A. Use compounds with low VOC emissions or use low-impact wet curing methods such as water, burlap and plastic sheeting.

   B. When the project requires documentation, track the amounts of aforementioned materials and require Contractor to provide an MSDS submittal. Refer to appropriate section in Division 1 for documentation instructions.

8. Water Reduction Agents (normal range water reducers and superplasticizers):
   A. Verify agent specified is compatible with the mineral admixtures chosen in the cementitious mix. Use superplasticizer as necessary to achieve low water/binder ratio and to incorporate mineral admixtures. Normal-range water reducers should be used where sufficient. Normal water reducers are generally made from ligno-sulfonates, a by-product from the paper industry, where as superplasticizers are made from either polycarboxylates or naphthalene formaldehyde; these are relatively expensive, energy-intensive materials and some are toxic. .

9. Concrete Construction Waste Management:
   A. Ready-Mix supplier to have gray water system to use recycled water in plant operations (Contractor to give preference to such a supplier, for exception contractor must demonstrate due diligence in trying to locate a ready-mix supplier with this type of facility).
      i. Control truck wash-out and water run-off.
      ii. Designate dump-out sites where fill is required.

B. Segregate materials by types for recycling, such as wood, stone, metal, etc.

C. Designate areas for materials that can be reused on site such as formwork, rebar cutoffs, and fill.

Precast concrete division: Several aspects of these sections should be addressed when adding sustainable project goals; see the example below. In addition to the Division 3 information already detailed, a precast specification should include the following considerations:

Division 3: Precast Concrete (Reprinted with permission, Robert Silman Associates)

1. Early strength gain is more critical for precast applications, the larger the project scale the more likely it is the precast supplier will be able to accommodate large percentages of pozzolans. Steam curing, Type III portland cement, inert filler materials and silica fume will increase early strength accommodating the use of pozzolans.

2. Precast presents a design for deconstruction opportunity. (*Note to the readers: see Section 2.4 — Design for Deconstruction and Adaptability for more information on this topic.*)

3. Precast presents a higher Quality Control environment, the Structural Engineer should recognize this as an opportunity to use the maximum amount of waste material in the concrete mix, including mineral admixtures and reclaimed aggregates.

4. Precast plant operations must have gray water system to use recycled water in plant operations (no exceptions), thus this should be included in the Concrete Waste Management specifications when using precast.

Masonry division: Several aspects of these sections should be addressed when adding sustainable project goals; see the example below.

Concrete masonry units have many of the same specification directions that are found in a concrete and precast concrete specification. The structural engineer should verify the regional existence of at least one "green masonry" manufacturer before pursuing design and specification of these units. The environmental problems and solutions outlined in Division 3 should be adapted and included under the General Requirements for Division 4. An in-depth discussion of the environmental issues as well as a summary of strategies to lessen the impacts of steel are included in this Guideline in Section 3.3 — Masonry.

Division 4: Masonry (Reprinted with permission, Robert Silman Associates)

1. Consider requiring the use of units that are manufactured as follows:
    A. In a facility with gray water recycling

    B. Replacing specified percentages of portland cement with cementitious waste materials, (specify type and percentage)

   C. Replacing specified percentages of aggregates with recycled aggregates, (specify size limits and percentage)

2. Include VOC limits for sealants and adhesives.
3. Require submittals identifying the use of local materials (specify miles from project) and addressing construction waste management.
4. Consider using ungrouted, post-tensioned vertical wall reinforcement to facilitate future disassembly.

Steel division: Several aspects of this section should be addressed when adding sustainable project goals; see the example below.

Listed below is a sample of issues related to steel construction the structural engineer should consider for each project. It is important to make the informational paragraphs distinct from the prescriptive/mandated sections that follow. This can be done through writing style, formatting, or both. Below is a suggested format wherein both environmental problems and generic solutions are outlined. An in-depth discussion of the environmental issues as well as a summary of strategies to lessen the impacts of steel are included in this Guideline in Section 3.4 — Steel.

Division 5: Steel (Reprinted with permission, Robert Silman Associates)

ENVIRONMENTAL ISSUES
(This section is for educational purposes only. For requirements related to meeting environmental goals, see the body of this specification following this section).

Problems associated with the production and use of structural steel:

- *Smelting process generates greenhouse gases and other hazardous air pollutants, as well as a large quantity of waste-by-products (e.g. slag).*
- *The production of steel is an energy intensive process. Energy consumption varies with the method of manufacture and the type of end-product. For structural steels, heavy shapes use the least specific energy to produce. In the United States the embodied energy of W shapes averages 13.13 GJ/tonne (5,650 BTU/lb [Stubbs 2000], which is equivalent 0.313 tonnes of oil (2.06 U.S. barrels) or 0.45 tonnes of coal (World Energy Council). The reliance on coal for coke as well as U.S. based electricity generation means that the average tonne of steel produced by mini-mills emits 1.09 tonnes of CO_2 per tonne of product (Stubbs 2000).*
- *Thermal bridging occurs when steel is used in an exterior wall without proper detailing. This results in higher than necessary energy use and condensation problems which promote mold growth and can cause "sick building syndrome."*
- *Some primers, paints, and other coatings/treatments used for steel emit volatile organic compounds (VOCs) and some contain hazardous heavy metal pigments. VOCs contribute to indoor air quality (IAQ) problems and ground level ozone, commonly known as smog.*

Recommendations:

- *Choose steel components originating from the mill or fabricator located nearest to the building site.*
- *Require mills and fabricators have ISO 14001 (2009) certification. This standard requires that the manufacturer have an environmental management program in place.*

- *Maximize the re-use of salvaged steel (as approved by the structural engineer) and, for work on existing buildings, alert the design team to any existing steel which could be re-used but has not been indicated on the drawings.*
- *Maximize the recycled content of all steel products. 66% to 95% total recycled content may be achievable for EAF products.*
- *Design details penetrating the envelope insulation so as to avoid thermal bridges.*
- *Use low VOC and the least toxic solvents, primers, paints, and sealers necessary to comply with the requirements of this section. Where possible do not use paint/primers.*
- *Where possible all connections should be made using bolted as opposed to welded details to facilitate disassembly and reuse.*
- *Where welding is required, the Submerged Arc Welding (SAW) process is environmentally preferable because it generates least toxic fumes and smallest amount of total emissions of all the welding methods relevant to structural steel. The Gas Metal Arc Welding (GMAW) should be used where SAW is not applicable (such as for angled connections and anything irregular or short). Field welding should be allowed only in special circumstances; in such cases Flux Core Arc welding (FCAW) should be specified with the use of a portable fume exhaust system.*
- *Use surface preparation techniques that minimize the use of halogenated solvents and solvents classified as volatile organic compounds. When specifying SSPC-1, require less hazardous and volatile solvents such as D-Limonene blends. Consider specifying physical processes (SSPC-6) using recyclable plastic pellets, baking soda or wheat starch to replace sand as the particulate medium for blasting.*
- *Consider using 'weathering steel' (ASTM A847 2005) for exterior steel to eliminate the use of coatings all together.*
- *Use high-strength HSS round tubes instead of ASTM A36 (2008) steel pipes. HSS tubes can have three times the recycled content of standard pipe. When one ton of steel is recycled, 2,500 pounds of iron ore, 1,400 pounds of coal and 120 pounds of limestone are conserved.*
- *Use braced frames instead of moment-resisting frames to reduce material use. If possible, locate braced frames at building perimeter and around cores to improve adaptability of the space.*

The sections below outline the specific areas in a green steel specification that will require attention.

1. Recycled content of all metal elements:
    A. For LEED certification, letters stating typical recycled contents will not suffice. For recycled material credit, the actual recycled content must be quantified and submitted by the supplier. A chain-of-custody statement may be required.

    B. If the project is not seeking certification, the tracking of recycled steel content is not critical but will help the project team and owner recognize and understand the project's environmental achievement.

2. Structural steel:
    A. Structural steel, including shapes, miscellaneous steel, plates, bars, shear connectors, anchor rods, bolts, and nuts should contain recycled content. When the project requires documentation, track the aforementioned amounts of materials above, the recycled content (the specified percentage of pre-consumer and post-consumer), the local

source of scrap and other raw materials, production, and fabrication (specify miles from project), and the construction waste.
    i. Note that presently, Grade 65 high-strength steel is not produced domestically and therefore may have higher embodied energy content for domestic projects due to transportation.

  B. When the project requires documentation for steel joists, track the recycled content, the local source of scrap and other raw materials, production, and fabrication (specify miles from project), and the construction waste.

  C. When the project requires documentation for steel deck, specify and track the recycled content (specify percentage of pre-consumer and post-consumer), the primer VOC limits, the local source of scrap and other raw materials, production, and fabrication (specify miles from project), and the construction waste.

  D. Certification of recycled zinc content for galvanized products: Provide cut sheets clearly indicating whether the galvanized products used meet the minimums for post-consumer OR pre-consumer recycled contents. Or, if cut sheets are not available, obtain a written affidavit from the manufacturer stating the recycled content percentage and if the recycled content is post-consumer or pre-consumer.

  E. Expansion joint assemblies can be specified using recycled materials. When the project requires documentation, track the recycled content (specify percentage of post-industrial and post-consumer), primer VOC limits, local raw material extraction and fabrication (specify miles from project), and the construction waste.

  F. Refer to appropriate section in Division 1 for documentation instructions.

3. Cold-formed steel: When the project requires documentation for cold-formed metal framing specify and track the recycled content (specify percentage of pre-consumer and post-consumer), the primer VOC limits, the locations of raw material/scrap source, production, and fabrication (specify miles from project), and the construction waste. Refer to the appropriate section in Division 1 for documentation instructions.

4. Connections: Avoid welded connections unless shown on details. Field welding should not be allowed without written instruction from the Architect or Structural Engineer.
    A. Welding: The following environmentally preferable welding processes shall be used as described for the related application.
        i. Submerged Arc Welding (SAW) shall be used for plate girders, fillet, and butt joints in pipes, cylinders, columns, and beams and welds where 'downhand' or horizontal positions are possible.
        ii. Gas Metal Arc Welding (GMAW) shall be used were SAW is not applicable (such as for angled connections and anything irregular or short). Shielding gas shall be an Argon/CO_2 blend. Argon in the blend makes the process more efficient and reduces emissions. The Contractor shall use Pulse Transfer technology (another way to reduce fume generation is to use a waveform controlling power source). With pulsed GMAW, for

example, fumes produced are typically less than with a conventional constant voltage power source.

iii. Field welding shall be allowed only in special circumstances; in such cases Flux Core Arc welding (FCAW) shall be specified. If shielding gas used is pure CO2 then a portable fume exhaust system shall be employed. If shielding gas used is an Argon/CO2 blend then the portable fume exhaust system is not required.

iv. Containment surface preparation debris must meet The Society for Protective Coatings Guideline SSPC-61 (CON) (2009).

B. Bolting *(Note to the readers: see Section 2.4—Design for Deconstruction and Adaptability for more information on this topic.)*

5. Paint, Finishes, and Surface Preparation: The structural engineer typically describes acceptable protective paint and primers in the steel specifications. Coordinate the VOC limits with the Architect of Record and require the contractor to submit MSDS documentation. Refer to appropriate section in Division 1 for documentation instructions.

   A. Where possible, consider specifying self-weathering steel (no painting required).

   B. To facilitate the selection of appropriate paints and acceptable VOC limits for protective paints refer to the Master Painters Institute and Paint Researchers Association web site www.specifyinggreen.com. Here you can download the latest GPS (green performance standard) and look up approved products. This is a good resource to include in your specification to help the contractor find greener paints without sacrificing performance.

   C. Where coatings are necessary, powder-coated fabrication is preferred to painting and plating (powder-coat material can be re-claimed and it is generally less polluting). Plated metals contribute to water pollution; avoid using plated metals especially those using cadmium and chromium as plate material or cyanide or copper/formaldehyde based electro-less copper as the plating solution.

   D. Shop painting and factory finishing shall be used whenever possible.

   E. Where applicable, and where effective containment is possible, finishes, and surface preparations based on a physical process such as abrasive blasting, grinding, buffing, and polishing are preferred to coatings and solvent-based cleaning. Consider specifying physical processes (SSPC-6) using recyclable plastic pellets, baking soda, or wheat starch to replace sand as the particulate medium for blasting.

   F. Use surface preparation techniques that minimize the use of halogenated solvents and solvents classified as volatile organic compounds. When specifying SSPC-1, require less hazardous and volatile solvents such as D-Limonene blends.

   G. Use surface preparation classification recommended by paint manufacturer, SSPC or Master Painters Institute (MPI) for paint product used.

- H. SSPC-61 (CON) (2009) – Guide for Containing Debris Generated During Paint Removal Operations must be followed for all applicable surface preparation techniques

6. Construction Waste Management: Coordinate with other sections of Specification. Separate and handle general construction waste in accordance with the Construction Waste Management Plan.
    - A. Separate for recycling and place in designated containers the following metal waste in accordance with the Construction Waste Management Plans: Steel, iron, galvanized steel, galvanized sheet steel, stainless steel, aluminum, copper, zinc, lead, brass, and bronze.
    - B. Collect all metal cut-offs and scraps and recycle as above.
    - C. Fold up metal banding and flatten and recycle as above.
    - D. Close and seal tightly all partly used paint and finish containers and store protected in a well-ventilated, fire-safe area at moderate temperature.
    - E. Designate unused paint for the following:
        - i. Immediate reuse,
        - ii. Long term maintenance needs, or
        - iii. Recycling by an appropriate facility.
    - F. Place empty containers of solvent-based paints in areas designated for hazardous materials.
    - G. Do not dispose of paints or solvents by pouring on the ground. Place amounts too small to reuse in designated containers for proper disposal.

Wood division: Several aspects of this section should be addressed when adding sustainable project goals; see the example below.

Listed below are some of the issues related to wood construction that the structural engineer should consider for each project. Under Part 1, General Requirements, it is important to lay out the big picture in informational paragraphs. This helps educate the sub-contractor in charge and gives them a value as a stakeholder in the successful achievement of the green goals. It is important to make the informational paragraphs distinct from the prescriptive/mandated sections that follow. This can be done through writing style, formatting, or both. Below is a suggested format wherein both environmental problems and generic solutions are outlined. An in-depth discussion of the environmental issues as well as a summary of strategies to lessen the impacts of wood are included in this Guideline in Section 3.5 — Wood.

Note that certified wood cited here refers only to the Forest Stewardship Council (FSC) certification program. As of this writing, FSC is the only system recognized by the LEED rating system. However, other standards and rating systems recognize the SFI, CSA, and American Tree Farm System in addition to FSC. There is considerable debate on this issue. The reader is urged to check the current requirements of the rating system in use, if applicable; the reader is also referred to the Section 3.5 — Wood for more information on the various systems.

Division 6: Wood (Reprinted with permission, Robert Silman Associates)

ENVIRONMENTAL ISSUES
(This section is for educational purposes only. For requirements related to meeting environmental goals, see instructions in the body of this specification following this section).

Problems associated with the production and use of lumber:

- *Using large timber from non-certified sources especially threatens the health of old growth forests. Old-growth trees of certain species such as Redwood, Western Red Cedar, and Douglas Fir are endangered.*
- *Tree plantations are more susceptible to disease than natural forests, and compromise indigenous habitats and biodiversity.*
- *Chemicals used in wood treatments, binders, and some construction adhesives are energy intensive to manufacture and some are known to off-gas or leach highly toxic chemicals over long periods of time.*
- *Some chemicals used in wood treatments, binders, and construction adhesives make the wood they are applied to difficult to recycle or dispose of safely.*

Recommendations:

- *Use Forest Stewardship Council (FSC) certified wood products. This will help ensure trees are being harvested in a sustainable manner. Use of FSC-certified wood products will help assure that the biodiversity of the ecosystem is preserved, use of pesticides/herbicides is restricted such that biodiversity is not adversely affected, the integrity of the land base is maintained to obviate soil erosion and the silting of river systems, a portion of the trees are allowed to mature, and a portion of dead/fallen trees are allowed to decay in-situ. These practices classify a forest as "well-managed". Wood certified using other certification systems such as SFI and CSA is preferable to uncertified sources, although these standards are generally not as stringent as FSC, particularly with respect to social equity.*
- *Avoid old-growth timber, wood from threatened species, and illegally harvested wood. Certified wood will satisfy this requirement.*
- *Design for and specify wood species that grow locally.*
- *Use salvaged wood. Sawn lumber and large sections of engineered wood products obtained from the demolition of existing structures may be rated and used in new structures.*
- *Use engineered wood products or double up smaller sawn lumber sizes in lieu of large dimension sawn lumber. Engineered wood is made from smaller wood sizes,. Use of engineered woods can help reduce the harvesting of old growth forests.*
- *Source engineered woods from the nearest manufacturer.*
- *Choose engineered woods that use least toxic and least energy-intensive binders available.*
- *Encourage designs that minimize the building's exposure to moisture. Properly designed structures incorporate adequate roof overhangs and design details that eliminate water traps.*
- *Choose the least toxic wood preservative treatment appropriate for the application.*

- *Choose the most durable wood treatment appropriate to the application: e.g. wood not exposed to water may be treated with borates or physical barriers.*
- *Use the minimum amount of chemicals: e.g. consider recycled plastic lumber or plastic-wood composites for outdoor decking as this eliminates chemical durability treatments for new construction and the eventual surface sealers required to maintain durability.*
- *Use mechanical and other barriers (termite shields, termite mesh, or sand barriers) to prevent insect infestation and reduce the requirement for wood treatment.*
- *Maximize framing efficiency.*
- *Minimize job-site waste.*
- *Since January 1, 2004 the U.S. Environmental Protection Agency (EPA) disallowed the use of chromated copper arsenate (CCA) as a preservative treatment for lumber in residential applications. CCA-treated waste wood must be directed to a municipal landfill; C&D landfills are not lined and are therefore incapable of containing leaching toxins associated with CCA.*
- *Other preservative treatments are available. If using wood treated with other preservatives, ensure that all preservatives are adequately fixed in the wood. Reject lumber with surface residues of white salts. Wood that is kiln-dried after treatment and/or prefinished with a sealer is preferable.*

The sections below outline the specific areas in a green rough carpentry specification that will require attention.

1. Wood framing:
    - A. When the project requires documentation for wood framing, specify and track the recycled content, certified wood, the sealant and adhesive VOC limits, the local materials requirement (specify miles from project), and construction waste. Refer to appropriate section in Division 1 for documentation instructions.
    - B. Specify wood species available in the project region.
    - C. Certified New Timber and Sawn Lumber: Provide wood certification documentation from the distributor, declaring conformance with certification system requirements. For FSC-certification, the FSC accredits third-party organizations (listed below) as qualified to determine the conformance of forest operations with the sustainability criteria outline by the FSC. Note—Sustainable Forest Initiative (SFI) certification is NOT currently acceptable for LEED credit without additional certification from an FSC accredited certifier.
        - i. Scientific Certification Systems, Inc., Oakland, Calif.
        - ii. Smart Wood Certification Program, Rainforest Alliance, New York, New York
        - iii. Other FSC-accredited certifying agencies. For additional 3rd party certification agencies refer to http://www.certifiedwood.org/
    - D. Salvaged Lumber:
        - i. Provide documentation certifying products are from salvaged wood sources. If cut sheets are not available, obtain a written affidavit from the supplier stating the origin of the material.
        - ii. For salvaged lumber used in structural applications grading certificates (or stamps) are required. Lumber must be visually

graded per standards applied to new lumber, unless specifically noted otherwise. If there are existing grade stamps these are acceptable if the piece has not been modified or damaged (for example ripped into smaller sections, frequent bolt holes or other penetrations or evidence of newer splits and checks).

iii. Certified and salvaged wood may require longer lead times to procure. It is the responsibility of the contractor to obtain materials at the time required and to ensure that procurement delays do not adversely affect the construction schedule.

2. Sheathing:
    A. When the project requires documentation for sheathing, specify and track attributes requiring documentation; such as, the recycled content, certified wood, the sealant and adhesive VOC limits, the local materials (specify miles from project), and the construction waste. Refer to appropriate section in Division 1 for documentation instructions.

    B. Binders: Do NOT use wood materials using urea formaldehyde binders. Instead choose Phenol formaldehyde OR Polymeric diphenyl methylene diisocyanate (PMDI—sometimes referred to as MDI). This is a polyurethane-type binder that is waterproof and contains no formaldehyde. [Note: Phenol formaldehyde resins modified or extended with soy, casein, and pyrolysis oil is an emerging technology.]
        i. Periodically check EBN http://www.buildinggreen.com/ for the availability of new, more environmentally benign binders. In particular, look out for binders derived from bark resin.

    C. Disposal: Never incinerate woods containing any adhesives or binders in open fires. These woods may only be burned in incinerators approved by the EPA as per RCRA. Refer to the Waste Management section for further restrictions.

3. Engineered Woods and Glued-Laminated Construction:
    A. When the project requires documentation for glued-laminated construction, specify and track attributes requiring documentation; such as, the recycled content, certified wood, the sealant and adhesive VOC limits, local materials (specify miles from project), and the construction waste. Refer to appropriate section in Division 1 for documentation instructions.

    B. Specify wood species available in the project region

    C. Engineered woods (LVL, PSL, LSL, etc.) should replace sawn lumber sizes of greater than 2 in. x 10 in. for members used as joists, rafters, and headers. All headers, and non-visible posts shall be constructed of engineered wood or multiple 2x members to limit the use of members 4x and thicker or 10x and wider.

4. Wood Treatment: The use of chromium- and arsenic-based treatments such as Chromated Copper Arsenate (CCA) should be *prohibited* when applied to sawn lumber. Wolmanized and other CCA type treatments should be acceptable in engineered woods only AND only where there will be NO direct human contact with the member once installed and NO possibility of leachates reaching the ground water system.

A. Reject all pressure-treated lumber with powdery surface residues — this is an indication that treatment was not properly fixed in the wood.

B. Where pressure treatment is not required use a moderately-to-very decay resistant species, a low-toxicity site-applied solution treatment, or some combination thereof.
   i. Naturally decay-resistant species include the cedars, redwood, chestnut, cypress, and red oak

C. Acceptable treatments and methods to protect wood and increase its durability include the following:
   i. Borate-based treatments are preferred where applicable (no direct exposure to moisture).
   ii. Ammoniacal Copper Quat (ACQ)
   iii. Copper Hydroxide Sodium dimethyldithiocarbamate (CCDC)
   iv. iv. Consider specifying recycled plastic-wood composite lumber for decking applications
   v. Consider specifying mechanical barriers such as termite shields, insect barriers, and sand traps.

5. Waste Management and Hazmat Disposal:

A. Never incinerate wood containing any chemical preservative treatments in open fires. Wood products containing Chromated Copper Arsenate (CCA) based treatments are not to be incinerated under any circumstances. These woods may only be burned in incinerators approved by the EPA as per RCRA. Set aside any sawn lumber or engineered woods treated with chromium or arsenic (such as CCA and "Wolmanized") for disposal at a municipal landfill. Chromium and arsenic are hazardous materials and as such cannot be disposed of at C&D landfills. Municipal landfills are lined; they are designed to sequester toxins. C&D landfills are not lined and therefore cannot retain the hazardous leachates associated with these treatments.

B. The following restrictions apply when disposing of wood by means of burning.
   i. Do not burn scrap at the project site.
   ii. Do not burn lumber that is less than a year old.
   iii. Never incinerate engineered woods, or treated woods in open fires. They may only be burned in incinerators approved by the EPA as per RCRA. Chromated Copper Arsenate (CCA) treated woods are not to be incinerated under any circumstances.

C. Separate corrugated cardboard used for shipping wood products and place in designated areas for recycling according to the Waste Management Plan.

D. Metals
   i. Fold up metal banding, flatten, and place in designated area for recycling.
   ii. Collect damaged anchors, hangers and miscellaneous metals, and place in designated area for recycling

E. Separate wood waste and place in designated areas in the following categories for recycling according to the Waste Management Plan:

  - i. Softwood
  - ii. Hardwood
  - iii. Composite and engineered wood (for example, plywood, OSB, LVL, I-Joist, PSL, LVL, MDF, particleboard).
  - iv. Treated, painted, or contaminated wood.

- F. Separate wood waste and place in designated areas in the following categories for re-use on site:
  - i. Sheet materials larger than 16 in. x 16 in.
  - ii. Framing members longer than 18 in.
  - iii. Multiple off cuts of any size larger than 18 in.
  - iv. Store separated reusable wood waste convenient to cutting station and area of work.
  - v. Set aside damaged wood for acceptable alternative uses, for example use as bracing, blocking, cripples, or ties.

Finishes division: An aspect of this section should be addressed when adding sustainable project goals; see the example below.

Division 9: Finishes

Finishes are often specified also with sections such as Division 5. Coordinate those Specification requirements such as paint and primer with the Architect of Record to make sure the correct products and/or LEED requirements for those products are clearly indicated.

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American Society of Testing and Materials (ASTM) Subcommittee A01.02. (2008). Standard Specification for Carbon Structural Steel. ASTM A36-08, ASTM, West Conshohocken, PA.

ASTM Subcommittee A01.09. (2005). Standard Specification for Cold-Formed Welded and Seamless High-Strength, Low-Alloy Structural Tubing with Improved Atmospheric Corrosion Resistance. ASTM A847-05, ASTM, West Conshohocken, PA.

ASTM Subcommittee C01.10. (2008). Standard Performance Specification for Hydraulic Cement. ASTM C1157-08a, ASTM, West Conshohocken, PA.

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ASTM Subcommittee C09.40. (2009). Standard Specification for Ready-Mixed Concrete. ASTM C94-09, ASTM, West Conshohocken, PA.

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Additional Resources

Federal Green Construction Guide for Specifiers – www.wbdg.org/design/greenspec

Construction Specifications Institute's *MasterFormat* – www.masterformat.com

Construction Specifications Institute's *OmniClass* – www.omniclass.org

EPA Construction Waste Management, Guideline for Section 01 74 19 – www.epa.gov

Waste Management Triangle J Specification – www.recyclecddebris.com/rCDd/Resources/Documents/CSNModelSpecWasteReduction.pdf

Building Green/Environmental Building News; GreenSpec Directory – www.buildinggreen.com/menus/divisions.cfm

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2.0

SUSTAINABLE STRATEGIES

Sustainable design is most successful when incorporated throughout the entire project. Understanding strategies that consider overall sustainability goals can have significant impacts on all projects. This section will discuss the following strategies in more detail:

Section 2.1 — Recycled Content

Section 2.2 — Local Sourcing and Local Manufacturing

Section 2.3 — Durability and Reduced Maintenance

Section 2.4 — Design for Adaptability and Deconstruction

Section 2.5 — Reuse of Buildings, Structural Components, and Non- Building Structures

Section 2.6 — Life Cycle Assessment

Section 2.7 — Structural Materials and Toxicity

2.1

RECYCLED CONTENT

Gary D. Garbacik, P.E.

Throughout human history, there have been many instances where recycling and the use of recycled materials were used to benefit society. For example, during pre-industrial times scrap bronze and other precious metals were melted for perpetual use. The pre-industrialists understood that bronze was able to be recycled. During the Middle Ages in Britain, dust and ash from wood and coal fires created the base material for brick making.

Recycled content has become an active term in our vocabulary in response to the green movement that has been taking hold of the construction industry. In fact, many companies have adopted standards for the use and quantification of recycled content within the parameters of a design and construction project. Recycled content can be considered very important to the structural engineering community because we have control over the materials that are being used to construct the building.

Most structural engineers are more familiar with recycling and recycled content of building materials than they might otherwise think. For example, structural steel and aluminum have a percentage of recycled content. Concrete and masonry have constituents that are recycled from other industries. This section explains current terminology, discusses why and how structural engineers can leverage recycled materials, as well as provides resources.

Definitions

In order to understand recycled content, some general definitions are provided.

Recycling — Recycling is the reprocessing of useful and usable materials into other usable materials that would otherwise be sent to a landfill or become waste. The process also reduces the consumption of raw materials and can reduce the amount of energy that would be used to make products from virgin materials. Recycling helps spread the cost of the original mining or extraction of the ore or virgin material over a longer or infinite amount of time. According to the United States Environmental Protection Agency (EPA), "While recycling has grown in general, recycling of specific materials has grown even more drastically: 50 percent of all paper, 34 percent of all plastic soft drink bottles, 45 percent of all aluminum beer and soft drink cans, 63 percent of all steel packaging, and 67 percent of all major appliances are now recycled." (USEPA 2008)

Recycled content — Recycled content on the other hand is a measure of how much recycled product is contained in a finished product (AISC 2005). The percentage of recycled content is a measure of the recycled efficiency of a material. The rate of reclamation is a measure of how often a product is actually recycled at the end of its useful life. Conversely, recycled content can also be defined as that portion of a product that is composed of materials that have been recovered from waste. This may include both post industrial (pre-consumer) and post-consumer waste (USGBC 2006).

Recycled content is defined by the International Organization for Standardization, ISO 14021 – Environmental Labels and Declarations – Self Declared Environmental Claims (Type II Environmental Labeling). The ISO 14020 series standards are documents that convey information on the environmental aspects of a product. Each environmental label or declaration is to be used for encouraging demand for and supply of those products that cause less stress on the environment. Type II environmental declaration uses symbols to show the environmental aspects of a product in order to promote the environmental benefits of a product to environmentally concerned consumers. ISO 14021 is an international standard providing guidance on how to make self declared environmental claims that will maintain a level playing field in the market place (Lee and Uehara 2003, FTC 2007). ISO 14021 is important because it provides a framework for evaluating recycled content.

Post-consumer waste — Post-consumer waste is waste produced by the end consumer. Households, commercial, industrial or institutional facilities produce materials which can no longer be used for their originally intended purpose. It is in the trash that is thrown out. On a construction site, the post-consumer waste is the waste material placed in the dumpsters. Conserving post-consumer waste is important because it avoids using virgin resources and strengthens recycled material markets (USGBC 2006).

Post-industrial (pre-consumer) waste — Post industrial waste, also known as pre-consumer waste, is material produced from manufacturing waste that is never used as a consumer product. It diverted from the waste stream during the manufacturing process. Post industrial waste is often not considered recycling in the traditional sense, but for many recycled content metrics it is an important constituent.

Recyclability — The recyclability of a product or material is the amount that can be collected, separated, or otherwise recovered from the solid waste stream for reuse or in the assembly of another product. Conversely, reusability (discussed in detail in Section B.6.d) relates to how many times a product may be reused. Some reusable products have more up-front costs than disposable products. A life-cycle assessment (LCA) can be estimated for certain products to determine if it is economically or environmentally feasible to recycle or reuse a material or product; see Section 2.6.

Downcycling — Downcycling is the reduction of the quality of a material over time or recycling of a material to a material of lesser quality. An example of downcycling is plastic. Plastic cannot be returned to its original state. It can only be recycled into a lesser quality product. During the recycling process of plastics, the recycled plastic is mixed with other plastics to create a “hybrid” of a lower quality (McDonough and Braungart 2002).

Downcycling goes beyond the material. It looks holistically at the product, including the coatings on the material. In many cases there are paints or other coatings that cannot be recycled and there are no efficient or in some cases practical ways to separate the material from the coating. The strength and value of the material is lessened or lost.

The process in which products are downcycled takes a significant amount of energy. Starting with the trucks that haul the waste material to the reprocessing plant, continuing with energy required to remanufacture the waste product into a usable product. Most recycling is considered downcycling. However, the addition of some virgin material to the production of a particular material may be able to bring the quality of a downcycled material to an acceptable strength level for use. This is not to say that the lesser product is not useful because in many cases there is a demand for a lesser grade material.

Some benefits of downcycling include the economic advantage of using recycled material instead of acquiring virgin material. This is especially true for materials such as steel (see Section 3.4). Since materials are being reused at least to some degree, the downcycling process reduces the need to use valuable landfill space to dispose of the used product.

An unfortunate side effect of downcycling is the creation of what is termed “monstrous hybrids” (McDonough and Braungart 2002), which is a classification of products, components or materials that combine both technical and organic nutrients (such as recycled paper and polyvinyl chloride) in such a way that these materials cannot be easily separated, thereby rendering it unable to be recycled or reused by either system. These products can only be thrown out and not recycled in any way. Monstrous Hybrids are created from many recycled products in good faith but when it comes to recycling them into the component parts it becomes cost prohibitive or impossible to recycle (McDonough and Braungart 2002).

Why should structural engineers specify recycled content?

One reason to specify materials that use recycled content is because it reduces the impacts from the extraction and processing of virgin materials. Other benefits are the reduction of solid waste, water and energy use, pollution, and impacts to the landfills.

Much of the construction industry has moved toward recycling for economic reasons. In the past, the price of copper has skyrocketed making it economically attractive for contractors to sell the recycled copper. Many construction materials are and will continue to be recycled either as pre-consumer or post-consumer wastes.

Product markets are emerging for materials that were considered waste in the past. For example, a by-product of the electric power industry is fly-ash. Fly ash can be used in the production of concrete. Previously, power plants were landfilling fly ash until research was performed on how and at what percentage fly ash could be effectively used in the production of concrete. As industries work together to come up with uses of by products or waste materials, recycling of materials will spread to even more products.

Utilizing the recycled content within building materials offers other economic advantages. For example, obtaining recycled feedstock is generally less expensive compared to obtaining virgin material. Additionally, leveraging recycling has the potential to reduce transportation costs, while encouraging the innovative use of materials in existing waste streams for new product manufacturing.

How structural engineers should specify recycled content

While it has become a trendy buzz word recently, recycling is the last of the goals of the 3Rs Waste Hierarchy — Reduce, Reuse, and Recycle. Therefore, in combination with other strategies, specifying recycled content is a very important aspect of how structural engineers can contribute to sustainability. When selecting materials for a project considers the following:

- Choose the highest recycled content available or acceptable for the required material.
- Search for the highest post-consumer content available. Reducing manufacturing waste is beneficial, but recycling post-consumer material has a more positive impact.
- Consider materials that are not just recycled prior to the project use, but those that can be recycled after their useful life.

Quantification of recycled content

In order to successfully quantify the amount of recycled content within a building, recycled content goals should be established early in the design phase. Research into building materials is required to determine the achievable recycled content goals for the project. Once the project materials are selected and a preliminary design has been completed, a preliminary calculation can be performed to set project objectives for recycled content. As the project continues, the structural engineer may be asked to obtain documentation from suppliers, manufacturers, and vendors to confirm the actual recycled content for each material or product. Below are listed a few of the major organizations that quantify recycled content within the engineering/architectural/construction industries. Validation of recycled content for a particular product comes in the form of a written affidavit from the manufacturer or supplier stating the material has the specified amount of recycled material within the product. Additional information provided to justify the recycled content is product cost, manufacturer data, and pre-consumer/post-consumer recycled content percentage.

Established building rating programs — The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Green Building Rating system gives points or credits for material use with recycled content as shown in the credit designation (which is based on cost) of the total value of the materials in the project. More details about LEED are discussed in Section 1.3.

Another method of determining recycled content is through the Green Building Initiative (Green Globes, Section 1.4). One of the objectives stated in the

Resources, Building Materials and Solid Waste section of the Green Globes initiative under the heading of "Minimized consumption and depletion of material resources" is to determine the proportion of building materials that contain recycled post–consumer content. Points are awarded based on the percentage cost of recycled materials versus the total cost of materials.

Recycled product database — Since recycled materials are a waste to some industries and benefit to others, databases and organizations have been created to broker the materials. The U.S. Army Corps of Engineers (USACOE) has a Recycled-Content Product Database, which is a searchable database for recycled content products.

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2.2

LOCAL SOURCING AND LOCAL MANUFACTURING

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Local sourcing and local manufacturing of building materials and systems are frequently part of the discussion in sustainable building design. Local sourcing means that natural resources are extracted or harvested in the region near the project site. Local manufacturing means that fabrication or the manufacturing process of building materials or systems is taking place locally.

How far away is "local"?

There are numerous definitions of how far away might be considered local to a given project site. In some industries, local would be defined as a 100-mile radius and regional would be some multiple of that. Within the U.S. Green Building Council's Leadership in Energy and Environment Design building rating system (LEED), "regional" is defined as within a 500-mile radius of the project site. Project teams may determine that this is too large, or too small, of a limit for their intents. Some proposals have been made, but not yet adopted, to introduce into LEED varying acceptable distances based upon the mode of transportation. LEED Canada-NC has adopted this approach allowing 500 miles for road transportation or 1,500 miles by rail or water.

The Cascadia Region Green Building Council has published the Living Building Challenge standard, which was developed by Jason McLennen (2006). This Challenge gives a maximum distance allowed for various types of materials and services. Material transport distance limits will be based upon a rating of whether the material is lightweight (1,000 miles), medium weight (500 miles) or heavy weight (250 miles). There is also a limit of 1,500-3,000 miles for varying types of project consultant travel.

For small-scale construction, particularly in a rural or residential context, community members' definition of "local" may be limited to what can reasonably be brought to the site by car or even by foot.

Advantages of local sourcing and local manufacturing

There are some compelling reasons why sustainable construction would favor using materials and systems that originate from local sources. This approach reduces transportation energy, carbon emissions, and air quality impacts due to the transport of materials. The amount of reduction varies based upon project location and specified materials, but on average, transportation energy accounts for about 20 to 25 percent of total construction energy, which translates to 20 to 25 percent of carbon dioxide (CO_2) greenhouse gas emissions. Although to keep this in perspective, the transportation energy used during material production and construction may be as low as 2 to 5 percent of the energy used by a modern building over an 80-year lifecycle (Malin 1996).

As mentioned earlier, energy use and CO_2 emissions vary by transportation mode. Energy use by mode of transport is as follows (Malin 1996):

- truck = 2,946 Btu/ton-mile,
- barge = 398 Btu/ton-mile,
- railroad = 344 Btu/ton-mile, and
- oceangoing ship = 170 Btu/ton-mile.

There are additional benefits to local sourcing and manufacturing beyond the true cost of transportation energy. Social benefits include support for the local economy by keeping dollars and jobs in the region (Schumacher 1973). This adds to the local tax base, which contributes to better community benefits, infrastructure, and schools. Using local materials sometimes encourages vernacular building styles, which may be appropriate choices for the given climate or for historical or cultural reasons. Local sourcing also more directly connects users with the impacts of their choices, although it cannot by itself produce sustainable thinking about resource use.

Trade-offs

Sometimes local sourcing is at odds with other sustainable objectives or with other factors involved in selecting a structural system. A local material may not be the most environmentally preferable choice for a given project. All factors including environmental attributes, project type and size, structural system and climatic concerns are to be considered in making material selections. Decisions about local sourcing are best made in the context of the overall lifecycle of the material, multiple environmental factors, and the structure in question. What can be sourced locally may or may not be the most durable material choice. What is most durable may not be environmentally preferable or re-used or safely disposed of at the end of the project's life.

In some cases, manufacturing considerations present tradeoffs with local sourcing. Large, centralized plants generally make more efficient use of raw materials and may have better pollution control. The manufacture of some energy-saving or environmental products could require sophisticated equipment that is not economically viable on a small scale.

Strategies

Project specifications are a key component to achieve the use and verification of locally sourced materials and systems. If pursuing a green building rating based upon any of the currently defined systems (such as LEED) for a particular project, the project team will need to clearly specify the documentation submittals to be obtained and provided by the purchaser. This documentation should indicate the name of the manufacturer or vendor, the product cost and weight, the percent of the product that is compliant with rating system requirements, the distance between the project site and the manufacture or extraction site, and the city and state of manufacture or extraction. Verification of local sourcing is typically based upon this documentation. There is currently no third-party independent verification system that certifies LEED project claims for the location of raw material extraction, processing, or manufacturing.

Another important component includes a knowledgeable design and construction team who are aware of locally sourced and locally manufactured materials and products near the project site. Early collaboration with the local business community and valuable suppliers will also contribute to successful achievement of local sourcing goals.

Local sourcing and local manufacturing have environmental benefits and should be weighed, along with many other factors, in material and system selection. There is no single distance that determines how far away is local, but most green building rating systems have provided a starting point. The use and verification of local sourcing can be achieved through proper specification, knowledgeable design and construction teams, and early collaboration with local suppliers.

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2.3

DURABILITY AND REDUCED MAINTENANCE

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A durable structure is one that can effectively and safely resist environmental, structural and operational demands throughout its service-life with a minimal amount of additional resources expended for maintenance and repair. Durability reduces environmental impact by minimizing additional resources, both material and energy, that must be expended during a building's service-life. Durability also reduces environmental impact by reducing the pollutants to water and air that are associated with replacement or renovation. If durability can extend the service-life of a structure, it also contributes to sustainability by providing a longer period over which to amortize the cost and environmental impact of construction (Wilson 2005).

A structural engineer's view of durability is often limited to material degradation due to environmental effects, such as corrosion of metals or freeze-thaw damage to concrete. A much broader view of durability is required in the context of sustainability. One such definition that has been proposed by Canadian Architect (2008) in "Measures of Sustainability: Durability" is "a material, component or system may be considered durable when its useful service life is fairly comparable to the time required for related impacts on the environment to be absorbed by the ecosystem." This definition highlights the important relationship between the life span of a structure and the environmental impacts required to construct, operate and maintain a structure. In general, structures that are made of energy- and resource-intensive materials will need to have a long lifetime to be considered durable. In contrast, structures that are built largely of natural materials do not necessarily need a long life span to be considered durable and sustainable.

Ochsendorf (2004) discusses the relationships between embodied energy, life span and durability by comparing a Roman stone arch bridge to an Inca suspension bridge built from grass rope. Although both types of bridges are constructed of natural materials and provide safe passage, they achieve durability in contrasting ways. The stone arch requires a significant amount of energy (albeit human powered) to quarry, transport and assemble into a bridge. Once completed the bridge remains functional for a long time with minimal maintenance and its materials may be reused at end-of-life. The stone arch is also highly adaptable over its life span as it can carry traffic loads much larger than originally intended. In contrast the Incan suspension bridge is constructed from natural grass fiber harvested from the land adjacent to each abutment. The bridge is also constructed entirely with human power, but over the course of only a few days with participation of the entire local community. The bridge has high maintenance requirements — it is entirely reconstructed every year. The materials of the bridge cannot be reused. However, the materials are returned directly to the ecosystem with virtually zero impact because the grass has not been physically or chemically processed in any way. Although this bridge does not have a long life-span it is still a durable bridge because of the low impact nature of the materials and construction. Its service life is approximately equal to the time required for the ecosystem to naturally recreate all of the required materials.

Durability is closely intertwined with many other aspects of sustainable building design discussed in this report, such as life cycle assessment, design for deconstruction, adaptability, and natural building materials. Material-specific issues related to durability are discussed in Section 3 of this report.

Elements of durability

A structural engineer can consider features of durability as criteria in many aspects of design, from the building envelope to extreme load events.

Primary structural systems — For typical buildings the primary structural members are often well-protected from environmental deterioration. However, primary structural systems may be affected due to failure of the building envelope to provide protection against environmental degradation. For example, an ineffective roofing system may lead to premature failure of the roof framing members beneath.

Certain types of buildings may have extreme indoor environments and require specific consideration of material degradation, such as natatoriums or industrial facilities. Other buildings, such as parking garages, require significant attention to durability due to their exposed structural elements. Infrastructure — bridges, tunnels, pipelines, roads — also requires significant attention to durability on the part of the structural engineer. Foundations can be subject to extreme environmental effects, in particular retaining walls or piles in oceanfront buildings (Webster 2004).

Modeling of aging and corrosion of structural materials over time is one possible approach to designing for durability. References such as Bijen (2003), Frangopol et al. (2004) and Yu and Bull (2006) provide detailed information on aging and corrosion processes for many structural materials, as well as methods of predicting loss of strength due to deterioration. For projects where such detailed analysis is not warranted, some guidelines for best practices are available (see Section 3). Prevention of corrosion or undue aging may take a variety of forms depending on the materials involved. For example, the durability of concrete may be enhanced by additives such as slag or fly ash, which are also sustainable because they are reclaimed by-products and replace portland cement (see Section 3.2 — Concrete). Other material-specific measures to enhance durability and sustainability are discussed in Section 3 of this report.

Building envelope — The building envelope is subjected to numerous environmental demands that affect durability, such as moisture, heat, or ultraviolet light. Wilson (2005) discusses many of the common aspects of durability related to the building envelope. Although building envelope materials are often specified by the architect, careful review and analysis by the structural engineer can avoid future problems related to durability. Structural engineers are often responsible for the design of support systems for the building envelope, such as lintels or curtain wall supports. Inattention to details related to moisture migration in the envelope system can result in premature failure of the secondary structural elements. Designing an envelope system to ensure proper air flow and prevent excess moisture may allow the use of natural building products or eliminate the need for corrosion-protective coatings, which often contain environmentally harmful chemicals.

Extreme loads, natural hazards, and performance-based design — Durability also includes proper design against extreme load events and natural hazards. A durable structure should continue to meet its operational demands without the need for undue repair or maintenance. Current strength and safety based structural specifications do not necessarily address durability and repair due to extreme load events. A structure may perform safely (for example, there is no loss of life), yet suffer significant damage that requires extensive repairs or even demolition of the structure well before its intended end-of-life. A large portion of the damage may be associated with non-structural components. Control of such damage often involves design of the primary structural system and may include supplemental damping devices or isolation systems.

Performance-based deign (PBD) is becoming a common design strategy for extreme load events (such as earthquakes). Its methodology allows for the consideration of other performance criteria that fall outside the traditional bounds of strength and safety oriented structural design specifications. One common PBD objective for seismic design is to limit damage to non-structural components of a building, e.g. cladding and interior wall finishes. Not having to replace non-structural building components contributes to the durability profile of a building. Although the design and specification of these elements is typically beyond the scope of the structural engineer, design of the primary structural system is used to prevent such damage and therefore falls well within the scope of the structural engineer. With PBD the designer can include a specified level or economic cost of maintenance as performance criteria. The drawback is that assessment of the established criteria may require a detailed, state-of-the-art analysis of the structure's complete life-cycle.

Maintenance and renovation planning — Maintenance and renovation planning should be a part of initial building design. In cases where life cycle analysis (LCA) is used, this may be a component of the LCA. Bijen (2003) discusses several possible objectives which could form the basis of a maintenance strategy, such as: prevention of corrective maintenance, quick repairs, low-cost repairs, repairs to minimize occupant disruption. An effective maintenance strategy must consider inspection and preventative maintenance, and also accessibility for inspection and ease of remedial action without widespread disruption to the structure or its function. Renovation planning ties in closely with design for adaptability and deconstruction (see Section 2.4).

Existing standards and guidelines

Traditionally, durability of building products has been measured only in terms of service-life, with the data often provided by the manufacturer. American Society for Testing and Materials' "Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials" (ASTM 1982) provides the basis for service life prediction of building components and materials using accelerated testing. However, professional organizations are developing broader standards related to durability in buildings.

The Canadian Standards Association (CSA) has published "Guidelines on Durability in Buildings" (2007) to address the durability of both buildings and building components. The standard explicitly considers issues of durability which are typically only implied in national building codes. The CSA Guideline discusses mechanisms of premature deterioration, and design, operation and maintenance methods to improve durability. This Guideline is based on the concept that life expectancy of a building and its components must be addressed at the design stage. The Guideline includes a comprehensive bibliography on durability with references from researchers and building organizations worldwide. The material in the Guidelines can be applied to building design, operation, and construction in the United States.

The International Organization for Standardization (ISO) is in the process of developing the ISO 15686 series of standards (ISO 2008) entitled "Buildings and constructed assets — service life planning," published between 2000 and 2008 with several parts still being developed or under revision. These standards consider the maintenance and durability requirements at the planning stage that will be necessary to achieve the desired service life. The standards provide overall guidelines and specific methodology used to estimate the service life of structures and components, and procedures for evaluating service life data from practice. The standards provide guidance to manufacturers on the determination and presentation of service life declarations.

The International Council for Research and Innovation in Building and Construction (CIB) , in collaboration with The International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM), has recently published two documents related to durability. CIB Publication No. 294 (Hovde and Moser 2004) is a state-of-the art report on service life prediction, based in-part on the existing ISO 15686 standards. The report discusses methodology, available calculation tools, and uncertainty in predictions. It also includes examples specific to buildings and components. CIB Publication No. 295 (Jernberg et al. 2004) is a compilation of research related to durability from 1991 to 2002, including a substantial annotated bibliography.

Finally the *GreenSpec Directory* (Wilson et al. 2005) includes "Exceptional durability or low-maintenance" as one of its attributes for building products.

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2.4

DESIGN FOR ADAPTABILITY AND DECONSTRUCTION

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True material sustainability means using only renewable natural resources, and using renewable resources no faster than they can be renewed. While this goal is probably unachievable, applying Design for Adaptability and Deconstruction (DfAD) strategies to a project can get designers and engineers closer to this ideal, since salvaged and recycled materials are effectively "renewable" resources. Planning for future reuse of materials installed in buildings today makes it easier for the next generation of builders to reuse materials from today's buildings when they are no longer needed. Further, designing for adaptability will make it more likely that the building will be long-lived, further increasing environmental benefit.

Structural materials generally account for the majority (by weight) of the materials in a building. Therefore facilitating the reuse of structural materials offers the potential for great environmental benefit. Structural engineers play the largest role in determining which structural materials and components are used and how they are connected together, making them a key player in implementing DfAD strategies.

Terminology

Awareness of specific terms will enable the structural engineer's ability to incorporate DfAD into project design.

Adaptability — Adaptability is the ability of a structure to accommodate varied and often unknown future uses and changes with minimal cost and effort. Two types of adaptability are flexibility (the ability to make minor changes to space usage) and convertibility (the ability to accommodate changes in use) (Moffatt and Russell 2001).

Deconstruction — Deconstruction is a demolition method where a structure is carefully and methodically disassembled so as to salvage and recycle as many components as possible; also known as "disassembly."

Reuse — The reuse of a previously used item (brick, piece of lumber, steel column) with minimal processing. Example: remove a steel column from a building, refabricate it, and install it in another building. Reuse is less environmentally damaging than recycling, and more aligned with the ideals of sustainability.

Recycling — The destruction of a used or waste item so that it can be manufactured into a new product. Example: remove a steel column from a building, send it to a mini-mill where it is merged in an electric arc furnace with other scrap steel and rolled into a new section, fabricate a new column, and install in a building.

Down-cycling — Recycling material into a new product that has lower value than the source material. Recycling materials to the same use as the source material is preferable to down-cycling, since it allows for the preservation of the material value through multiple uses. An example of down-cycling is crushing used concrete for fill.

Benefits

The benefits of DfAD include the following:

- increases salvage and recycling rates by making it easier to reclaim materials during renovation and demolition;
- reduces consumption of raw materials ("closes the materials loop") and of energy by fostering the use of salvaged and recycled materials;
- reduces waste and landfill demand by redirecting used building materials into new construction;
- increases building lifespan by facilitating adaptation, simplifying repair and maintenance, and improving durability;
- can simplify construction by using standard connections and repeating geometries, making initial construction and later modifications more economical;
- adds to building value by making maintenance, system replacements/upgrades, and adaptation easier and less costly.

The net value of materials at end of life will likely be increased since the materials will be easier to extract and be suitable for reuse, which also increases the market value.

A study by the Athena Institute (2004) found that most of 227 building demolitions it reviewed over a three-year period in St. Paul, MN were not demolished because of deterioration, but rather because of factors such as neighborhood redevelopment (35 percent), unsuitability for intended use (22 percent), and fire damage (7 percent). Of those demolished due to physical condition, the most common reason for the poor condition was poor maintenance. DfAD would help address in particular unsuitability for intended use (by making the building more adaptable) and redevelopment pressure (by making reusable materials easier to salvage).

Drawbacks

Initial construction when using DfAD may be more expensive because of the use of extra material (for example, if designing for future adaptation with higher live loads). However, simplified geometry and assemblies can reduce cost, making actual economics difficult to predict.

Additionally, more design time may be needed to incorporate the goals of DfAD because the designer must consider not only the service life of the project, but also the after-life.

DfAD also adds constraints to design. Certain structural systems that are now in common use are not well suited for deconstruction, limiting the designer's choices and possibly raising initial project costs.

Strategies

Strategies may vary if designing for recycling instead of reuse. Reuse is preferable to recycling to a material of equal value. Recycling to a material of equal value is preferable to down-cycling to a material of lesser value. The strategies discussed below are directed primarily at reuse. For reuse, the goal is to be able to remove the members easily with no damage. If recycling is the goal at end-of-life, then damage is acceptable as long as the materials can be easily separated.

Although some of the following strategies may appear to lie more in the purview of the architect than the structural engineer, in integrated team design environments, structural engineers have the opportunity to introduce these strategies even if the architect does not.

Simplicity — Simple buildings with independent systems simplify deconstruction and adaptation. Renovation and deconstruction contractors can easily identify the building framing layout and can rely on repeating elements, reducing surprises and saving money on renovation and deconstruction projects. Simple buildings tend to have repeating bays with similar geometry, beam sizes, and connection types.

Independent systems — Building systems have different longevities (Brand 1995). Maintaining separate building systems, such as mechanical and building envelop systems, makes renovations and deconstruction easier, providing environmental and economic benefits throughout the building lifecycle.

Mechanical systems may be upgraded several times during a building's life. Separating mechanical systems from the structural system facilitates mechanical upgrades, reducing their cost and extending the building life. Separation may be accomplished using dedicated vertical chases in the building, and/or a raised floor system, which permits the mechanical systems, such as piping and ductwork, to be installed above the structural floor but below the finish floor. Such approaches also benefit deconstruction, since the mechanical systems can be easily separated and removed, and the structural members remain intact, without holes and notches for piping, ductwork, and so on.

Envelope systems are also frequently updated during a building's life, particularly commercial buildings. Envelope elements, such as curtainwall panels, should be attached to the structure with easily accessible, mechanical fasteners.

Durability — Durability may be defined as "the ability of a building or any of its components to perform its required functions in its service environment over a period of time without unforeseen cost for maintenance or repair" (CSA 2007). Durability of and differential durability among elements and systems should be considered to ensure that the "disassembled" elements or systems have a useful remaining life for reuse purposes.

Material and connection choices — Choice of materials and connections circumscribes end-of-life options. Structural strategies that make buildings easier to adapt and deconstruct include the following:

- Use simple connections with clear load paths.
- Use standard details and components.
- Use mechanical fasteners, avoid adhesives and welding.
- Minimize the number of different member sizes.
- Use few larger members rather than many smaller members. When deconstructing, it is less labor-intensive to handle fewer members. An exception may be residential-scale construction, where much of the renovation and disassembly work likely will be performed using hand labor. Examples: Specify 3–inch–deep steel deck with longer spans instead of 1 1/2–inch-deep deck; Use larger timbers at 4 feet-on-center instead of smaller 2x lumber at 16 inches-on-center.
- Use salvaged materials. If they can be reused once, the chances are they can be reused again.
- Avoid composite systems unless they can be reused as such. An example of a composite system with reuse potential is one comprised of structural insulated panels mechanically fastened together. New, creative details are needed to convert commonly used systems such as cast-in-place concrete on steel deck with composite steel beams into systems that can be dismantled. A concept for a deconstructable composite slab system, developed by the author and Dirk M. Kestner, now of Walter P. Moore, won an award in 2007 in the Lifecycle Building Challenge (Fig. 2.4-1).

Framed structures of wood and steel are good choices for DfAD projects, since the components may readily be designed for disassembly. In steel structures, using mechanically attached fire protection such as drywall is preferable to sprayed-on and especially cast-in-place concrete fire protection. Framed cast-in-place concrete structures are not readily deconstructable, but precast concrete systems may be deconstructable with thoughtful detailing and member selection; in Europe, some pilot projects have successfully utilized deconstructed precast floor panels in new construction. Similarly, cast-in-place concrete walls are effectively not deconstructable. Interior wall systems that are demountable and movable are preferable for both flexibility and deconstructability. Moment-resisting frame lateral systems that present no interior obstacles are a good choice for maintaining flexibility, as opposed to lateral systems that include interior braced frames and shear walls.

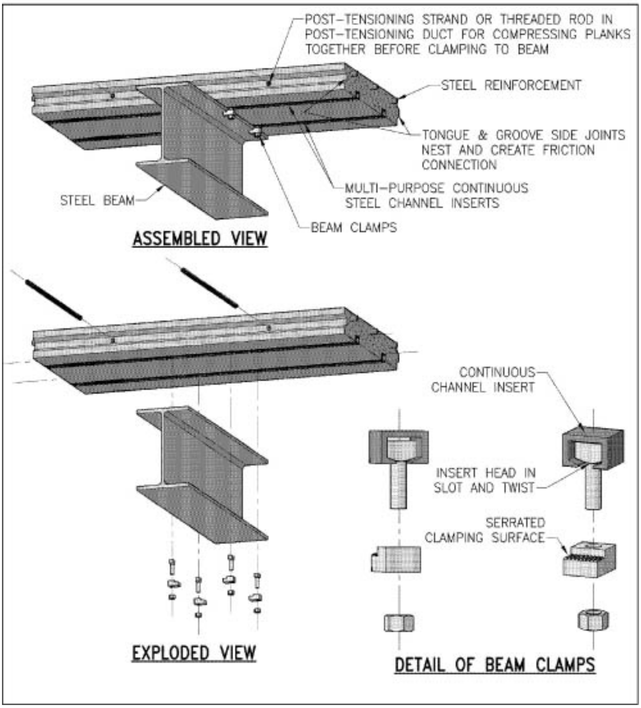

Figure 2.4-1. Deconstructable and reusable composite slab system
(Image copyright Simpson Gumpertz & Heger Inc., used with permission)

General considerations for successful DfAD projects

A number of best practices have been developed and should be considered when embarking on a DfAD project.

Consider handling and safety — How will the deconstruction workers safely access the members and connections to disassemble them? Do heavy, large members require clearly marked lifting points for removal? Will the frame remain stable as components are removed?

Label materials — One of the most time-consuming and expensive aspects of renovation is the identification of existing materials. Often, in the absence of identification, we make conservative, worst-case, assumptions regarding existing materials, so that they are not reused to their maximum capacity. Along these lines, labeling also adds value to materials salvaged for reuse.

Safeguard original as-built drawings — During renovation and deconstruction work, original drawings are an invaluable resource. They generally disclose hidden conditions and describe framing sizes and locations that could take days or weeks to identify in the field. An inventory of the structural members (as shown on the drawings) will help the used materials broker find buyers even before the building is dismantled. In new design, consider providing a designated, locked cabinet for storage of original construction documents. Only the facility manager should have access, and instructions should be included to always return the documents after use.

Other documentation — In addition to labeling materials and safeguarding original drawings, other design information that may be useful includes design requirements, disassembly instructions, limit states, demand-capacity ratios, safety factors, and so on. This information could be included on the safeguarded design drawings, included in a "deconstruction manual," and/or posted in the building.

Design with non-hazardous, non-toxic, durable materials — Clearly future renovation and deconstruction workers do not want to handle dangerous or toxic materials, nor will they have market value.

Markets — Although markets and distribution channels are presently not well developed, by the time the building that is under design today reaches the end of its life, these markets will likely have matured.

Building use — Different building uses have different average lives. DfAD may be more desirable for buildings with short projected life-spans, although the adaptability benefits of DfAD can also extend the life and reduce the cost of maintaining long-life buildings as well. The use of higher live loads in design than code minimums can extend building life by making conversion to new uses more feasible.

Maintenance — "Maintenance" of adaptable and deconstructable building features must be considered during the building life. The building owners should keep records of modifications to the building, including construction documents, and not perform renovations that compromise the integrity of the building systems' original adaptive or deconstructable qualities.

Life-cycle considerations

The extent and the number of times that the material/element/system can be disassembled/re-assembled/reused may be included in conducting a life-cycle assessment (LCA) of the original design, such that the benefits of the DfAD can be more accurately reflected when comparing design options. While LCA with respect to materials is rather well understood, LCA for elements and systems (especially as specific as DfAD) is not as well established. For further discussion, see Section 2.6 — Life Cycle Assessment.

Green building rating systems

The draft Green Globes standard (GBI 2008) rewards three points for designs allowing the removal of reusable materials without substantially damaging the materials or their surroundings. The 2009 Collaborative for High Performance Schools (CHPS) standard includes a credit in the Leadership, Education, and Innovation category that offers up to 4 points for DfAD, as follows:

- Two points for preparing a disassembly plan for major systems during renovation and at end-of-life.
- One point for designing major systems to be "disentangled" from one another.
- One point for providing reversible connections that are accessible for at least one major short-life system (e.g. roof or HVAC).

The LEED rating system does not at present reward DfAD.

DfAD design guidelines, standards, and other references

A number of government agencies have developed excellent guides to design for deconstruction (CSA 2006, By Design Consultants 2002, Guy and Ciarimboli 2006, Morgan and Stevenson 2005). CIRIA, a British construction research association, published a detailed guide in 2004 (Addis and Schouten 2004). Two papers on DfD with an emphasis on structural materials are Pulaski et al. (2003) and Webster and Costello (2005). Finally, a Swedish doctoral thesis available on the internet offers a good overview of the topic (Thormark 2001).

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2.5

REUSE OF BUILDINGS, STRUCTURAL COMPONENTS, AND NON-BUILDING STRUCTURES

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This section is devoted to finding new value in used structures. Finding new uses for structural components and whole building structural systems is very often the most sustainable approach to a project. An enormously positive impact on the environmental footprint is realized by not using the energy and water required to manufacture new materials; by not mining or harvesting virgin materials; by not emitting the green house gases (GHGs) and other pollution associated with manufacturing and sourcing materials; and by not sending unwanted materials to the landfill. Whole building reuse also avoids polluting the local air with particulates from demolition.

This section will hopefully encourage engineers to consider reusing both whole buildings and individual structural components on their projects. There are three main categories of reuse — whole building, structural components, and non-structural components — and guidance is given for each. Most structural engineers are likely familiar with projects that reuse a whole building or most of it; here we discuss some considerations to make the project as successful as it is sustainable. Few structural engineers will have experience reusing structural components, except perhaps in the limited case of relocating an element within the same project; the section on reusing structural components provides key information relevant to designing new buildings with salvaged parts. Finally, structural engineers must be at least as nimble as architects, their usual clients, in their knowledge of reusing non-building structures. With this in mind, this section includes discussion on designing for the appropriation of non-building structures into buildings.

Terminology

Awareness of specific terms will enable the structural engineer's ability to incorporate reuse into project design.

Reuse — Literally the using again of a building or building component. The second life of a reused building or component can be the same as the original use or quite different. In this section, the focus is entirely on the reuse of structure for another similar or different structural purpose. For example the reuse of large timber beams to make furniture is not the goal, but turning a post into a beam may be. Reuse typically implies minimal if any refurbishment or fabrication, at least as compared to the energy and resources needed to manufacture a new version of the same item. In the context of reusing components, the terms salvaged or reclaimed (as opposed to recycled) are commonly used to characterize the elements' state.

Adaptive reuse — Refers to the reuse of whole buildings where the new program or service requirements are distinctly different from the original. Adaptive reuse is applicable to certain, but not all classes of historic buildings. An adaptive reuse project may include partial demolition and rebuild or new additions to the original structure; however the majority of the original structure remains in place even if it is not readily recognizable. These projects may involve significant architectural changes, and in some cases even altered load paths.

Renovation — Usually refers to relatively minor improvements that usually do not involve structure unless specifically stated. A major renovation herein refers to a reuse scheme for which the structural system must be evaluated and possibly altered.

Historic buildings — A common form of renovation is the reuse of historic structures. As design professionals we should understand the effects of significant buildings on the community. Often historic structures are the center point of a downtown or even the centerpiece of a new development. It is important to retain these buildings to preserve the community. Structural engineers can lead this effort by explaining to other stakeholders how historic buildings are typically structurally robust and can have a very long and useful extended service life.

Conservation and historic preservation — For conservation the primary goal is to preserve the building in its current state, yet protect it from further deterioration. This approach must balance several conflicting goals: the aesthetics of an arrested state of decay, design interventions to ensure the building will endure, and structural safety concerns.

Historic restoration — The primary goal is to restore the building as much as possible to its original condition. Depending on the building's intended function, there may be compromises in order to comply with modern building codes.

Salvaged vs. recycled — Knowing the difference between *salvaging* and *recycling* is fundamental to a reuse strategy. Salvaging is the reuse of an item (such as brick, a piece of lumber, or a steel column) with minimal processing such as trimming, drilling holes for connections, and so on. Recycling is the destruction of a used or waste item so that it can be manufactured into a new product based on its raw material content. (See Section 2.1 — Recycled Content for more information on this topic.)

Adaptive reuse of existing buildings

Structural engineers can make a significant contribution to green design by taking a lead role advocating for the reuse of existing structures. The repurposing of a building usually means all interior features are removed, while the "bones" of the building remain. The familiar saying "a building has good bones" refers to the strength and durability of the structure. Buildings with "good bones" are the best candidates for adaptive reuse and structural engineers should be persuasive and proactive in recommending a plan of adaptive reuse for these structures.

In fact, structural engineers should lead this effort because they have the expertise to understand how a building's structure works, including the existing load path and how it may be safely altered. The viability of a major renovation project often hinges on the adaptability of the interior spaces to serve new uses. The ingenuity of the structural engineer is often required to determine new ways to enhance the capacity of existing structural systems. A successful adaptive reuse renovation avoids the need for large amounts of new structural and envelope materials and often many finish materials as well. Reducing the amount of new material used in buildings is a large part of the sustainability picture. Building and material reuse reduces the use of nonrenewable resources (steel, cement); the energy used to extract, produce and transport the materials; and the pollution and GHGs emitted during manufacturing and transport.

Engineering considerations — The structural engineer must provide guidance to the architect and owner in determining the suitability of the existing building to meet new programming needs. Such needs may require additions to increase square footage or increased load capacity.

For projects that include partial demolition of the structure or the demolition of an adjacent building the structural engineer must evaluate the ability of the structures to withstand the disturbance. In these cases, the structural engineer should consider if a vibration monitoring program is required, particularly for older and historic structures. The structural engineer should be prepared to design and oversee such monitoring programs.

Initial assessment — This assessment should be undertaken with the spirit of discovery. A decision on whether a building is suitable for reuse and appropriate to the proposed program should not be made until a full reporting of the initial assessment is made to the owner. In the case of registered historic buildings, the assessment may serve to inform the type of reuse and restoration.

Condition and durability: A crucial part of the initial assessment is a general and thorough condition survey, which is discussed in more detail below. To protect the owner from cost overruns the team must have a full understanding of the building's condition before committing to a reuse project. The structural engineer must insist on full access and testing during the initial assessment to ensure that all the major structural repairs that will be required are known. Probes should be taken in all areas of high risk, such as locations subject to water infiltration or with a suspected history of over-loading.

Existing drawings: The most useful information for a project team evaluating a building for possible reuse are the original design documents. Beyond providing crucial details about the structure, the drawings provide a template on which all condition data can be recorded and the new program designed. If existing structural drawings are available the structural engineer should verify that they depict the as-built structure. In some cases, verification will require a probe plan, non-destructive evaluation (NDE), and materials testing.

No existing drawings: When documents are not available, as-built construction drawings must be generated. This can be a difficult and time-consuming process; it is essentially a project phase in itself. The engineer must collaborate with the architect to generate as-built working drawings. An extensive probe plan will likely be necessary for the engineer to determine the structural system and measure components. NDE may be useful for laying out probes as well as verifying reinforcement in concrete elements. Material testing will be required for concrete strengths. For steel components strength can sometimes be reliably determined by historic standards. An indispensable reference for those working on older buildings is the American Institute of Steel Construction Steel Design Guide 15 (SDG 15), AISC Rehabilitation and Retrofit Guide: A Reference for Historic Shapes and Specifications (AISC and Brockenbrough 2002), which is a free download for AISC members. For buildings constructed before 1910, testing the steel strength is a necessity. In the 20th century the American steel industry became highly standardized, so the engineer can be fairly confident about the yield strength of a steel member if the era in which it was rolled is known. According to AISC SDG 15, historic ASTM standards required 30 kips per square inch (ksi) minimum yield from 1900 until the early 1930s and 33 ksi minimum yield from then until the early 1960s. The ASTM A36 standard, requiring 36 ksi minimum yield, was first published in 1962. These are minimum values and steel usually tests higher. See Table 2.5-1 in "Reuse of Structural Steel" below.

Younger buildings may use high-strength steel (typically 50 ksi, but may be as high as 65 ksi), in which case there will most likely be existing documents noting the steel properties. See "Seismic concerns" below for additional testing recommendations.

Condition and durability — The current condition of a structure reflects several aspects of its history and its inherent durability including the quality and durability of the original materials; the quality of the original construction; the appropriateness of the original design; and the diligence of the maintenance plan over the building's lifetime.

The condition survey may determine that a lack of quality in the original materials or construction have contributed to deterioration in a certain area. In such cases, the engineer should recommend ways to repair the component or suggest alternatives to keeping the original scheme in the affected areas. An example of this is the early use of fly ash aggregate as a filler in concrete slabs, which can lead to carbonation, corroded reinforcement, and unstable slabs (fly ash aggregate as filler should *not* be confused with the fly ash used today as a cementitious component). If the original design is contributing to condition problems (such as the perfectly flat roofs of some mid-century modern buildings) then the engineer should work with the architect on a more durable design for that area.

A failed or non-existent maintenance plan can make what was essentially a good building look really bad. In most cases, the extent of *structural* damage due to deferred maintenance is limited to elements connected to the building envelope such as the façade and roof. It is important to note that moisture infiltrations may also result in mold problems that may require the removal or remediation of finishes and surfaces. A traditional brick façade offers an example of problems that can result from deferred maintenance. Window lintels in the brick façade are often steel angles behind a wythe of brick. It is normal that over many decades the lintels will corrode and require in-situ reconditioning, but the service period between needed repairs is severely shortened by neglecting to repoint the brick or repointing with inappropriate mortar. When the lintel corrodes and expands it cracks surrounding bricks making the larger area more susceptible to water infiltration and mold growth as moisture is trapped in the wall.

The main structural condition issues are deterioration and failure. Deterioration is usually a result of exposure to moisture and wet-dry cycles. This means the engineer will spend considerable time surveying elements that are connected to the envelope, in the basement, and anywhere water leakage and condensation is likely.

An event history can provide crucial information about unseen conditions in the structural materials. It is important to work with the architect and the owner to identify critical service life events that may have affected material properties. For example, has the building been subjected to an earthquake? Has a fire occurred? Has there been an unvented boiler room? One cause of deterioration for concrete is the high concentration of carbon dioxide (CO_2) exhaust in boiler rooms, which over many decades can accelerate carbonation.

Condition assessments should pay close attention to large cracks as they may hint at an unintended load path or the overloading of certain components to or near failure. In older buildings with a history of ad-hoc renovations, it is common to find that extra levels have been installed or that lightly framed areas are supporting heavy storage loads.

For every adaptive reuse project, the structural engineer should expect a combination of building investigation and design of basic repairs alongside designs to revitalize the structure and its capacity.

Design process — The structural engineer should assist the architect with new programming layouts. A successful and efficient adaptive design will maximize the reassignment of structurally robust areas of the building to meet the needs of programs with similarly high loads. For example, when turning a school into a mixed-use space the programs with higher dead loads would work well occupying the school's old library area. The engineer should be proactive in making the architect aware of these opportunities. Generating color-coded dead and live load floor plans is a helpful tool.

Seismic concerns — Some older buildings may not have been designed to any code at all. Certain materials and structural systems used in older buildings may not comply with current building codes, especially in seismic regions. Materials such as unreinforced masonry and hollow clay tile were once building systems of choice, but these materials are not considered safe to withstand a major seismic event. Even relatively modern buildings might require upgrades. After significant seismic events, building codes are typically revised to improve safety. For example, concrete column tie spacing was increased after the 1972 Sylmar earthquake and steel moment frames were overhauled after the 1994 Northridge earthquake.

What do we do with outdated systems and components? Unreinforced materials used only for infill can be removed and replaced with a more secure system. In some applications, the components and systems deficiencies can be mitigated by strengthening measures. The engineer's approach to a building reuse project should include an evaluation of the materials and systems, showing (under the current methods set out by the governing code) how they affect the structure during a seismic event. Some projects may be eligible for and seek code waivers. However, a performance evaluation is still necessary so that the risks are understood.

For steel buildings, modern seismic design may require the engineer to know the ductility and toughness of steel. These properties were not controlled by early ASTM standards. If existing steel framing is to be used in a lateral system designed to meet current codes, ductility and toughness tests may be required.

A larger discussion of seismic retrofit is beyond the scope of this guideline, for more on this topic refer to the American Society of Civil Engineers' Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41) (2006) and Seismic Evaluation of Existing Buildings (ASCE 31) (Hom and Poland 2004).

Code issues — Code issues will depend on the class of building. Historic buildings are often afforded waivers depending on the new occupancy levels. Variances for seismic requirements are likely to be the most challenging issue the structural engineer will face. The engineer is advised to explore potential code violations with building officials and the project team very early in the process. Having access to the local code from the buildings construction era can help clarify discrepancies and facilitate the waiver request process.

Contamination — Typical contaminants that are found on steel members include lead paints and asbestos fireproofing. Working/as-built drawings are helpful in mapping out a remediation plan. Lead paint must be encased or removed. In most cases asbestos must be removed, which is an expensive, labor-intensive process that typically involves evacuating the building. However, this is generally not an added cost item to a project budget because the asbestos would also have to be removed before demolishing the building.

Reuse options — Adaptive reuse projects abound with examples of creative problem-solving with little expenditure of new resources. The options in this field are truly limited only by imagination. However, the sustainable options for each individual project are not unlimited. The team should carefully consider and seek out the adaptive solution that best exploits the existing structure, while meeting the needs of the future program. In other words, the design should respond to the existing building and not force a design idea into, onto, or next to it.

Economics — Whether it will be economical to reuse a building depends on many things. First, it is generally assumed that the appropriate economic comparison is between the design and construction costs of adaptive reuse versus demolition and new construction. This simplistic formula does not include important factors like the added value to a community when an older building is revitalized and a judicious use of resources is demonstrated. But even looking only at the more tangible economics of construction it is often less expensive to adapt an older building. The structural costs are nearly always much lower. The costs associated with adaptive reuse are largely in removing finishes, remediation, and adapting and updating the mechanical, electrical, and plumbing systems. While many buildings are great candidates for reuse, a bad candidate will likely be a very costly building to reuse.

Reuse of existing building components and materials

Most green building guidelines encourage the use of salvaged materials in new construction, and for good reason. Using salvaged materials diverts potential waste from landfill, reduces the consumption of new materials, and often contributes to the aesthetics of the new construction. Unfortunately, structural materials are seldom salvaged. The intent of this section is to encourage the salvage and reuse of structural materials by providing the following:

- techniques for evaluating these materials, and
- a review of real obstacles and potential solutions.

Within Section 5.0 — Case Studies are examples of projects incorporating substantial quantities of reused materials, such as Section 5.4 — The Nomadic Museum and Section 5.8 — BedZED.

One way to obtain salvaged materials is to “deconstruct” an existing building. Deconstruction is a demolition method whereby a structure is carefully disassembled with an eye towards salvaging as many components as possible. (See Section 2.4— Design For Deconstruction and Adaptability for more information on this topic.)

When using salvaged materials, it is helpful to know where the materials came from. Knowing the era and location of the building can provide clues as to the structural properties of the material. In the best of cases, original construction documents might be available which explicitly state the required design properties.

Structural materials with good salvage potential include: brick, steel, precast concrete, and wood. Brick and wood timbers are already frequently salvaged for specialty applications. Steel framing, precast concrete, and dimension lumber are rarely salvaged. For a detailed discussion of the reuse issues associated with salvaged wood, brick, and steel, see “The Use of Salvaged Structural Materials in New Construction” (Webster 2002).

Reuse of wood

The salvage rate of wood members is roughly proportional to the member size. Timbers (6x and larger) are frequently salvaged, while dimension lumber (4x and smaller) is rarely salvaged. Timbers can be much more easily removed from a building without damage. One timber can be cut into many boards for use in flooring or furniture; or it may be reused whole in another structural capacity. Dimension lumber is often full of nails and nail holes, particular near the ends of the members, and tends to be shorter in length, reducing salvage options.

There are no technical obstacles to the reuse of both dimension lumber and timbers in structural applications (Fig. 2.5-1). Structural reuse is preferable to downgrading the material by burning it, mulching it, or cutting it up for non-structural use (flooring, furniture), because it maintains the integrity of the wood, maximizes its potential, and leaves the option open for reuse again and again in future buildings. A beautiful old-growth 12x12 timber post removed from an old mill building can continue to amaze viewers if it is reused as a post in a new building, but if it is cut up and spread across a floor it loses much of its grandeur, and will less likely be salvaged for future use at the end of the building's life.

Figure 2.5-1. Market constructed using salvaged wood timbers (Photo copyright Mark D. Webster, used with permission)

Engineering considerations — For certain structural uses of salvaged lumber, the design values need to be determined. The properties of salvaged lumber vary widely. However, compared to new lumber, it is more likely to have come from old-growth forests, where large, slow-growing trees provide dense lumber with few knots, resulting in greater strength and durability. On the other hand, it may be notched, contain bolt or nail holes, or have suffered decay. These properties can be evaluated by grading. Species identification along with member grading provides key information allowing the engineer to proceed with a salvaged wood project with a high level of certainty.

Identification: A reasonable degree of confidence in the species can often be derived from the historical narrative (such as typical building practices) and documents. Much can be understood from the salvage source building itself. Age can help determine the available species, for example, the American Chestnut blight started in 1904 and by 1940 had virtually wiped out the commercial use of formerly popular chestnut timbers, (Oak 2002). Location will determine the regionally available species. Species/grade stamps may exist if the source building is newer construction.

If the source and history is unknown, or if uncertainty still exists, the species can easily be determined by an expert. The United States Forest Products Laboratory (FPL), based in Madison, Wis., provides free species identification and is a great resource for information on wood species characteristics. See the Resources at the end of this section for FPL information.

Grading: The grade and allowable design strength of salvaged lumber can be determined either by a visual procedure or a combination of visual grading and mechanical testing.

One way to grade salvaged lumber is to hire a certified professional from a U.S. or Canadian grading agency to *visually grade* it. The grader will use the same rules that apply to new lumber. Standard grading rules are based in part on the appearance of the wood; surface defects from use and removal will cause much of the lumber to be "down-graded" by about one grade relative to its actual strength. Northeastern Lumber Manufacturers Associate (NELMA) graders are permitted to certify salvaged wood for grade, but will not certify the strength.

Another option is to use ASTM D245 (2006), Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber, to determine the design strength and stiffness. This procedure grades for strength alone; there are no deductions for visual characteristics that do not influence strength. The grader examines all four faces and ends of the piece of lumber, noting the size and location of defects, such as knots, slope of grain, etc. When applied to salvaged lumber, bolt holes and other reuse damage may be treated as knots. The allowable stress for the piece is taken as a percentage of the allowable stress of a defect-free member.

The FPL is in the midst of a large-scale testing program to develop specialized grading rules for salvaged lumber. To date, the lab has tested thousands of salvaged timbers and pieces of dimension lumber (Horne-Brine and Falk 1999, Falk et al. 1999, Falk et al. 2008).

A *mechanical stress rating* (MSR) can be used in conjunction with a visual grade to certify strength and stiffness. Using a correlation between member stiffness and strength, MSR machines measure a member's flexural stiffness in the weak direction and assign a strength based on the result. When a large number of members need grading, MSR may be a good option, keeping in mind that the degree of automation and speed varies with the price of the machine, and that MSR is not a stand-alone grading system — it must be used in combination with visual grading criteria.

Code issues — Codes generally specify who may grade and approve the use of wood for structural purposes. For example, the International Building Code (IBC) (ICC 2006) states that "sawn lumber...shall be identified by the grade mark of a lumber grading or inspection agency that has been approved by an accreditation body that complies with DOC PS 20 [NIST American Softwood Lumber Standard] or equivalent." These requirements prevent unapproved agencies from grading lumber for structural use. Following are some useful tips:

- local building officials may agree to allow an unapproved agency, such as a wood technologist or structural engineer, to determine the strength of wood members in some cases;
- most common building codes include provisions for "alternative" materials, which may be interpreted to include salvaged materials, see IBC (ICC 2006) section 104.11 for an example; and
- see IBC 2303.1.1 (ICC 2006) for more on grading requirements.

Contamination — The most common contaminant on salvaged wood is lead-based paint. Paint may be sand-blasted or planed off, but the associated cost is justifiable only with large timbers, which are often planed down anyhow, to remove dirt and surface damage. Deeply contaminated members (featuring oils, solvents, asbestos dust, creosote, or other toxins) from certain industrial facilities are rarely suitable for reuse. Old nails are another contaminant. Usually nails are removed by hand, which can be expensive. Metal elements, such as nails, can create a thermal bridge in exterior walls, which reduces the effective R-value. In some cases any thermal bridging in the envelope is a large concern, if so the wood should be scanned with a simple metal detector to ensure that all the nails have been removed. Consult with other project members — architect or mechanical engineer — to determine the envelope sensitivity before calling for nail removal.

Reuse issues and options — The sizes of salvaged lumber are likely to differ from modern finished sizes, so marrying them into existing construction may be difficult. However, salvaged lumber is usually dry, so less shrinkage can be expected compared to new lumber. Dimensional lumber with edge-nail holes should be placed with the damaged face at the compression side, or at least away from high tension areas (Falk et al. 2008). The most common structural application of salvaged wood is currently framing for post-and-beam houses and other small buildings. The timbers are usually obtained from the demolition of old mill buildings.

Reused dimensional lumber for stud, floor, and roof framing is less common. With the increased awareness of resource and energy issues associated with our built environment there is a high potential for growth in this reuse area. Ungraded reclaimed dimensional lumber (and plywood) can be obtained through salvagers, including the non-profit franchise The ReUse People (more information available in the Resources list at the end of this section).

There is a vast potential supply of dimensional lumber from demolished housing, which is waiting to be exploited. In today's market, using existing techniques, economics do not favor deconstructing houses to salvage their lumber. Methodologies must be developed to make deconstruction more economical. One approach that holds promise is to cut the roofs, floors, and walls of a building into panels and remove them from the structure. These panels may then be deconstructed by specialized teams off-site, or on-site if space permits. This approach permits the rapid removal of the structure demanded by most construction schedules. It also allows most of the deconstruction to occur on the ground where is can be performed more safely and systematically. The structural engineer should suggest this approach on applicable projects (wood building will replace wood building or a project with an ambitious target for waste diversion).

The ends of salvaged dimensional lumber are often damaged and so must be cut off leaving the member slightly shorter than new material. New technologies and construction methods must be developed to effectively utilize this wood. Two technologies which could make use of these shorter members are metal-plate-connected wood trusses and finger-jointed lumber. These are excellent potential markets as grading rules for salvaged wood are established and promulgated. An increase in the price of virgin lumber would help this market grow.

Reuse of brick masonry

Brick is the most commonly salvaged structural material. When brick is salvaged, it is most often for aesthetic reasons. Brick is often left exposed in construction. Its appearance varies widely, depending on the color of its constituent ingredients, its size, how it was formed and fired, how it has weathered, and so on. Therefore, when repairs or patching of an existing brick wall requires the introduction of additional units, brick is often salvaged from the building under repair to achieve a close match. Salvaged brick may be used on a project even when brick matching is not an issue, for many people prefer the warmth and color of aged, molded bricks compared to the appearance of modern bricks (Fig. 2.5-2).

Engineering considerations — Our interest here is with bricks salvaged for structural use. Salvaged bricks are a popular choice for applications such as patio pavers. These bricks are not subject to the stress levels encountered in a wall and if they fail the consequences are not serious. For a multi-wythe bearing wall or a single-wythe veneer wall tied to a back-up, it is critical to understand the strength, durability, and leakage potential of salvaged brick.

Brick strength: Walls constructed of salvaged brick are generally weaker than walls constructed of new brick. The bricks themselves are weaker, the new mortar must be weaker, and the bond between the brick and mortar is weaker.

Bricks salvaged from buildings constructed before 1920 were not as consistently fired as modern bricks. Bricks were stacked and fired in wood- or coal-burning kilns, producing two categories and quality of brick: *hard-burned* bricks from the kiln's high-temperature zones and *salmons* — so called because of their color— from the low-temperature zones. The hard-burned bricks are stronger and more durable than the salmons, and were typically used in the outer wythes of multi-wythe exterior walls. When brick walls are demolished, the durable exterior bricks normally become mixed with the softer interior bricks. When they are salvaged, it is very difficult to distinguish between the salmons and the hard-burned bricks. A concerted effort during demolition could keep the salmons separated.

Bricks salvaged from post 1920s construction should be of a more consistent quality. This should be confirmed by complete testing on a representative sample, see below.

Mortar strength: The mortars used for salvaged brick walls should generally be weaker than mortars used for modern walls. Most authorities recommend using a "weak" mortar to prevent damage to the weaker bricks. A lime (instead of cement) and sand mortar offers three advantages: it imposes lower stresses on the brick due to shrinkage and temperature changes, it bonds well with porous bricks, and the potential for efflorescence is reduced because it is lower in salts (Ritchie 1971).

Mortar residue and dirt on salvaged brick clogs the brick's pores and reduces the strength of the bond between the bricks and new mortar, (BIA 1988). The bond strength for salvaged brick typically approaches 80 percent of the bond strength for new brick (Biggs 2001). See below for testing.

Durability — Achieving durability is a fundamental principle of sustainable design. This is especially important when using salvaged materials, engineers must ensure that these worn materials are used appropriately. With respect to salvaged brick there are serious concerns about using it in exterior walls, especially in climates subject to freeze- thaw conditions. Because all salvaged bricks from pre-1920s sources are very likely less durable than modern bricks, it is recommended to limit their use to interior walls (or inner wythes). An exception could be made for climates that are mild and dry, and where the materials perform well in freeze-thaw testing (as is required by common building codes). Poor bond between mortar and brick can increase the penetration of moisture into the wall and further reducing durability.

Code issues and testing — Section 2103.7 of the IBC (ICC 2006) permits reuse of salvaged units that conform to the requirements of new units. The units shall be of whole, sound materials and free from cracks and other defects that will interfere with proper laying or use. Old mortar shall be cleaned from the unit before reuse.

The relevant test standards are ASTM C216 (2007) for "facing brick" and ASTM C62 (2008) for "building brick." Both standards specify minimum requirements for compressive strength and durability, as measured by water absorption or freeze-thaw testing. ASTM C216 (2007) has tighter standards on size, distortion, and surface defects, as facing brick is visible in use. Keep in mind that the 50-cycle freeze-thaw test takes up to 10 weeks to complete.

The test methods, including sampling requirements and minimum number of specimens, are defined in ASTM C67 (2009). Salvaged brick is more variable than new brick, so it is advisable to increase the sample size beyond the minimum.

Strength testing: Standard tests may be used to better understand the strength properties of the materials and wall assembly including the following:

- compressive strength of brick units by ASTM C62 (2008) and ASTM C216 (2007);
- initial rate of absorption (IRA) testing, described in ASTM C67 (2009), use to evaluate the likely bond strength;

- bond-wrench tests (ASTM C1072 2006) measures the bond between brick and mortar; and
- tests prisms may be constructed and tested (ASTM C1314 2007).

Contamination — The primary contamination concerns are lead-painted bricks, and tarry or oily deposits on former chimney brick. In both cases, it is rarely practical to salvage the brick because removing the material is difficult and may damage the brick.

Reuse options — Salvaged bricks are commonly used in repair operations. In these projects, the bricks are often removed from a building, cleaned, and either replaced or used elsewhere in the same building. Thus the source of brick is known, allaying quality concerns, and the brick will blend in well with the brick left in place. As previously mentioned, durability is the main concern, thus interior applications and warm climate projects are ideal for salvaged brick. The C.K. Choi building at the University of British Columbia was constructed using salvaged paver bricks for the exterior veneer.

Figure 2.5-2. Salvaged brick chimney
(Photo copyright Edward Webster, used with permission)

Reuse of structural steel

While structural steel from buildings is nearly always recycled, it is very seldom salvaged in today's construction environment. The steel industry proudly touts its recycling rate, and rightly so; structural rolled shapes such as wide-flange members sold in the United States have nearly 100 percent recycled content.

However, producing steel, even from recycled material, is highly energy intensive and generates a considerable quantity of greenhouse gases. Why use this material when you can salvage? The environmental impact of salvaged steel is limited to its transportation and refabrication; making structural shapes from recycled steel requires the source steel be returned to a molten state, and this is energy intensive. Therefore the energy use and associated environmental impacts of using recycled steel are much higher than salvaged steel.

Engineering considerations — The engineering properties of salvaged steel are relatively easy to identify if the vintage is known, because the manufacture of steel has been standardized since about 1900, when ASTM A7 (1967) and ASTM A9 (1940) were introduced, resulting in a uniform product.

Identification: A number of iron-based materials have been used in buildings over the past two centuries. Knowing the age of the building from which the material was salvaged is therefore helpful in identification, according to Newman (2001). Appearance can also serve as a guide (Beckmann 1995). Metallurgical tests are the most certain way to identify the material, and they provide information on weldability, which may be useful, as is described below. Table 2.5-1 summarizes how age and appearance may be used to identify the material. Cast iron, malleable iron and wrought-iron were all gradually supplanted by steel, which arrived in about 1885.

Strength: If the age of the material is known, standards dating from the time of manufacture may be used to estimate the material strength. Testing small samples (also called coupons) cut from the member provides the most reliable measure of strength. The material can be used more efficiently if the strength can be determined, so testing may pay for itself in saved material.

Weldability: Many older iron-based materials, especially cast and wrought iron, are difficult or impossible to weld. Even some early steels had too much iron, phosphorous, and/or sulfur to weld. As a rule-of-thumb, all steel produced before 1923 should be checked for weldability (Newman 2001). Metallurgical tests may be used to determine weldability.

Ductility and toughness: Contemporary seismic design may require the engineer to know the ductility and toughness of steel. These properties were not controlled by early ASTM standards. The more stringent ASTM A992 (2006) standard was developed in response to high contents of recycled steel driving up the yield-to-ultimate ratio in ASTM A572 (2007) Grade 50 steel, thus making it less ductile. Material salvaged from very modern buildings may use high-strength (50 ksi) steel. If salvaged steel is to be used in a lateral system designed to meet current codes, ductility and toughness tests may be required. As a practical matter, most beams in a building's structure will not be part of a lateral system, so if testing will be a barrier to using salvaged steel, reuse of beams should be pursued for gravity framing only.

Table 2.5-1. Identifying steel and pre-steel members

Material	Years	Appearance clues	Notes on properties
Cast iron	1800 – 1910s	Pitted surface from sand mold casting; some have larger bottom flanges, some flanges wider at mid-span	Test for strength, not weldable, not ductile
Malleable iron	1840 – 1910s	Identify by shape, take precise dimensions and refer to AISC SDG 15 for historic shapes	Test for strength, not weldable
Wrought iron	1850 – 1910s		
Steel (early)	1885 – 1910s		Test for strength, toughness, ductility, and weldability as required
Steel (pre-modern)	1910s – 1930s		30 ksi min. per ASTM, may test higher; test for toughness, ductility, and weldability as required
Steel (modern)	1930s – 1960s	Common, includes "S" shapes	33 ksi min. per ASTM, may test higher; test for toughness, ductility, and weldability as required
Steel (current)	1960s - 2000s	Common, mostly "W" shapes	A36 first appears in 1962 AISC specification
Steel (high-strength)	1980s - present	Common, "W" shapes	A572 (50 ksi) test for ductility; A992 introduced about year 2000

Code issues — The IBC does not specifically address the use of salvaged steel. The IBC requires conformance with the American Institute of Steel Construction (AISC) steel specification. The AISC specification requires that structural steel meet certain ASTM material standards. For example, ASTM A36 (2008) places limits on the chemical composition of the steel, depending on the type of shape and the shape's thickness; and the tensile strength of the steel. If these properties, determined by laboratory testing, show that the salvaged material does not conform to modern material standards, it may still be possible to obtain approval from the local building official. This is particularly true if the structural engineer stands behind it.

Contamination — The most common contaminant is lead paint. Even if the steel member does not have a finish coat on it, it may have a lead-based shop coat. It is a good idea to remove lead paint even if local regulations do not require it. Sand-blasting or hand-stripping are two options. Both options require precautions to protect workers and contain any airborne lead.

Reuse options — With the limited supply of salvaged steel currently available in the used material markets, it's helpful to know where the steel is coming from when starting design of a new structure. For instance, if there is a building on the site or nearby with a supply of salvageable steel, it may be possible to survey the available material before laying out the new structure and to tailor the new building to match that material, say by establishing bay sizes and floor-to-floor heights that permit reuse with the minimum amount of refabrication. Creative engineering can make the most of existing material. For instance, cantilever beam construction could be considered where there is a mix of long heavy beams and short light beams.

Bridge girders are the most frequently salvaged structural steel members, driven by the high cost and long lead time of new girders. A recent project in the Boston area used salvaged steel bridge girders in the construction of a new house (Fig. 2.5-3).

Figure 2.5-3. House constructed with salvaged steel, designed by SsD (Photo copyright SsD, used with permission)

The reuse of open web steel joists is somewhat complicated by their relative frailty compared with heavy steel beams. It is easy to imagine they could become damaged if not carefully deconstructed and stored. For information analogous to reusing these components the engineer should stay current with the technical bulletins published by the Steel Joist Institute (SJI). SJI's Technical Digest No. 12 – Evaluation and Modification of Open Web Steel Joists and Joist Girders (2007) provides information for the application and usage of steel joists and joist girders. The document covers the evaluation of existing steel joists and joist girders to carry additional loads not accounted for in their original design; it also addresses making field modifications to the configuration and/or the original geometry of the steel joists or joist girders.

Ultimately, steel should be routinely salvaged from demolished buildings and stored for resale, perhaps near a steel fabricator. With a good supply of material, the fabricator could select the beams required for a given design, splice and refabricate it to meet the project requirements, and perhaps ship it out at a lower cost than if the steel were new.

Reuse of steel bolts

At this time, the reuse of high strength steel bolts is not recommended. Assessing these components for safe reuse is highly complicated (loading history, plastic deformations, loss of lubrication, etc must be considered). Both ASTM A325 (2009) and ASTM A490 (2008) bolts have performance issues when reused. It is not a practical application of sustainable practice at this time.

Reuse of precast and prestressed concrete

Precast and prestressed concrete elements could be widely salvaged, but currently this is very seldom done. Unlike cast-in-place concrete, it is not a huge leap in design to make precast concrete easy to deconstruct. In order to salvage precast components the connections must be detailed for reversibility. (See Section 2.4—Design For Deconstruction and Adaptability for more information on this topic.) One common use of precast concrete in the United States is tilt-up construction for big-box stores. The transient nature of these businesses and buildings make for an ideal application of wide-scale reuse. Responding to a new awareness of the carbon footprint associated with concrete, we will likely see an increase in the salvage and reuse of tilt-up panels in the future. Precast plank can be salvaged and reused if the connections are properly detailed. In many cases the plank has a topping slab, so the deconstruction requires saw-cutting and is less elegant; however, the plank may still be suitable for reuse with the topping attached. The engineer must examine the condition of the panels. If documentation of panel construction is not available, sacrificing a few panels for destructive testing will be necessary to determine yield strength and ultimate capacity. Even if project documents are not available, specifications may still be retrievable via the precast manufacturer.

Post-tensioned concrete sections, such as those that make up bridges, are in a special category when considering reuse. Usually unique to their application, it is unlikely that post-tensioned sections are practical to reuse even in a similar design. Further, the liability and technical challenges are significant. It is imaginable that post-tensioned sections might find creative reuse in lower capacity applications.

Reuse of foundations and retaining walls

Sustainability and waste minimization potential will encourage consideration of the reuse of all foundation types (Chapman et al. 2007). Foundation reuse is not a new concept, but it has been largely forgotten within the modern design framework. Existing foundations can be incorporated and/or reused in-situ for a second superstructure. However, under most circumstances, it does not appear that foundation reuse is driven by principles of sustainability, but rather by drivers such as site constraints (Butcher et al. 2006). Site constraints can include ground congestion, archaeological protection requirements, economic, and environmental factors.

Two of the best guides to consult on the reuse of foundation structures is the RuFUS Reuse of Foundations for Urban Sites – Best Practice Handbook (Butcher et al. 2006) and the CIRIA C653 Reuse of Foundations texts (Chapman et al. 2007). These handbooks were developed in Great Britain, but they provide a wealth of information that can be directly applied to design and construction practices in the United States. The books focus on the reuse of piles; however shallow foundation reuse is also covered.

The engineer must undertake a thorough evaluation of the foundation system before making a decision to reuse. The reuse of existing foundations adds some complexity to a project. Challenges associated with foundation reuse include following questions:

- Can the existing structural performance and reliability be verified, for example material, foundation location, size, and capacity?
- Can geotechnical performance and reliability be verified?
- Is the existing foundation capacity sufficient?
- Will the new loads applied by the superstructure align with the centroids of the existing foundation elements?
- Is it feasible to make connections between new and existing elements?
- Can all project team members accept the risks associated with foundation reuse? Legal, financial, and insurance implications need to be reviewed by developer.
- Will local building jurisdictions and authorities grant necessary approvals?
- Will the demolition of the original structure and subsequent unloading of the foundation cause uplift and differential settlement?

Such challenges, though, can be overcome with innovation and proper care. Close collaboration with the geotechnical engineer is essential. The main structural concerns associated with foundation reuse are differential settlement and load-deformation compatibility between foundation elements, whether new or existing. Differential settlement concerns can be approached by providing stiff vertical elements or mat foundations to aid load redistribution in the event of localized settlement.

In dense urban environments, the engineer should investigate providing additional capacity and depth to new deep foundations to facilitate future reuse. Although, the design cannot account for all future superstructure configurations, a small investment can provide great future returns.

Redeveloping on top of existing building foundations reduces a project's use of energy and new materials. There are economic and environmental costs associated with the demolition and disposal of existing foundations: transportation costs and landfill fees, air and noise pollution, and the possible disruption of adjacent properties by vibration beyond allowable limits.

The installation of new foundations is energy intensive, normally consuming large amounts of concrete and steel. "Reusing foundations should show a quantitative reduction in the use of these materials and reduce the 'embodied energy' in a new development thereby improving its 'carbon accountancy' balance" (Chapman et al. 2007).

The innovative reuse of existing structures for earth retention is a relatively novel but not exceptional practice. Prior to demolition of existing structures, the subgrade basement walls should be anchored with tiebacks or braced with rakers, before the building structure is demolished. Such reuse strategies minimizes the time and materials required to construct new earth retention structures, but may require new building offsets and/or incorporation into the final structure.

Reuse of non-building structures, components, and materials

This section has concentrated on the reuse of building-related structures, components, and materials; but engineers and architects should not (and need not) be limited to the building sector. Out-of-service structures and components from other industries can be creatively incorporated into building design. At this juncture, examples of such projects are few and they certainly represent the edge of the reuse envelope. In addition, reuse of non-building structures is probably never going to be a major sector of the construction market. Some of the non-building reuse ideas here are discussed briefly simply to illustrate the value of creative thinking and a flexible approach to design.

Temporary structures (shoring and formwork) — Non-building components and systems designed for multiple reuses are not usually sustainable choices for reuse as building components. While a product (such as formwork or shoring) is still in serviceable condition its best use is its original purpose, otherwise a new product will be manufactured to replace it. Once it is no longer serviceable it has likely lost its structurally integrity and should only be reused in a non-structural role, and thus beyond the scope of this guideline.

Temporary truss structures, such as cranes, have substantial strength and stiffness to meet various construction specifications and temporary loadings. These long span structures could potentially be used in structures requiring large clear-spans. As for all types of structural reuse, the engineer should conduct an evaluation of the structure for fatigue and corrosion damage and available material strength. Reuse and/or repair/modification of such structures could potentially be cost-effective in certain project settings. Consult Ratay (1996) and Shapiro et al. (1999) for additional design data and descriptions concerning these structures. The sustainability of using a temporary structure in permanent application depends on the alternative fate of the item. For example, if the reuse is diverting the item from the scrap yard or landfill it may be a great idea; on the other hand, if the item could be returned to active service, it probably is not the best approach.

Aerospace and aeronautics sector components — Elements from the aviation and aerospace industry can be used creatively, but require specialized understanding of material strengths, behavior, construction, hazards, and detailing of such structures. Bruhn (1973) and Flabel (1986) provide insightful information into the mechanics, materials, and structural behavior of flight vehicles.

Wings and fuselages have great structural capacity and stiffness to span large distances and provide unobstructed views. One innovative project is the “Wing

House" by architect David Hertz. Located in Malibu, Calif., this mansion incorporates the wings and fuselage of a Boeing 747-200. The wings serve as the main roof elements. The 747 nose was used as a meditation chamber with the cockpit serving as a skylight.

Shipping containers — The use of shipping containers, also known as Intermodal Steel Building Units (ISBU), as components of residential and commercial buildings has become a trendy expression of the reuse movement. Shipping containers have been transformed into mobile hospitals, condominiums, hotels, offices, shopping centers, and even hotels, such as the London Travelodge made from 86 containers (Guevarra 2008). See the Case Studies section of this guideline for a description of the Nomadic Museum, which was constructed in large part from shipping containers.

The sustainability of this trend is in question. The perceived availability of unused containers (Fig. 2.5-4) may actually be misguided. The idle shipping container is a symbol of globalization and a symptom of complicated trade deficits and shipping practices. While it is shocking that many containers are used for one-way conveyance (typically from China to the United States), it may be very shortsighted to remove ISBUs from potential service by converting them into permanent structures. A better use of the creative thinking that turns ISBUs into houses is to design a container that can be deconstructed, packed flat, and shipped back to the exporting country.

Figure 2.5-4. Shipping containers
(Photo copyright Grit Consultants, used with permission)

A project team can obtain shipping containers that no longer meet the quality control requirements of the shipping industry, mainly due to damages such as penetrations. It is not a sustainable practice to purchase brand new or slightly used containers with the potential for long service lives. The engineer must evaluate the structural integrity of the system. Freight containers may be damaged as they are exposed to numerous environmental conditions during conveyance by road, rail, and sea. As toxicity from lead-based paints and pesticides commonly used to fumigate the containers can pose serious health risk, testing must be performed to ensure the container meets aggressive indoor air-quality standards. Additionally fungus and bacterial residues should be evaluated and removed prior to construction. At the time of purchase, there will be a transfer of liability from the shipping container manufacturer to the engineer and architect of record.

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2.6

LIFE-CYCLE ASSESSMENT (LCA)

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Life-cycle assessment (LCA) is a method of measuring the total environmental impact of a manufactured product or manufacturing process, from acquisition of raw materials to end-of-life, reflecting the 'cradle-to-grave' concept. The Environmental Protection Agency (EPA 1993) defines LCA as the evaluation of "the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth." Some typical environmental effects (or impacts) are energy use, global warming potential, and natural resource depletion.

LCA was initially developed to measure the environmental impact of industrial processes and consumer products, but it has since been extended to encompass a wide range of other applications, such as buildings. Buildings require large amounts of raw materials and manufactured products from various sources, require a wide variety of on-site operations, and involve design and construction professionals from various disciplines. This wide scope of the building design and construction process makes LCA of whole buildings extremely complex and challenging. Using LCA to predict the total lifetime impact of a building as a single number in each impact category — such as gigajoules (GJ) of energy or tons of carbon dioxide (CO_2) — remains an advanced research-level undertaking. The LCA of a concrete framed office building in Finland by Junnila and Horvath (2003) provides a good example of the fine level of detail that can be used for a comprehensive, whole-building LCA. Although some of their specific numerical data may not be transferable to the United States, the methodology and overall conclusions remain valid.

It remains difficult to calculate a single, standardized numerical measure of building impact that is consistent across the building design and construction industry worldwide or even within the United States. The boundaries or scope of an LCA and its level of detail will affect the calculated impacts, in some cases significantly. Also certain input data may be difficult to collect or have significant uncertainty or inconsistency. One example of this is documented in a study by Guggemos and Horvath (2005) based on a 4,400 square meter (m^2) office building with either steel or concrete structural framing. Guggemos and Horvath (2005) found impact measures per square meter for energy and emissions to be significantly larger (between 4 and 17 times) than previous analyses of similar buildings. They were not able to identify specific sources for the differences, although noted several likely factors such as differences in the energy mixes, construction processes, building design as well as the level of detail of the LCA model.

Despite these complexities, the science of LCA is advancing rapidly and it is quickly becoming a fundamental part of sustainable building design. The International Standards Association has recently published or updated a series of standards on life cycle assessment and sustainability in building construction (ISO 14040 series), as well as a standard on environmental declarations of building products (ISO 21930). These ISO standards are discussed in more detail under the heading "Resources and tools: Standards" below and listed in the references. An LCA with a properly defined scope can provide meaningful results related to the environmental impacts of the structural system of a building. Existing studies from the literature and specialized building LCA software (see "Resources and tools" below) make it possible for the structural engineer to assess environmental impacts of his or her own designs without the need for a research-level LCA. Several of the LCA studies cited here and discussed in more detail in the section "Examples of LCA" below — in particular Environmental Building News (1999), Lippke et al. (2004), and Webster (2004) — have focused only on the structure of buildings, but at the same time have been thoroughly performed and produced meaningful results. These case studies demonstrate that basic LCA is well within the capabilities of the interested structural engineer and do not necessarily require highly-specialized knowledge of LCA methodology

Perhaps the most critical aspect of sustainable building design is an integrated or holistic design process, which involves interaction of all building design professionals throughout the entire process. Therefore, structural engineers need to understand the basic methodology of LCA so that they can participate more fully in the sustainable building design process and can use LCA to inform and improve their own design work. Using LCA to make structural design decisions in isolation from their related impacts on the building as a whole may not be an effective path to improving building sustainability. The objectives of this section are to introduce the terminology and concepts of LCA, and to provide a starting point with resources and references for structural engineers to pursue more in-depth technical details of LCA.

Why structural engineers need to know about LCA?

As discussed in the Introduction of this guide, building construction, use and demolition is widely recognized as one of the leading consumers of energy and natural resources. In the United States building construction and operation accounts for about 40 percent of energy use (DOE 2005). Building construction and demolition generates more than 123 million metric tons of waste per year, or about 1/2 ton per person per year (Webster 2004).

It is often assumed that life-cycle impact of a building is dominated by building operation, and that structural engineers have minimal influence on that phase of the building life cycle. In some cases the structure itself may directly and significantly impact operational energy use, but other aspects of the building life cycle are often more closely tied to the building structure. Webster (2004) examines the relative impacts of the various phases of a building life cycle across several building types and geographic locations. Energy use during building operation is the largest component of life cycle energy use (about 85 percent to 95 percent). However, as building energy use becomes more efficient, the contribution of the structural engineer related to initial construction and end-of-life demolition will become *increasingly* important. A focus solely on building energy use also neglects other environmental impacts that are more closely tied to structural engineering. For example, Webster (2004) shows that the structure of a building can be a significant part of life cycle impacts related to solid waste generation (up to 40 percent) and water pollution (up to 60 percent). LCA of a 15,600 m^2 office building studied by Junnila and Horvath (2003) found that the structural system contributed between 20 percent and 50 percent of the environmental impact in some categories.

There are many examples of the positive impact (both environmental and economic) of integrated building design. For example at the Pennsylvania Department of Environmental Protection's Cambria Office Building, selection of a paint color with a higher reflectance allowed downsizing of the lighting system due to more effective day-lighting, and downsizing of the HVAC system due to less heat being radiated. These changes reduced the constructed cost of the building, and the operating cost through decreased energy consumption. In the same building, early coordination of the mechanical systems with the architectural design allowed the mechanical room to be moved from a penthouse to a central location on the ground floor, resulting in a first-cost savings of $40,000 plus additional lifetime savings due to increased efficiency (PA DEP 2001). While these examples involve integration of mechanical, electrical, and architectural design, similar advantages may be achievable through more complete integration of structural engineering into the building design and construction process.

What structural engineers need to know about LCA?

Malin (2005) provides an accessible general overview of LCA. Kotaji et al. (2003) provides a detailed state-of-the-art review of LCA methodology of buildings with an extensive list of references.

Building life cycle stages — LCA divides the lifetime of a building into four primary stages: initial construction, building operation, recurring maintenance and renovation, and end-of-life (Fig. 2.6-1).

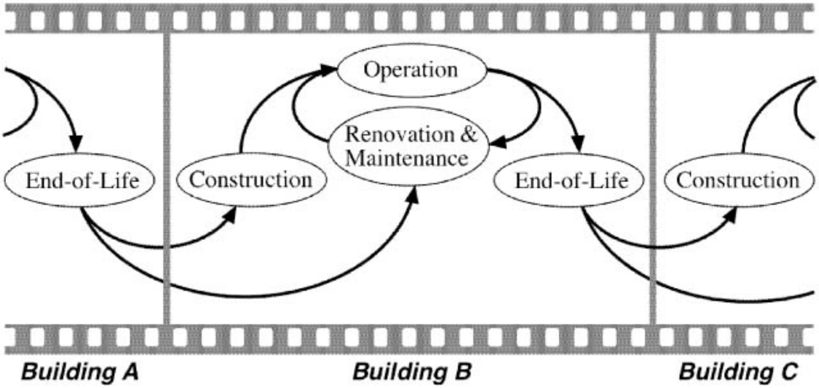

Figure 2.6-1. Building life cycle stages and their inter-relationships.
(Courtesy of S. Buonopane)

Initial construction accounts for environmental impacts required to complete the building; including extraction of raw resources, production of the building materials, transportation of materials to the site, and construction activities themselves. Initial construction contributes to a number of impact measures, such as energy use, solid waste generation, greenhouse gas emissions, and water pollution. One common impact measure for initial construction is embodied energy, which approximates fossil fuel consumption. Embodied energy is the total amount of energy required to extract the raw materials, manufacture the building product, install it in the building, and maintain it over the lifetime of the building. (Embodied energy may sometimes be subdivided into 'initial' and 'recurring,' in which 'recurring embodied energy' refers to the energy required to maintain building products and materials over the lifetime of the building. In such cases recurring embodied energy would be included in the recurring maintenance and renovation building phase.) Embodied energy takes into account all of the upstream energy use at every stage in the building's life-cycle, including all related transportation. Typically embodied energy for basic building materials is expressed in terms of an energy density per unit mass (GJ/kg) or unit volume (GJ/m^3). Tables of representative values are available in Kibert (2005), although project-specific values will depend on the sources of materials and the location of the building. Embodied energy of building products, assemblies or systems may be measured based on the functional unit. A functional unit is defined in ISO 14040 (2006) as "quantified performance of a product system for use as a reference unit." For example the embodied energy of a roof system might be based on the functional unit of a certain area of roof over a specified service life.

Embodied energy is only one of many possible environmental impacts associated with initial construction, and the use of embodied energy alone is not sufficient for a complete understanding of environmental impact. Additional information on impact categories is provided in the section "Components of an LCA" below.

Building operation accounts for impacts related to daily use of the building; including energy consumption (electrical and fossil fuel), water consumption, solid waste generation, and greenhouse gas emissions. Some of the major contributions to impacts in the building operation phase are due to HVAC, lighting, electrical plug loads, and water use.

Recurring maintenance and renovation accounts for the material and energy use required for regular maintenance (such as painting) or replacement of items with short lifetimes (such as lights, roofing, or floor finishes), and also for energy required for substantial renovations of the building to accommodate a change in building use or tenant. Many of the considerations for the renovation phase will be similar to those of the initial construction phase and will be characterized by the same impact measures. At the design stage of a building, predicting the number and scale of renovations that will occur over the lifetime of a building will be extremely difficult and subject to substantial uncertainty, thus emphasizing the importance of adaptability as an element of sustainable building design; see Section 2.4 for more information on design for adaptability.

End-of-life accounts for impacts related to deconstruction and demolition, such as solid waste generation. The end-of-life phase also presents an opportunity to reduce impacts through recycling and salvage of building materials. Design for deconstruction — a strategy for sustainable building design that directly involves structural engineers — employs design and construction methods that allow for future salvage and reuse of building components; see Section 2.4 for more information on design for deconstruction.

Components of an LCA — There are four components of an LCA of a building: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation.

Goal and Scope defines the goals and boundaries of the LCA by defining the question(s) to be answered, the alternatives to be compared, the use to which the results will be put (for example, comparative assertions versus internal improvement goals), the quality of data including requirements for peer review, and the acceptable level of uncertainty in both the input and the results. Due to the complexity of building design, construction and operation, proper definition of the scope and boundaries of the LCA is essential to achieve meaningful results. A practical application of LCA for buildings is to compare several design alternatives, thus limiting the required input data to only the design features that differ, but still providing a quantitative comparison. LCA data which is difficult to obtain or has large uncertainty may be excluded if it is common to all alternatives being considered.

Figures 2.6-2 and 2.6-3 demonstrate the wide range in scope that is possible for building-related LCA. One approach is to individually consider building products or assemblies, such as in the LCA of steel framing used by the BEES software and shown in the schematic diagram of Figure 2.6-2. Another approach to limiting the scope is to focus on a particular phase of the building life cycle. Figure 2.6-3 is a schematic diagram of the model used by Guggemos and Horvath (2005) for an LCA of the construction phase only of a reinforced concrete structure.

Example of the importance of scope: Paper vs. plastic — Perhaps the most familiar illustration of the importance of an LCA's scope and boundaries is the "paper or plastic bag" choice at the grocery store. A well-known LCA published in 1990 by Franklin and Associates Inc. (ILEA 2004) compared the environmental impacts of paper and plastic grocery bags using a state-of-the-art LCA. The study used both energy and pollutant production to measure environmental impacts and concluded that two plastic bags had less impact than a single paper bag.

However, the study limited its scope to the comparison of paper and plastic. If the scope of the study had been to answer the question *"What is the most sustainable type of grocery bag to use?"* then the answer may well have been neither paper nor plastic, but a reusable bag produced with a high-recycled content. In fact the ILEA web site discussing this issue now states "Or just avoid the question altogether by bringing a cloth bag."

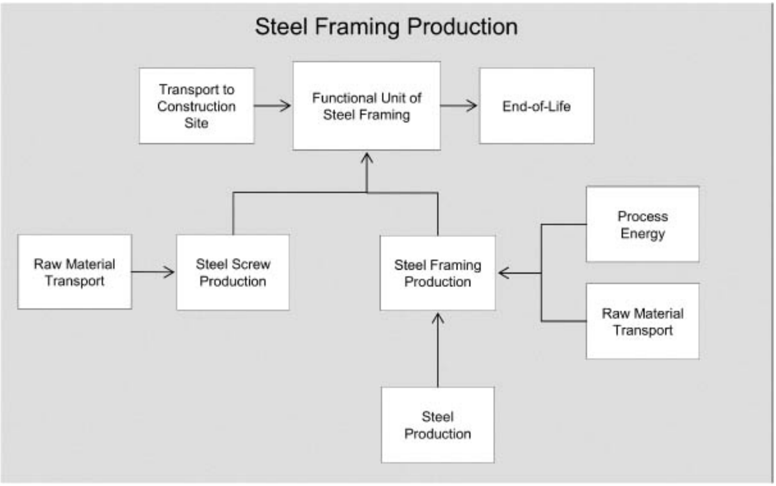

Figure 2.6-2. An example of schematic diagrams for a BEES LCA model of steel framing. (Lippiatt 2007)

We could widen the scope of our LCA even further and ask "What is the most sustainable way to transport your groceries home?" The answer probably has little to do with the type of bag and more with the mode of transportation. A recent article on local food in *The New York Times* (Martin 2007) ends with the admonition: "Don't drive your sport utility vehicle to the farmers' market, buy one food item and drive home again. Even if you are using reusable bags."

Inventory, or life-cycle inventory (LCI), is the primary data collection phase of LCA. The inventory lists all of the energy and material flows associated with a process or product throughout its life cycle. The inventory includes items 'from nature' that are required to produce a product (such as energy or raw materials) as well as items 'returned to nature' during production, use or end-of-life (such as pollutants or waste materials). For a single factory-manufactured product, much of the data required for the inventory may be under control of the manufacturer. However, for a complex system like a building, the inventory can represent a significant effort. The inventory for building LCA is often subdivided in terms of typical structural assemblies or building products. An example inventory flow diagram for roof trusses is shown in Figure 2.6-4.

The quality of the data assembled during the inventory phase will have a substantial effect on the value of the overall LCA. It is imperative that the LCI data conform to applicable standards. ISO 14044 (2006) provides guidance on performing LCI. In an effort to improve the quality of LCI data and provide wider access to standardized data, the National Renewable Energy Laboratory (NREL 2005) maintains the U.S. LCI Database; more information is provided in "Resources and tools" below.

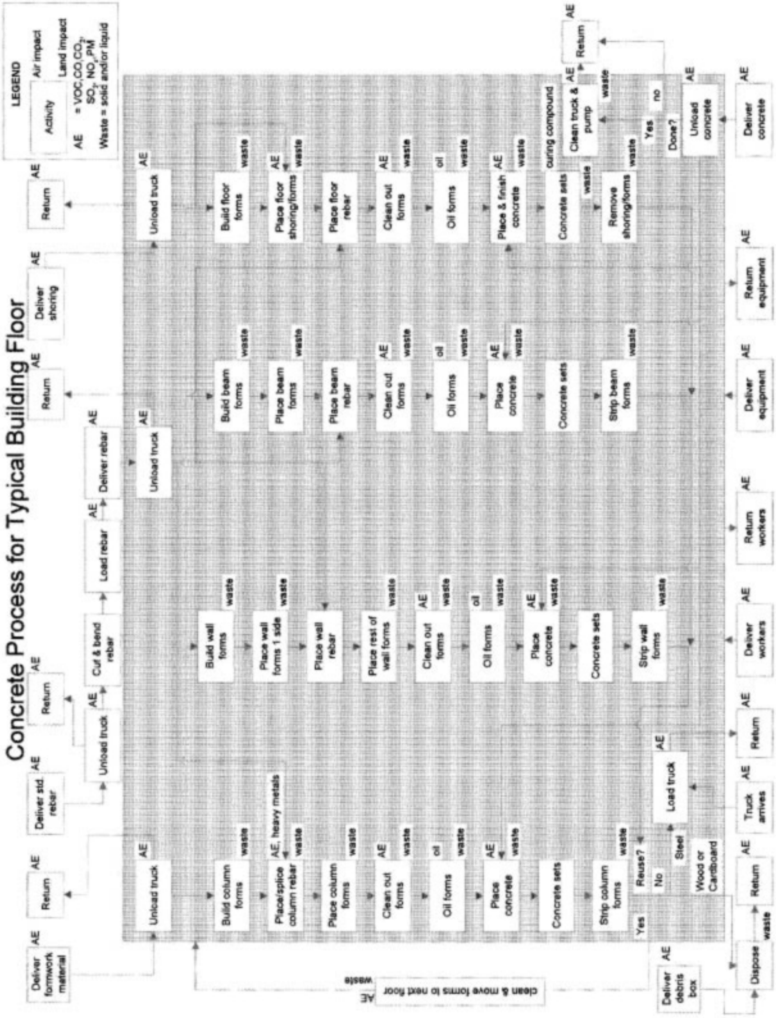

Figure 2.6-3. A process diagram for LCA of a reinforced concrete building floor. (Guggemos and Horvath 2005)

Impacts defines the environmental indicators that will be used to measure the environmental impact of the building.

Environmental impacts considered in ISO 21930 (2007) are as follows:

- climate change,
- depletion of stratospheric ozone,
- acidification of land and water sources,
- eutrophication,
- formation of tropospheric ozone,
- depletion of non-renewable energy and material resources,
- use of renewable energy and material resources,
- consumption of freshwater, and
- generation of hazardous and non-hazardous waste.

A given LCA may consider these or other relevant impacts. Typically each of the items in the inventory will influence multiple impact categories. Composite impacts, such as global warming potential or water pollution, combine the effects of individual pollutants. Recent LCA standards such as ISO 21930 provide guidance on appropriate impact measures for buildings and building materials.

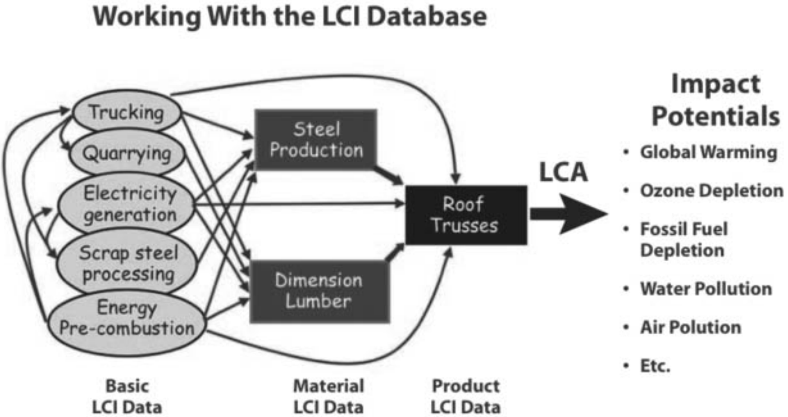

Figure 2.6-4. An example of an LCI flow diagram for roof trusses.(NREL 2005)

Interpretation analyzes the results of the LCA and translates the results into practical terms that can be used to improve the sustainability of the building. Ideally the LCA will provide a rational basis for selecting building products, systems or design options based on the criteria of sustainability. As with any complex engineering analysis, LCA is typically an iterative process — the initial results may raise additional questions or provide insights which suggest a more refined or different LCA that needs to be performed.

How can structural engineers can contribute to LCA

A whole-building LCA typically will be performed by a specialized consultant, but structural engineers can play an integral part in the process by providing input information and interpreting the results in structural engineering terms. For example, the structural engineer can provide information on the nature of specific structural materials to be used, the sources and transportation distances of structural materials, types of construction equipment to be used, and use of temporary construction materials. The structural engineer can also follow-through on the structural implications of design alternatives explored through the LCA to ensure that the alternatives are modeled in a realistic and thorough manner. Kotaji et al. (2003) discuss an example where an alternative wall-system appears to be more sustainable than the originally specified wall system. However if the alternative system is heavier, requires larger structural supports and a larger foundation, the sustainability benefit may be offset or eliminated. This example again highlights the importance using a whole-building approach in LCA.

Examples of LCA

Many examples of the practical application of LCA relevant to structural design are available in the literature. One common approach is to compare several different structural systems. Guggemos and Horvath (2005) use LCA to compare a steel- versus concrete-framed office building of 4,400 m^2 in the Midwestern United States over a 50 year life span. All other aspects of the building, except the structural system, were considered identical. The overall energy use and emissions were found to be comparable for both structural systems. Significant differences between the systems were only seen within particular phases of the buildings' life cycles. The study confirmed that the building use phase is the largest contributor to energy-use impacts (typically about 80 percent). Of particular interest to structural engineers was the finding that a large part of energy and emissions during the construction phase is associated with temporary materials and diesel-powered equipment. Junnila et al. (2006) compares the concrete-framed 4,400 m^2 U.S. office building to a similar building in Europe and provides a detailed breakdown of energy and emissions impacts associated with each building life-cycle stage. The conclusions of Junnila et al. (2006) emphasize the importance of embedded materials and maintenance in the overall impact of the buildings. Other studies such as Bensahel et al. (1998), Eaton and Amato (1998) and Jonsson et al. (1998) have also compared steel and concrete structural systems.

Lippke et al. (2004) compares residential construction of wood, steel, and concrete structural systems for a building in a cold climate (Minneapolis) and a warm climate (Atlanta). The LCA uses impact categories of overall embodied energy (including manufacturing, transportation, and lifetime energy use phases), greenhouse gas emissions, air and water quality indices, and solid waste generation for a typical residential building. The study concludes that typical building systems used in residential construction each have their own advantages and disadvantages when measured against these four attributes.

Environmental Building News (1999) compares LCA results for three different floor framing systems (steel, glulam, and laminated veneer lumber (LVL)) within the context of a typical 1,000 m^2 building space. This LCA, performed using the AthenaIE software, limits the scope to the structural system only and does not attempt to quantify impacts associated with other variables such as fireproofing, finishes, or thermal performance, which may or may not differ with the structural system.

Cole (1999) compares the energy use and greenhouse gas emissions for various structural systems of wood, steel and concrete due only to the on-site construction phase. This single-stage, partial LCA does not consider embodied energy of the building materials themselves or energy related to building use. This study concludes that transportation of labor is a major contributor to energy and greenhouse gas emissions during the construction phase and suggests that prefabrication may be one strategy to reduce the impacts during this phase.

Resources and tools

Many resources a re available to enable designers to evaluate LCA.

Standards — Standards for LCA have been developed during the past decade, but most provide only a general framework and not a detailed prescriptive method. Their application to building design and construction still requires significant interpretation. Fava (2005) provides the following summary of the development of the ISO 14040 series standards related to LCA. The ISO 14000 series addresses LCA as applied to all products, not just building-related.

- ISO 14040 (2006) provides general principles and framework for LCA, and it defines methodology and components of an LCA.
- ISO 14044 (2006) provides additional detail on the requirements for each of the LCA components and methods of reporting. ISO 14044 also provides informative examples of data collection sheets and interpretation of LCA. (ISO 14040 (2006) and 14044 (2006) replace prior versions of ISO 14040, 14041, 14042, 14043 and 14044.)
- ISO 14048 (2002) specifies documentation requirements for LCA.
- Two technical reports (ISO 14047 (2003) and ISO 14049 (2000) provide examples of impact assessment, goal and scope definition and inventory analysis.

More recently ISO has published a number of standards and specifications specifically addressing sustainability in building construction (ISO 15392, 21929-1, 21930, 21931-1), including the following:

- ISO 15392 (2008) discusses general principles of sustainability in the context of building construction, including the building life cycle. LCA is only one aspect of this broad-based document.
- ISO 21929-1 (2006) presents a framework for developing sustainability indicators (environmental, economic and social) related to buildings. Such indicators would be to define and calculate impacts in an LCA.

- ISO 21930 (2007) provides a uniform standard for declaration of environmental impacts of building products. Consistency of such input data is essential for LCA of buildings.
- ISO 21931-1 (2006) presents a framework for assessment of the environmental performance of buildings. ISO 21931-1 describes methods that are consistent with the overall aspects of LCA from the ISO 14040 series, but it provides additional guidance to constrain the assessment in cases where acquiring the data for a broader LCA is simply not practical.

ASTM Committee E06.71 on Sustainability has developed a number of standards related to buildings. ASTM E1991-05 presents standards for the LCA of building materials and products, and ASTM E2129-05 provides a standard for the collection of data to be used in environmental assessment of building products. Both of these standards are important to the development of consistent data to be used in the LCA of buildings. ASTM E2114-08 and E2432-05 provide general principles and terminology related to sustainability of buildings. These two standards do not discuss LCA directly, but provide important context.

Sources of data — Standardization and availability of basic LCA data remains an ongoing effort. The NREL Life Cycle Inventory (LCI) Database project (www.nrel.gov/lci/) is currently working to develop a standardized and publicly available database of life cycle information for common materials, products, and processes (Trusty and Deru 2005). The database includes a category for building and construction products and will grow as researchers, practitioners, and industry representatives submit LCA data for products. All of the data is reviewed by NREL before being incorporated into the database.

Software — Two specialized software tools have been developed which can access and customize previously collected LCA information on building systems and building products. These software packages are accessible to the interested SE but do not constitute a whole-building LCA.

ATHENA® Impact Estimator for Buildings (AthenaIE) is commercial software specifically designed for LCA of buildings by the Athena Sustainable Materials Institute of Canada (www.athenasmi.org/tools/impactEstimator/). AthenaIE can perform LCA of residential and commercial buildings, including most common structural and building envelope materials and systems. The current version of AthenaIE (4.0 released December 2008) uses both its own proprietary databases and the NREL LCI Database. AthenaIE accounts for all of the phases of the building life cycle from material extraction to end-of-life. It calculates all of the common impact indicators including energy, global warming potential, air and water pollution, and solid waste generation. When using AthenaIE for comparison of structural framing systems, output compares the impacts of the different buildings in six different categories including detailed breakdowns of emissions to air and water subdivided by building assembly group. Similar breakdowns are available for other impact categories as well. AthenaIE also outputs numerical data in tabular form.

Athena Sustainable Materials Institute has also recently released ATHENA® EcoCalculator for Assemblies, a freely accessible impact estimator for common structural and building envelope assemblies. The EcoCalculator has been developed for use with the Green Globes rating system.

Building for Environmental and Economic Sustainability (BEES) is public domain software developed by the National Institute of Standards and Technology (NIST) (www.bfrl.nist.gov/oae/software/bees/). BEES performs LCA for individual building products, not entire buildings, and it is based on applicable ISO and ASTM standards. It accounts for all stages of the product life cycle from extraction of raw materials to end-of-life. Since BEES is product-based, it can be particularly useful for specification and procurement of specific building products. BEES includes many environmental impact categories as well as an economic analysis. BEES models use both environmental and economic impacts for analysis and typical graphical output can compare the overall environmental and economic impacts for multiple design alternatives, including for global warming. The most recent version of BEES (4.0 released August 2007) incorporates the NREL LCI database.

Summary and conclusions

Life-cycle assessment (LCA) is an evolving method for measuring the total environmental impact of a building throughout its entire life, from extraction of materials to end-of-life. Sustainable building design requires a holistic and integrated design approach, and therefore structural engineers will be expected to be conversant in the fundamentals of LCA. Comprehensive LCA of buildings remains a significant challenge due to the complex nature of the building design and construction process. LCA is divided into four components: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. A well-defined scope is crucial to a meaningful LCA, in order to establish boundaries and control uncertainty and due to the difficulty in obtaining certain data.

LCA can be used by structural engineers to compare various design alternatives in order to make informed decisions to enhance the sustainability of their designs. Many published LCA studies comparing various structural systems or products are available. Current software tools make it possible for structural engineers to perform basic LCA calculations for many common structures and structural systems.

LCA will continue to evolve rapidly in the coming years. Building-specific guidelines, methods, and tools are now being developed to help standardize LCA of buildings. Basic data sources are also being standardized and made publicly available. Of the two primary green building rating systems in the U.S., GreenGlobes recently adopted LCA as a performance-based alternative in the materials section, and LEED is considering the adoption of a similar LCA-based option as a pilot credit. See Sections 1.3 and 1.4 of this guide for more information. Sustainability is becoming a recognized structural engineering design criterion, along with strength and serviceability, and LCA can be a valuable tool in measuring the sustainability of buildings.

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2.7

STRUCTURAL MATERIALS AND TOXICITY

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Nobody wants to build with toxic materials. But that's exactly what we do. In some cases, materials with toxic ingredients perform better than less toxic options, or are less expensive. In many cases, we may not even be aware that we are specifying toxic materials. As we strive for sustainability, we must educate ourselves about the toxicity of the materials we use. Even if toxic materials do not affect the users of a building, they will most likely affect the environment or workers upstream during extraction and manufacture or downstream during demolition and disposal.

Most chemicals used for commercial purposes have not been fully tested for human and environmental health effects. The U.S. Environmental Protection Agency (EPA) has identified nearly 3,000 chemicals used in the United States in quantities of 1,000,000 pounds or more. No basic toxicity information (neither human health nor environmental toxicity) is publicly available for 43 percent of these "high-volume" chemicals. Complete basic toxicity information is available for only 7 percent of these chemicals (EPA 1998). The United Nations Environment Program (UNEP 1998) estimates that 20,000 to 70,000 chemicals are marketed, with little known about the toxicity of 75 percent of them.

Some of these chemicals are finding their way into animals and into humans. People can ingest toxins that have accumulated in animal flesh, such as mercury in fish. Other sources of contamination are the water we drink and the air we breathe. Not much is known about the health effects of many of these chemicals, particularly in combination. Even very low doses can have consequences. According to the UNEP report, "It is the widespread presence of small amounts of many chemicals which is causing increasing concern, because alone, or in combination with other agents, they may contribute to cancer, allergies, impacts on reproduction and the immune response system, and neurotoxic effects."

Toxicity is receiving increased attention in green building circles. For example, a proposed pilot credit in the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) for Healthcare rating system awards the avoidance of materials containing persistent bioaccumulative toxins; for more on LEED, see Section 1.3. Life-cycle assessment, which generally measures toxic emissions to the environment during a product lifecycle (see Section 2.6), is becoming more sophisticated and better integrated into LEED and other green building rating systems. The move away from toxic materials towards less-toxic substitutes will likely grow stronger in coming years.

Significance to structural engineering

Many of the products we specify contain — or could release — toxic substances that can affect human and environmental health. Such substances can be released, knowingly or unintentionally, into the environment at any life-cycle stage (such as extraction, manufacturing, assembly, demolition, or disposal). Sometimes the most toxic life-cycle stages are extraction and manufacturing, with few, if any, known toxins in the final product. By reducing the use of materials containing such toxins (or which produce toxins in intermediate stages of manufacturing and production that may not occur in the finished product), we reduce the risk of exposure to both human beings and the environment. Structural engineers need to be informed about the toxic effects of the products they specify and be aware of less toxic options.

Environmental and human toxicity

Emissions to land, air, and water can harm ecosystems and human beings. The burning of coal, for example, to create the electricity required to power an electric arc furnace and produce steel, releases sulfur dioxide, nitrogen oxides, and mercury into the environment (steel is only one example of the many structural products that require electricity to manufacture). Sulfur dioxide is a primary contributor to acid rain, which harms aquatic species in lakes and trees (EPA 2007a). Nitrogen oxides also contribute to acid rain, as well as to the formation of smog, and can have human health consequences, such as respiratory distress, and has been shown to have toxic effects on fetuses in animal tests (the effect on human fetuses is not known) (ATDSR 2002). Mercury is an extremely toxic heavy metal that accumulates in body fat. Excessive exposure can permanently damage the brain, kidneys, and fetuses (EPA 2007b).

Persistent bioaccumulative toxic chemicals (PBTs) — Persistent bioaccumulative toxic chemicals resist natural breakdown and build up over time in the environment and in the bodies of organisms, including humans. Persistent organic pollutants (POPs) are a category of PBTs. According to the EPA, POPs are a set of chemicals that are toxic, persist in the environment for long periods of time, and biomagnify as they move up through the food chain. POPs have been linked to adverse effects on human health and animals, such as cancer, damage to the nervous system, reproductive disorders, and disruption of the immune system. Because they circulate globally via the atmosphere, oceans, and other pathways, POPs released in one part of the world can travel to regions far from their source of origin (EPA 2007c).

Some types of POPs — such as PCBs (polychlorinated biphenyls) and DDT — are no longer used in the United States, due to their persistence in the environment and toxicity. Others, such as dioxins and furans, are unwanted byproducts that continue to be produced.

Dioxins and furans — Dioxins are a class of chemicals that fall into three families: chlorinated dibenzo-*p*-dioxins (CDDs), chlorinated dibenzofurans (CDFs), and certain polychlorinated biphenyls (PCBs) (FDA 2006). Furans are similar to dioxins. Dioxins and furans are mostly produced unintentionally as a result of combustion. According to an EPA draft report on dioxin, the largest sources of dioxin emissions in the United States are backyard trash burning and medical incineration, neither of much relevance to our work as structural engineers (EPA 2003). However, several of the following top ten sources are relevant to our work:

- coal-fired-utility boilers, such as those generating electricity;
- cement kilns burning hazardous wastes (note that cement kilns that do not burn hazardous wastes also emit dioxins, though in lesser quantity);
- industrial wood combustion, which is used by the wood products industry (hog fuel); and
- secondary aluminum smelting (recycled-content aluminum).

Another source that did not make the top ten is ferrous metal smelting and refining.

Dioxins and furans are known to cause immune system damage and liver damage. The State of California lists dioxins as recognized carcinogens and developmental toxicants.

Heavy metals — Heavy metals such as mercury and lead are also PBTs. Most structural materials do not contain heavy metals. However, as noted above, heavy metals can be released during the production of structural materials — particularly those produced using coal-generated energy sources. Excessive exposure to heavy metals such as mercury can cause permanent damage to the brain, kidney, and fetuses.

Types of toxicity

Toxins can affect human health in a number of ways. *Carcinogens* are agents that cause cancer. We are all familiar with the carcinogens asbestos and cigarette smoke. An example of a carcinogen that certain structural materials contain is formaldehyde. Structural products that may contain formaldehyde include chemical admixtures and structural adhesives such as those used for engineered wood products. *Mutagens* can alter the structure or sequence of DNA, potentially affecting fertility and causing birth defects. Benzene is an example of a substance that is known to cause chromosome damage. Benzene can occur in structural materials such as adhesives, form release agents, and concrete admixtures. *Endocrine disruptors* mimic or inhibit hormones, producing infertility and gender changes in some species. Phthalates, used in PVC, are known endocrine disruptors that may be found in PVC structural accessories such as waterstops. Carcinogens, mutagens, and endocrine disruptors are particularly troublesome because the health effects are not immediately seen. Exposure can result in illness months or years later.

Volatile Organic Compounds (VOCs) are released by many building products, including some specified by structural engineers, such as concrete curing agents and paints. VOCs contribute to ground-level ozone (smog) and can cause a host of health problems. According the EPA, VOCs can cause eye, nose, and throat irritation; headaches, loss of coordination, nausea; and damage to the liver, kidney, and central nervous system. Additionally, some organics can cause cancer in animals; some are suspected or known to cause cancer in humans. The ability of organic chemicals to cause health effects varies greatly from those that are highly toxic, to those with no known health effect (EPA 2007d).

Managing toxicity

Green chemistry — A new field of chemistry called "green chemistry" investigates and develops alternatives to chemicals that are known or likely toxins. Structural engineers should seek out and use products that have been developed using the principles of green chemistry (Table 2.7-1). As the building industry moves towards greener products, manufacturers likely will develop and market green chemistry products for use in structural systems. One such product is Hycrete, a non-toxic concrete waterproofing admixture that is Cradle-to-Cradle certified by MBDC. Cradle-to-Cradle is a rating system that screens products using human and environmental health criteria. Hycrete can reduce the need for more toxic waterproofing options.

Precautionary principle — The precautionary principle may be used to guide the selection of building materials and systems with unknown risks. If the results of an action are not entirely certain (or not scientifically proven), yet pose a risk of major or irreversible damage, the precautionary principle asserts that it is better to avoid that action when other options are available. For example, human-caused global warming has not been scientifically "proven" (although most climate scientists believe human actions are a factor). Nevertheless, the possible consequences of global warming are dire, including mass species extinctions and greater incidence of disease. The precautionary principle may be invoked to select available options that are less likely to contribute to global warming. Another application of the precautionary principle is the selection of materials that do not contain PBTs, even where PBTs are only listed as "possible" or "probable" human health dangers. If alternate materials are available that have good track records or have been studied for health impacts and found to be safe, these should be used in place of the substances that have not been well studied.

The USGBC, developers of the LEED rating system, cites the precautionary principle in its guiding principles: "USGBC will be guided by the precautionary principle in utilizing technical and scientific data to protect, preserve, and restore the health of the global environment, ecosystems, and species."

Sources of information on chemicals

Indices — Several useful on-line sources of toxicity information are available. These resources may be used to learn about chemicals that are in building products we specify, or that may be emitted to the environment during the production of building products and materials. Chemical lists typically include the "CAS Number," a unique numerical identifier assigned by the CAS Registry, a division of the American Chemical Society. These numbers are generally the best way to identify chemicals, because the common names may vary or may be too long for easy use.

Table 2.7-1. The Twelve Principles of Green Chemistry
(Developed by John Warner and Paul Anastas in 1998, used with permission.)

1. Prevention — It is better to prevent waste than to treat or clean up waste after it has been created.
2. Atom economy — Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Less hazardous chemical syntheses — Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Designing safer chemicals — Chemical products should be designed to affect their desired function while minimizing their toxicity.
5. Safer solvents and auxiliaries — The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. Design for energy efficiency — Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. Use of renewable feedstock — A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. Reduce derivatives — Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. Catalysis — Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Design for degradation — Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. Real-time analysis for pollution prevention — Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. Inherently safer chemistry for accident prevention — Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

U.S. Environmental Protection Agency (EPA) — After the disastrous release of methyl isocyanate in Bhopal, India that killed thousands of people living near a pesticide manufacturing plant in 1984, the U.S. Federal government passed the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA). As a result of this legislation, the EPA prepared a list of harmful chemicals that users must track. This list is referred to as the EPCRA Section 313 List or the Toxics Release Inventory (TRI) List. The original list included more than 300 chemicals and 20 chemical categories. In 1994, the EPA added 286 new chemicals and chemical categories to the list. The listing criteria include acute human health risks, cancer or chronic (non-cancer) human health effects, and/or environmental effects. Facilities using chemicals on the list are required to report releases, transfers off-site, and other waste management activities of quantities of the listed chemicals exceeding specified thresholds. The list of chemicals and toxicity information may be found at www.epa.gov/tri/chemical/index.htm#chemlist.

The listing includes the chemical name, CAS Number, and *de minimis* limit. If the chemical makes up less than the *de minimis* percentage of a material, it does not have to be reported. There are no *de minimis* limits for PBTs except for supplier notification purposes.

State of California Proposition 65 — In 1986, the voters of California passed a ballot measure known as Proposition 65, or the Safe Drinking Water and Toxic Enforcement Act of 1986. Proposition 65 is "intended by its authors to protect California citizens and the State's drinking water sources from chemicals known to cause cancer, birth defects, or other reproductive harm, and to inform citizens about exposures to such chemicals" (OEHHA 2007a). Under the act, the state has compiled a list of about 800 chemicals, available at www.oehha.ca.gov/prop65/prop65_list/files/P65single092807.pdf

The list includes the chemical name, the type of toxicity, the CAS number, and the date the chemical was added to the list.

Proposition 65 includes no specific threshold requirements specifying how much of the toxic substance must be in the product for the manufacturer to list it. Under Proposition 65, there are no acceptable concentrations established for any listed chemical in any given product. An exposure that causes a significant risk of harm from a listed chemical through the use of a product would trigger the warning requirement, not merely the fact that a listed chemical is present in a product. The concentration of a listed chemical would certainly factor into the level of exposure that would result from an individual using a given product. But concentration alone is not sufficient to determine if warnings are required (OEHHA 2007b).

It is the product manufacturer's responsibility to determine whether the product needs to be labeled as containing the listed toxin. The state has established "safe harbor levels" of exposure for many of the listed chemicals. If the manufacturer determines that its product will not expose people to toxin concentrations greater than the safe harbor levels, it need not list the toxin.

European REACH Legislation — The European Community enacted Registration, Evaluation and Authorization of Chemicals (REACH) in June 2007. According to the REACH website (EC 2008), "[t]he aim of REACH is to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances." The legislation will set up a chemical database administered by European Chemicals Agency (ECHA) in Helsinki. The use of the most dangerous chemicals will be phased out as suitable alternatives are found. As REACH is implemented, chemicals will be evaluated and listed. We expect these will be a good source of information as they become available.

Chemical Scorecard (www.scorecard.org) — The Chemical Scorecard provides toxicity information on more than 11,200 chemicals, including the most commonly used chemicals in the United States and all chemicals regulated under major environmental laws. Users may search the Scorecard database by chemical name or CAS Number. The database contains detailed information about each chemical including the following:

- human health hazards;
- hazard rankings; and
- chemical use profile.

For example, the MSDS sheet (see below for more on MSDS sheets) for a popular high-range water-reducing concrete admixture shows that it contains 45 to 60 percent naphthalenesulfonic acid (CAS# 037293-74-6) and 0.09 percent formaldehyde (CAS# 50-00-0). The Chemical Scorecard has no data on the naphthanlenesulfonic acid, but provides the following information on formaldehyde:

- recognized carcinogen in California Proposition 65 list;
- suspected gastrointestinal or liver toxicant based on several references;
- suspected immunotoxicant based on several references;
- suspected neurotoxicant in National Institute for Occupational Safety and Health's Registry of Toxic Effects of Chemical Substances;
- suspected reproductive toxicant based on several references;
- suspected respiratory toxicant based on several references;
- suspected skin or sense organ toxicant based on several references;
- more hazardous than most chemicals in 7 out of 12 ranking systems; and
- ranked as one of the most hazardous compounds (worst 10 percent) to ecosystems and human health.

Product information

Toxicity information relating to specific products is available through a few different sources.

Material safety data sheets (MSDS) — MSDS sheets are the most readily available source of information on the toxicity of building products. Many manufacturers post them on their web sites. Others will fax or mail them to you upon request.

The U.S. Occupational Safety and Health Administration (OSHA) specifies the requirements for MSDS sheets in section 1910.1200(g) of its regulations. OSHA requires the following information in sections 1910.1200(g)(2)(i)(C)(1) to 1910.1200(g)(2)(i)(C)(3):

- "The chemical and common name(s) of all ingredients which have been determined to be health hazards, and which comprise 1 percent or greater of the composition, except that chemicals identified as carcinogens under paragraph (d) of this section shall be listed if the concentrations are 0.1 percent or greater; and,
- "The chemical and common name(s) of all ingredients which have been determined to be health hazards, and which comprise less than 1 percent (0.1

percent for carcinogens) of the mixture, if there is evidence that the ingredient(s) could be released from the mixture in concentrations which would exceed an established OSHA permissible exposure limit or ACGIH Threshold Limit Value, or could present a health risk to employees; and,

- "The chemical and common name(s) of all ingredients which have been determined to present a physical hazard when present in the mixture."

The OSHA regulations refer to various government standards for the determination of a hazardous material. OSHA defines a "hazardous chemical" as "any chemical which is a physical hazard or a health hazard," where the following are defined:

- A health hazard "means a chemical for which there is statistically significant evidence based on at least one study conducted in accordance with established scientific principles that acute or chronic health effects may occur in exposed employees. The term 'health hazard' includes chemicals which are carcinogens, toxic or highly toxic agents, reproductive toxins, irritants, corrosives, sensitizers, hepatotoxins, nephrotoxins, neurotoxins, agents which act on the hematopoietic system, and agents which damage the lungs, skin, eyes, or mucous membranes."
- A physical hazard "means a chemical for which there is scientifically valid evidence that it is a combustible liquid, a compressed gas, explosive, flammable, an organic peroxide, an oxidizer, pyrophoric, unstable (reactive), or water-reactive."

Many manufacturers are following an American National Standards Institute (ANSI) standard for their MSDS sheets (Z400.1), even though this format is not required by OSHA. The ANSI standard includes a section on regulatory information that can be helpful in identifying toxic ingredients that are not listed in the "hazards" section described above. Here the manufacturer may include ingredients listed by the EPA under the EPCRA regulations, or that must be disclosed according to state regulations, such as California Proposition 65. These regulations may be more stringent than the OSHA regulations, and therefore ingredients may be listed in this section that are not listed in the hazards section.

The information that manufacturers provide in MSDS sheets varies widely. Some are extremely detailed and useful and others are not. The information is self-reported by the manufacturers, so the reader must rely on the truthfulness and integrity of the manufacturer that prepared the information. It is sometimes difficult to compare products from different manufacturers because the MSDS sheets may not include the same information. For example, some may include Proposition 65 chemicals while others do not.

Manufacturers — If information sought is not included in MSDS sheets, the manufacturer may be willing to provide it if contacted directly, especially if divulgence of such "right-to-know" information is required by law (such as Proposition 65 or EPA). Some manufacturers, however, particularly smaller ones, do not appear to have such regulatory information available. It can be difficult to track down a knowledgeable individual to speak with, particularly at a large or foreign company.

Manufacturing references — In certain industries, manufacturing reference books are available that detail the ingredients and processes used to manufacture a product. Such references may be used to determine the toxicity of an entire class of products, assuming they are all manufactured using a similar process. One difficulty in this approach is determining whether a particular manufacturer uses the process described in the book. Due to trade secrets, manufacturers may be unwilling to declare how their products are made, or may disguise the process using alternate terminology.

Life-Cycle Assessment (LCA) — As discussed in Section 2.6 — Life Cycle Assessment, LCA may be helpful in determining a product's toxicity. Popular LCA programs such as the Athena Impact Estimator for Buildings and BEES do not provide data on the toxic ingredients in products, but do provide information on toxic emissions to the environment. For instance, Athena provides water and air pollution indices for many building assemblies and products. The products in the Athena database are generic, though, based on industry averages, so Athena is not helpful when comparing similar products in the same product category. A few manufacturers are providing life-cycle data to the National Institute of Standards and Technology to be included in the BEES LCA software, so this resource may prove useful. LCA needs to be developed further before it can be a definitive source of toxicity information, but holds great promise, since LCA can comprehensively evaluate product toxicity. LCA does more than merely look at the toxicity of a product's ingredients; it also looks at the toxic emissions to the environment during the entire product lifecycle, for example capturing the impact of toxic ingredients that may be used and released during manufacturing that may not be present in the final product.

Obstacles and difficulties

Evaluating product toxicity and making product choices based on available information is difficult at this time. There are few standards to help with product selection and few regulations requiring manufacturers to divulge the content of their products or the toxic emissions associated with their manufacture.

Manufacturers are often not willing to divulge more than the minimum information required by law. They may be concerned about trade secrets, or that consumers may not want to buy their products if toxicity information were available to them. Since some manufacturers are more willing to share information about their products than others, one way to encourage the more secretive manufacturers to be more forthcoming may be to avoid specifying their products until they provide toxicity data. For example, some manufacturers list in their MSDS sheets detailed information on Proposition 65 chemicals in their products, including chemical names and quantities. Others may only state that the product contains listed chemicals, without providing the specific substances, or may not provide any Proposition 65 information at all. By specifying products from manufacturers that provide detailed information, you know what you are getting.

A serious difficulty is how to quantify and compare the toxic risks of alternate product choices. Which is more hazardous, for instance, a small quantity of a highly toxic substance or a large quantity of less toxic material? Certainly PBTs represent a particularly potent risk; should we avoid specifying products that contain even minute quantities?

Another question to consider is the type of hazard presented. Is the goal to minimize human health risk or environmental risk, or some combination of the two? Within the human health category, who is likely to be exposed: adults, children, or hospital patients? Certainly toxicity must be more seriously considered in hospital and school settings.

Another question to consider is the toxic risk at different life-cycle stages of the product. All of the following communities could be at risk at various stages of the product life-cycle:

- workers in the manufacturing facility;
- communities around the manufacturing facility that are exposed to plant emissions;
- users of the building;
- firefighters in the event of a building fire;
- people who construct and demolish (or deconstruct) the building;
- people down-wind of an incineration facility;
- people who scavenge in dumps, a particular problem in developing countries; and
- wildlife exposure to waste-streams and habitat damage.

As a society we are only beginning to come to grips with the health hazards presented by the thousands of chemicals to which we are exposed, much less to develop standards and regulations to address the risks. At these early stages of understanding, often the best we can do is to apply the precautionary principle to avoid those substances that are likely hazards where suitable less hazardous substitutes are available.

Structural engineering materials and toxicity

Examples of structural materials with potential toxicity impacts are listed below. Refer to specific materials in Section 3 for additional information.

- *Concrete and masonry*: admixtures, curing compounds, form-release agents, sealants, joint materials, waterstops, and emissions during manufacturing and transport (such as cement kilns);
- *Steel*: paint, galvanizing, and emissions during manufacturing and transport; and
- *Wood*: paint, preservatives, fire-treatment, adhesives, and emissions during manufacturing (especially engineered wood products) and transport.

Summary of recommendations

Structural engineers can contribute in may ways to efforts to mitigate the adverse affects of toxic chemicals including the following:

- Investigate structural materials for toxicity impacts during manufacturing, use, and disposal.
- Avoid the use of materials from manufacturers that do not divulge toxicity information on their products.
- Avoid the use of materials that contain or release substances known to be highly toxic to human health or the environment.
- Where materials contain substances that are suspected to be hazardous, but have not been fully evaluated, apply the precautionary principle and select options with less toxic potential when available at reasonable cost.

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3.0

BUILDING MATERIALS

Structural engineers can have significant impact on the sustainability of a project through thoughtful use of building materials. This section will discuss the following materials in more detail:

Section 3.1 — Materials Introduction

Section 3.2 — Concrete

Section 3.3 — Masonry

Section 3.4 — Steel

Section 3.5 — Wood

Section 3.6 — Natural Building Materials

3.1

MATERIALS INTRODUCTION

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Which building material is the most sustainable: concrete, steel, or wood? This is a common question that many structural engineers have either asked themselves or have been asked by others. The fact is that sustainability is not an inherent property of a material. One cannot attribute a numerical value to sustainability as it relates to materials for the purposes of direct comparison; there is no modulus of elasticity to measure and no strength-to-weight ratio to compare. Even if it were possible to make a fair comparison between materials — for example, somehow comparing the recycled content of steel with the renewable aspect of wood — the process would not give a meaningful answer with respect to which material is best for a particular application or building. Like designing structural systems for economy and efficiency, designing for sustainability requires structural engineering judgment and skill.

Identifying the challenges

There are two primary challenges structural engineers have to consider in assessing the sustainability of a building material: comparing the material to others, and identifying the right context for the material.

Comparing — How does one quantify the myriad impacts a material can have, in a manner that allows it to be compared with other materials? Structural options include wood, a renewable resource, steel, in these days highly recycled, and concrete, often with gravel and sand from local sources, and potentially using waste products as supplementary cementitious material. Some environmental impacts are quantifiable, albeit with some effort, such as carbon emissions, energy expended, land use lost, and so on. Quantifying impacts must be done throughout the entire life of the material, using a methodology known as life-cycle assessment (LCA) addressed in Section 2.6.

Context — Identifying the properties that make a particular material sustainable is only part of the solution. A material has related components, finishes, and connections that make it a part of a building system. When a material is successfully used in a building, it plays the desired part in the building system, has the desired lifespan, interaction with the environment around it, etc. Choosing the right material for the correct role is really at the heart of implementing sustainability. Ultimately, the choice of the right material cannot be done in isolation.

Lastly, understanding the sustainability strategy is critical to the right material choice. Therefore, realize that the following sections discuss materials somewhat in isolation, which is necessary, but only part of the picture.

The following materials specific sections should be read in combination with the preceding strategies sections.

- Section 3.2 — Concrete
- Section 3.3 — Masonry
- Section 3.4 — Steel
- Section 3.5 — Wood
- Section 3.6 — Natural Building Materials and Systems

In these sections, each material is discussed as it pertains to environmental impacts, engineering solutions, and material-specific implementation techniques that can be employed for sustainability.

A reasoned approach

Rather than try to undertake a full LCA of every material or system, what follows is a more abbreviated view that structural engineers can use to better understand a material's impact. In a formal LCA, it is easy to get lost and lose focus in the accounting process of quantifying impacts. Formal LCA can be a controversial process, because of the many uncertainties and the assumptions included, but using the theory as a framework can help structural engineers become better educated consumers of structural materials. Also, LCA is in its infancy and can not yet address the full complement of environmental impacts.

The following list describes sustainability considerations that can provide a baseline for understanding a material's impacts; many of these are addressed in the individual materials sections:

- Extraction: ecosystem impacts, methods, toxicity;
- Refining / Manufacturing: toxicity, waste production, recycled content, energy demand, emissions;
- Transportation: distance, mode;
- Construction: waste reduction from pre-assembly (such as prefabricated trusses or precast concrete components), associated material impacts (such as concrete formwork or epoxy anchors), material-handling equipment requirements and impacts (such as steel erection);
- In use: durability and maintenance requirements, impacts on external and internal (occupant) environment; and
- Demolition / Deconstruction: longevity of material, design for deconstruction, options for reuse or recycling, disposal as waste.

Conclusion

Full understanding of the impacts of the construction materials we specify is part of a structural engineer's job. Knowing the benefits and detriments of all materials enables structural engineers to be better informed. This information adds to the engineer's toolkit to make a more informed recommendation to the design team and ultimately the client. And just as the client's program desires impact the structural engineer, their specific sustainability goals may have impact on the structural material and system decisions that are made.

3.2

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Concrete has been used as a building material for millennia and is used today in almost every country of the world as a basic building material. Building properties it offers include high compressive strength; durability and resistant to deterioration; ability to form various shapes and sizes; workability; and global availability.

According to the World Business Council for Sustainable Development (WBCSD, www.WBCSD.org), "Concrete is the most widely used material on earth apart from water, with nearly three tons used annually for each man, woman, and child." Concrete in buildings is often utilized for many functions — from structural framing and foundation systems, to architectural elements including sound barriers and fire protection — its widespread use makes its impact on the environment an important consideration in sustainable design. While the primary focus within this material section is to guide practicing structural engineers in improving the environmental impact of their concrete use, the considerations listed here also apply to non-structural use of concrete.

Primary considerations to improve sustainability

Concrete applications can incorporate many sustainable attributes and opportunities, and contribute to environmental benefits. Because concrete usage inherently implies the use of cementitious materials, aggregates, water, reinforcing bars, and admixtures, there are many avenues available for sustainable consideration. The use of concrete provides structural engineers with two types of opportunities to make buildings more sustainable: leveraging concrete's advantages and mitigating the material's environmental impacts.

The engineer can utilize concrete's inherently sustainable attributes, such as using exposed concrete surfaces with an aesthetic finish that preclude the use of additional finishing materials. The designer may also take advantage of the concrete structure's thermal mass for certain energy conserving and passive solar applications. Additionally, the engineer has many strategies available to mitigate the problems of waste and pollution commonly associated with concrete production and usage. Using complementary cementing materials will reduce carbon dioxide (CO_2) emissions attributable to portland cement production; using recycled water for mixing, curing and washout and recycled aggregates for fill and structural concrete saves both resources and energy. Each of these methods, as well as all of the ingredients used in concrete, is discussed separately in detail in this section.

Concrete appearance — Concrete products can provide both the building structure and the interior and exterior finishes. Structural columns, beams, and slabs can be left exposed with natural finishes. Concrete does not need to be gray and dull. Interior and exterior concrete walls are available in a wide range of profile, texture, and color options that require little or no additional treatment to achieve aesthetically pleasing results. Exposed ceiling slabs and architectural precast panels are some examples of this environmentally efficient approach. This structure/finish combination reduces the need for the production, installation, maintenance, repair, and replacement of finish materials that in some cases degrade indoor air quality.

Energy performance and thermal mass — Field tests and analytical studies demonstrate that for most climates, buildings constructed with concrete use less energy for heating and cooling compared to buildings constructed with lighter weight materials (Gajda 2001). Thermal mass is a property that enables building materials to absorb, store, and later release significant amounts of heat. The use of concrete building materials can increase the thermal mass of a building, giving increased comfort in the heat of summer and the cold of winter. Concrete is ideal for passive solar applications that use night time heat purge to cool a building; it acts as a heat "sponge," absorbing daytime heat energy and thus moderating indoor temperatures and peak heating and cooling loads. As a result, the peak heating and cooling demand and energy consumption of high mass buildings can be reduced. The HVAC system capacity of an efficient, high mass building may be less than a lighter building of the same size.

Concrete's thermal mass, combined with the optimal amount of insulation and proper orientation, can save energy over the life of a building and reduce environmental impacts due to heating and cooling needs. Thermal mass in concrete construction has the following benefits and characteristics:

- delays and reduces peak thermal loads;
- reduces total loads in many climates and locations;
- requires that mass is exposed on the inside surface; and
- works well regardless of the placement of mass.

Additionally, in order to leverage thermal mass in combination with night time heat purge, night time temperatures must be 14 to 17°C lower than daytime temperatures. For this reason, concrete as thermal mass to cool a building works well on the Pacific Coast and in desert regions.

Light-colored concrete and other surfaces can reduce energy costs associated with indoor and outdoor lighting. Utilized correctly, the more reflective surfaces can reduce the amount of fixtures and lighting required.

Precast and cast-in-place concrete panels have negligible air infiltration properties (New Building Institute 2005). Some building codes now limit air leakage of building materials and concrete can meet these limits. Minimizing air infiltration between panels and at floors and ceilings can provide a building with low-air infiltration rates.

Concrete production and ingredients — These topics are discussed in detail later in this section.

Cross-reference

The following sections include related content and should be reviewed for a complete understanding of concrete:

- Section 1.1 — Design Integration and Synergies
- Section 2.4 — Design for Deconstruction and Adaptability
- Section 2.6 — Life Cycle Assessment
- Section 3.4 — Steel (for reinforcement)

Environmental impacts

The impact that concrete has on the environment will be discusses as it relates to extraction of the new materials and the effects of these as defined by CO_2 emissions.

Extraction and ecosystem impacts

As with all building materials, the extraction of the raw materials from the earth has an impact on our environment.

Portland cement — As discussed below, portland cement is defined as "hydraulic cement manufactured from clinker," which itself is primarily made from burning a mixture of limestone and clay. Portland cement manufacturing is a four-step process, as follows:

Step 1: Virgin raw materials, including limestone and small amounts of sand and clay, are transported from a quarry usually located near the cement manufacturing plant.

Step 2: The materials are crushed, ground, and blended for further processing.

Step 3: The materials are heated in a large (usually rotary) kiln, at temperatures of 1,500°C and higher. The heat causes the materials to partially melt forming marble size nuggets. Upon cooling, the material is called *clinker*, which ranges in size up to about 25 mm in diameter. There are different types of kilns, and energy use per tonne of clinker ranges from 3.2 to 7.3 GJ/tonne (Price and Worrell 2006). The biggest distinctions to be made are in the dry vs. wet process and horizontal (or rotary) vs. vertical (or shaft) kilns. The wet process at 6.6 to 7.3 GJ/tonne and shaft kilns at 3.7 to 6.6 GJ/tonne are the least efficient. In the United States 23 percent of cement is still produced using the wet process (van Oss 2008). China has made significant use of shaft kilns in the past, up to 55 percent in 2002 (Taylor et al. 2006), but is rapidly switching over to more efficient technologies.

Step 4: Typically, clinker is cooled by air and ground with about 5 percent gypsum to particles finer than 200 mesh. The end result is a fine gray-colored powder called portland cement. A wide variety of raw materials, such as industrial byproducts, are suitable for use as constituents in cement production, though the industry is not making full use of these potential materials.

Aggregate — Normal concrete is about 72 to 82 percent aggregate by mass (66 to 74 percent by volume). Aggregate is mined from quarries, historically located near concrete batch plants, and trucked to batch plants. Some natural aggregate deposits, sometimes called bank gravel, consist of gravel and sand that can be readily used in concrete after minimal processing. Natural gravel and sand are usually dug or dredged from a pit, river, lake, or seabed. Crushed aggregate is produced by crushing quarry rock, boulders, cobbles, or large-size gravel. Crushed, air-cooled, blast-furnace slag is also used as fine or coarse aggregate. The aggregates are usually washed and graded at the pit or plant. Some variation in the type, quality, cleanliness, grading, moisture content, and other properties can be expected.

Local, naturally occurring sand and gravel have low embodied energies, but generally their removal is damaging to more sensitive habitats as these deposits are usually from river banks. Crushing quarried stone and slag adds an energy component, but using slag recycles a waste product. Any aggregate that is not sourced locally, and must be transported, has an added energy component. Due to growth of urban and suburban areas, and due to resource exhaustion, aggregate is increasingly supplied by non-local quarries.

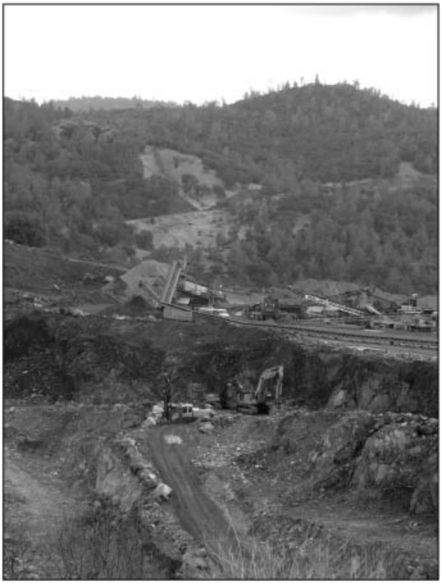

Figure 3.2-1. Aggregate quarry near the American River, Calif. (Meryman 2008)

Quarrying is intense and transient, as shown in Figures 3.2-1 and 3.2-2. Extracting any raw material takes a toll on the environment, as the surrounding ecosystems and their inhabitants suffer (Trusty 1994). At the end of their useful life, cement and aggregate quarries can be reclaimed as parks, recreational areas, or other developments. Local requirements generally determine whether the industry must pre-plan for the proper after-care of industry operations.

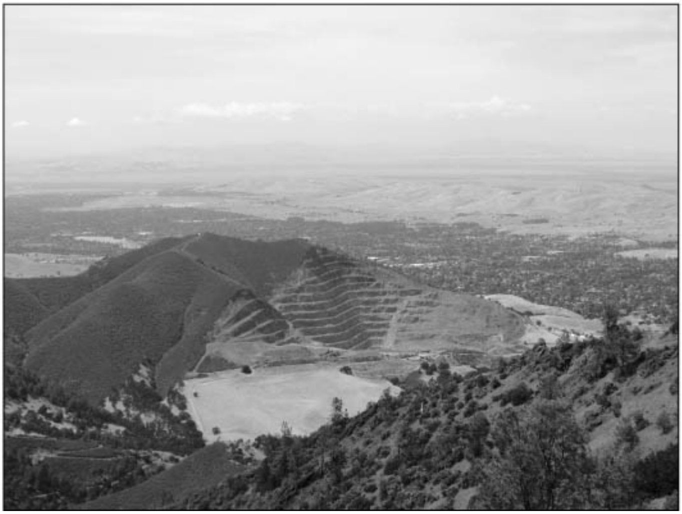

Figure 3.2-2. Cement quarry near Mt. Diablo, Calif. (Meryman 2008)

Clinker, cement, concrete, and CO_2

On average, for every tonne of cement produced a total of 0.9 tonnes of CO_2 are emitted. Carbon dioxide emissions from cement production mainly arise from two sources: from the decomposition of limestone and from the thermal energy needed to produce clinker. Approximately 40 percent of the total CO_2 emissions are related to clinker production, the remaining 60 percent are due to calcination of limestone.

Emissions — The CO_2 emissions due to calcination are formed when limestone is heated above 1,370°C and CO_2 is liberated from the decomposed limestone. The following chemical reaction shows a very simplified version of the process:

$$CaCO_3 \text{ (limestone)} + \text{Heat} \rightarrow CaO \text{ (quick lime)} + CO_2 \uparrow$$

Table 3.2-1. Molecular weights of clinker production chemicals

	$CaCO_3$	**CaO**	**CO_2**
Molecular weight	100	56	44
Weight fraction of $CaCO_3$	1	0.56	0.44

The calcination emissions factor is 0.53 (van Oss and Padovani 2003). Using the chemical properties shown in Table 3.2-1, the factor can be calculated as follows:

- If the typical CaO content of clinker is between 65 – 67 percent,
- Then, the amount required to produce 1 ton clinker with 67 percent CaO would be = 0.67 / 0.56 = 1.2, and the amount of CO_2 released per ton of clinker would be = 1.2 x 0.44 = 0.53.

Therefore, for every tonne of clinker produced 0.53 tonnes of CO_2 are released from limestone decomposition, as shown in the derivation above. Since limestone is an integral part of cement production, the cement industry has focused their efforts to reduce CO_2 emissions related to the thermal energy used to make clinker. Therefore, to reduce CO_2 emissions associated with concrete construction, the structural engineer should focus on minimizing the portland cement portion of cementitious materials in the mix design.

Global impact and demand — Worldwide, cement manufacturing accounts for about 7 percent of CO_2 emissions (IPCC 2005). The difference between the United States and worldwide emission percentages can largely be attributed to the greater overall energy use in the United States and its associated CO_2 emissions. Cement is a globally traded commodity and global warming is a global phenomenon, therefore it is logical to consider emissions on a worldwide basis.

To meet a demand greater than domestic supply, the United States imports cement from as far away as China. In 2003, the trade deficit for portland cement between the United States and all international partners was more than $873 million ($58 million was with China). For 2006, these numbers are significantly higher at more than $1.725 billion for world trade and $472 million for trade with China. It is worth noting that currently the second largest cement trading partner with which the United States runs a deficit is Canada (2003:$272 million; 2006 $270 million), which in some cases could be supplying cement in the United States from a location closer than the domestic supply. The increase in imported cement is alarming, and especially alarming is the growth in cement imported from China (U.S. Department of Commerce 2008).

Between 1995 and 2006 global cement production increased 80 percent from 1,390 to 2,500 Mtonnes/yr (U.S. Geological Survey 2008). Nearly half of global production is in China. Unit-based emissions vary from 0.73 to 0.99 kg of CO_2 per kg of cement, with an average of 0.90. While unit-based emissions have decreased somewhat, demand for cement has increased considerably. As a result there has been a significant net increase in CO_2 emissions by the cement industry. Demand is projected to continue to increase; even if best available practices are used to further reduce the unit-based emissions average, by the year 2050 the cement industry will contribute 9 percent of global CO_2 emissions with 70 percent of this coming from calcination (Taylor et al. 2006).

Energy performance indicator — The U.S. Environmental Protection Agency (EPA), as part of the Energy Star Industrial Focus Program, uses an Energy Performance Indicator (EPI) to rate the energy efficiency of cement manufacturers.

The EPI scores the energy efficiency of a single cement plant and allows the plant to compare its performance to that of the whole domestic industry. The tool is intended to help cement plant operators identify opportunities to improve energy efficiency, reduce greenhouse gas emissions, conserve conventional energy supplies, and reduce production costs. The tool scores a plant from 1 to 100. A score of 75 or higher deems the plant as energy efficient. Although a voluntary program, nearly half of domestic cement companies are participating in the Energy Star Industrial Focus program. Owners and engineers can encourage further industry participation by specifying cement from companies participating in this program.

Recycled materials as fuel — Cement production is mostly dependent on thermal energy, on average only 15 percent of the energy used is electrical (accounting for 10 percent of total emissions), so switching over to clean electricity sources like wind and solar will not go very far in reducing the overall energy related emissions. To supply the thermal energy required for burning clinker, mostly fossil fuels such as pulverized coal, oil and natural gas are used. Worldwide, the cement industry is increasingly using industrial wastes such as spent oils, old tires and other energy-rich alternative fuels to help meet their needs. Today, many plants meet 20 percent of their energy requirements with alternative fuels, and some have achieved 70 percent. On average, burning of waste materials currently satisfy 10 percent of the thermal energy needs of cement kilns.

These waste fuels include scrap tires, carpet, used waste oil, solvents, sludge from the petroleum industry, plastics, and agricultural wastes such as almond shells. Common wastes such as spent solvents, printing inks, paint residues, and cleaning fluids often are designated as hazardous because they are flammable; however they have high fuel value. These and other high-energy wastes, such as used motor oil and scrap tires, cannot be safely disposed in landfills. However, they can be burned to destruction as fuel in a cement kiln. Recovering their energy value in cement manufacturing helps reduce the use of fossil fuels for cement production; however, the impact on air quality has to be carefully evaluated.

The EPA has performed studies of the waste combustion technologies used in the cement industry and has also examined and revisited their impact on the environment. The EPA has previously concluded that using hazardous waste as a fuel in regulated, properly operated cement kilns poses no greater risk to human health and the environment than cement kilns that do not recover energy from waste. However, a recent EPA draft report indicates an eight-fold increase in dioxin releases compared to non-hazardous burning plants (National Center for Environmental Assessment 2003). To further complicate the issue, in some ways cement kilns are a good fit with waste fuels because the inherent alkaline scrubber effect of the system captures emissions such as hydrochloric and hydroflouric acids (Sintef and Cement Sustainability Initiative 2006). There is a large body of literature, much of it by the EPA, which discusses toxic emissions from waste combustion in cement kilns. The reader is encouraged to review this literature for more information on the subject.

Solid waste — Cement kiln dust (CKD) is created during the third stage of manufacturing when clinker is formed. Electrostatic and bag filters capture the dust for recycling. It is standard practice for CKD to be recycled at the plant back into the cement kiln as raw material. Recycling this byproduct reduces somewhat the amount of virgin limestone and other raw materials required. In the United States more than 75 percent of cement kiln dust is recycled at the plant. Other uses for CKD include agricultural soil benefaction and soil stabilization.

Engineering solutions

Each of concrete's three principal constituents — cement, aggregate, and water — can be specified to improve concrete's sustainability. Limiting the quantity of cement in a mix to that required to meet the specified design strength is an obvious and simple step. A more sophisticated step is incorporating complementary cementing materials (CCM) into the concrete mix as a substitute for cement. Properly graded aggregates will reduce cement requirements, and recycled aggregate can be used where appropriate, such as in sidewalks. Where quality and uniformity can be ensured and maintained, recycled aggregate can be used in structural concrete, also. Water reclaimed from concrete batch plant operations can be used in concrete production. Each of these engineering solutions is discussed below.

Mix design

The starting place for any concrete project, "green" or not, is a high-quality mix design. Engineers should have a solid understanding of what constitutes a good concrete mix design and what parameters they should specify or what is in the scope of the concrete supplier. Following the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI ACI 318-08) and Commentary (ACI 318R-08)* (ACI Committee 318 2008), the structural engineer is simply instructed that the mix shall be proportioned so that it meets the project requirements for workability, strength, and durability. For guidance on *how* to proportion the materials, ACI Committee 211 (Proportioning Concrete Mixtures) publishes a suite of guidelines giving standard practices for various types of concrete. *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete* (1991) gives a good overview of the fundamentals. When durability and other environmental concerns are absent, it is normally allowable for the structural engineer to simply specify slumps, maximum aggregates sizes, and 28-day strengths. The materials and water/binder ratio that are needed to meet the slump and strength requirements are left in the hands of the concrete supplier. It cannot be overstressed that providing good durability should be a goal for every project. Furthermore, since it is relatively easy and usually cost-neutral to satisfy green criteria such as reduced CO_2 emissions, structural engineers should be proactive in improving the quality and decreasing the impact of the concrete they specify. The structural engineer must be more involved in the specification of the mix design and materials used.

When environmental considerations such as extending the service life and reducing the ecological footprint of a structure are design factors the structural engineer must have an active role in developing the mix design. With just a little background reading structural engineers can be a lot more knowledgeable about what does and does not make sense for a quality concrete mix. This education is imperative for a structural engineer to be a valuable member of an integrated design team and the point of contact with the concrete supplier. Provided here is a very brief overview of how to use concrete in the age of global warming.

Main goal — Specify elements of a mix design that will provide concrete with the needed strength, durability, and workability. This should be achieved with the most efficient use of resources and least environmental damage possible. In short, the goal is to figure out how to use the least amount of cement without compromising performance goals.

Steps to minimize the portland cement content include the following:

- *Reduce water content*: Using a lower water/binder ratio can provide the same strength with less binder. Using fly ash and superplasticizers help improve workability without increasing water.
- *Do not use portland cement as the only binder*: Using coal fly ashes, slags, natural pozzolans and ultrafines reduces the cement content without raising the water/binder ratio.
- *Reduce the paste volume (binders plus water)*: Using the largest maximum aggregate size suitable reduces the surface area the paste needs to cover. If possible use well-graded aggregates with coarse sand only.
- *Select proper strengths*: Choose target strengths (f'_c) at ages that realistically reflect the needs of the project, rather than generic design strengths at 28 days. This will reduce the cement required and allow for a greater flexibility in the use of fly ash.

Good mix design is synergistic — The strategies listed above reduce cement use while maintaining strength and workability and they will also improve the durability of the concrete and extend the service life of the structure.

Strength

Strength of a mix design depends upon a variety of factors.

Water/binder ratio (w/b) — The term *binder* is used instead of cement so that it is inclusive of cement and all other materials that contribute to the paste content that binds aggregates together. The relationship between the water/binder (w/b) ratio and strength is commonly known — the lower the w/b ratio, the higher the strength, to a point. In concrete with a low w/b ratio a higher percentage of the cement grains may never come into contact with water. Unhydrated cement does not form any binder products. In low w/b mixes, superplasticizers and water-reducing admixtures are effective at ensuring a higher portion of cement grains are hydrated.

Non-cement binders — Moderate and high strength concretes can and should be achieved using more than just portland cement. Pozzolans, slags, and ultrafines can be used in varying amounts to target specific strength needs. These complementary cementing materials and their uses are discussed in detail in the next section. The primary chemical function of pozzolans and slags is to react with the calcium hydroxide (CH) formed by portland cement and water. The secondary reaction product is calcium silicate hydrate (C-S-H), which provides a much stronger bond especially in the critical area around aggregates. C-S-H takes longer to develop and therefore design strength requirements should be adjusted as necessary. In many applications a 28-day design strength is merely convention and not a functional requirement. For these cases a 56 or even 90 day strength should be specified. If early strength (such as 7 day) is required, a mix using highly reactive pozzolans (silica fume or rice husk ash) and/or ultrafines can provide a significant boost before the later pozzolanic reaction starts.

Aggregates — Normally available aggregates are stronger than the surrounding hardened paste. Maximizing the aggregate content is consistent with economical, environmental and high strength design.

Durability

Similar to strength, the durability of a mix design depends upon a variety of factors.

Water/binder ratio (w/b) — The relationship between the w/b ratio and durability is at least as important as w/b and strength. The maximum w/b ratio that will *not* introduce voids is 0.32. This is derived from the simple facts that cement has a higher specific gravity than water (typically 3.14 vs. 1.0), and as water and cement combine the new volume of paste is the sum of their individual volumes. So every volume unit of water combined with the same volume unit of cement corresponds to a w/b = 1/3.14 or 0.32 (Mehta and Monteiro 2006). Any increase in water weight means an increase in water volume, which results in “free water." Free water is unbound water that creates unwanted voids in the concrete as it cures and contributes to drying shrinkage as it evaporates. Unwanted voids and shrinkage cracking negatively effect durability by providing conduits for corrosive ions to the interior of the concrete where steel reinforcement is put at risk.

Non-cement binders — As CH becomes C-S-H both the strength *and* the durability of the concrete will improve. It is important to note that there is only a favorable correlation between high strength and durability in concrete containing pozzolans and slags. C-S-H is a much denser product that CH, thus it makes a more impermeable and durable concrete. Further, non-cement binders such as pozzolans will lower the heat of hydration. This is crucially important especially in high ultimate strength concretes. High heats of hydration are associated with the development of thermal cracking, which will increase permeability and can dramatically limit service life. Specific durability issues such alkali-silica reactions are discussed below in complementary cementing materials.

The National Ready Mix Concrete Association provides a free software program, called Life-365, to help designers optimize the durability of their mix designs. In addition to w/b ratio, paste volume and types of binders, design parameters include exposure environments, time span, reinforcement (regular, epoxy coated, or stainless steel) and clear cover. The program calculates estimates for service life, repair schedules, and cost benefit analysis. It is a very useful tool to see the life cycle benefits of one mix against another, however this program is not a substitute for testing and should not be relied upon to generate a mix design. It can be downloaded at: http://www.nrmca.org/research/life365_instructions.asp

Aggregates — Where available aggregates have a history of alkali-silica reactions (ASR), a high portion of fly ash is recommended.

Workability

Workability of a mix design will depend upon the same factors as strength and durability.

Water/binder ratio (w/b) — Workability is the ability to successfully place or pump concrete. It is normally specified by the slump measurement. High w/b ratios generally mean higher slumps. The required slump depends on the element being formed and the degree of congestion of the rebars. The higher the slump, the looser the concrete mix is and the easier it is to place in forms and around rebar. If the slump is too high the aggregates will segregate (larger ones falling toward the bottom), which is detrimental to the integrity of the concrete. In some concrete operations slump is increased as needed by the addition of water (and usually more cement to maintain a prescribed w/b ratio). This unnecessarily increases the paste volume and is wasteful of cement. Water-reducers and superplasticizers can be used to increase workability without increasing water and cement contents. These admixtures are a good way to minimize water content and use cement more efficiently. The dosage used should follow the manufacturers' instructions, but a good rule of thumb is to limit the water-reducers or superplasticizers to 2 percent of the mass of the binders (this is determined using the mass of the solids portion of the admixtures). Too much of these admixture can cause segregation and excessive bleed water.

Non-cement binders — Fly ash should be included in mix designs to help enhance workability. Its spherical shape acts as a physical lubricant and thus aids in cement hydration. Studies dating back as far as 1952 find that for every 10 percent of fly ash added approximately 3 to 4 percent of the water can be reduced without sacrificing workability (Joshi and Lohtia 1996).

Aggregates — An excessive amount of fines can make a mix sticky to work with. Using coarser sands will reduce water demand and is the most appropriate choice for most applications.

Complementary cementing materials (CCM)

Formerly known as supplementary cementitious materials (SCM), a more current and correct terminology is complementary cementing materials (CCM).

Pozzolans are not cementitious, but they do complement cement hydration products with a secondary reaction forming calcium silicate hydrate (C-S-H) cementing compounds.

Overview — For every tonne of cement replaced by a carbon-neutral waste product, 0.9 tonnes of CO_2 emissions are avoided (Taylor et al. 2006). The practice of using CCMs in concrete has been growing in North America since the 1970s. Some of these materials are currently going to waste and using valuable space in landfills. The CCMs discussed here — fly ash, slag cement, silica fume, rice husk ash, and ultrafine minerals — are industrial by-products and, therefore, carbon neutral. These materials are considered pre-consumer recycled materials; they are not manufactured, but are sold, as the byproducts of an industrialized process.

The use of CCMs as a partial replacement for portland cement improves the environmental footprint of the concrete structure in the following ways:

- reducing its embodied energy content;
- reducing CO_2 emissions;
- reducing the amount of materials that are placed in landfill;
- reducing the environmental impacts caused by extracting virgin materials;
- reducing the environmental impacts that result from the manufacturing of portland cement clinker; and
- improving durability and extending service life.

Use — CCMs are used as a partial replacement for the portland cement in concrete and are frequently used in ready mixed concrete. Fly ash is commonly used at replacement levels up to 25 percent; slag cement up to 60 percent; and silica fume is commonly used at replacement levels up to 7 percent. The binder content of concrete is typically about 10 to 15 percent, it follows that CCM replacement of cement will range between 2 to 8 percent of the mass of the concrete.

There are two methods of inclusion for incorporating CCMs into concrete, batch mixing and blended cements. Most common in the United States is to simply specify the CCM (classified as a mineral admixture) as a separately batched ingredient. This means the CCM is added into the mix at the batch or ready mix plant. A second method (more common in Europe) is to use a blended cement in which the pozzolanic or slag material is either interground with portland cement or mechanically blended to "attain an intimate and uniform blend" (ASTM C595-08a). A third approach to incorporating CCMs is to use a combination of batch mixing and blended cements. Blended cements are discussed in detail later in this section.

Testing can determine the maximum amounts of CCMs that can be used to meet the project's performance properties specified for concrete. When CCMs are used in high proportions, test mixes should be performed earlier than usual to allow for mix design modifications. As with all mix testing, these tests are to demonstrate that the concrete mix design (using the actual project materials) satisfies project requirements.

Using CCMs is good for concrete structures and sustainable development alike, because most CCMs enhance the durability of concrete. Large proportions of pozzolans dramatically increase impermeability and thus durability. The most problematic aspect of most CCMs (type F fly ash in particular) is that curing times increase. For most projects this is not an issue, but for some ternary blend mix designs only minimal CCM inclusions are appropriate.

The properties of fly ash, slag, and most CCMs vary; the structural engineer, project contractor, and the concrete producer should use judgment, testing, and control procedures to ensure good concrete performance. The project specifications should explain the required concrete properties for each building element, the acceptable range of CCM content, and any other project-specific caveats such as when cold weather placement or exposure to de-icing chemicals is likely, or if a high pozzolan content is required to provide enhanced durability. Limits to CCM content may be set based on previous performance where applicable, and the performance of new concrete tests in the field or laboratory. Contact your local ready-mixed concrete suppliers to determine what classes of fly ash or other CCMs are available and to verify its performance in quality concrete. This may vary between suppliers. Anecdotal experience from several practitioners suggests that your local supplier may need to be encouraged to locate CCMs.

Fly ash

According to a report issued by the Portland Cement Association (PCA) "Fly ash is commonly used as a partial replacement for portland cement— or as an addition to portland cement — because it can enhance the placement, engineering properties, and durability of concrete (Marceau et al. 2002)."

Fly ash, shown in Figure 3.2-3, is a pozzolanic by-product of the combustion of pulverized coal in electric power generating plants. It is commonly used as a partial substitute for 15 to 25 percent of the portland cement in concrete. In the United States, fly ash is normally used as a mineral admixture and added to ready mixed concrete at the batch plant.

Figure 3.2-3. Fly ash (Meryman 2007)

Fly ash is the most abundant CCM worldwide and domestically. Fly ash is available throughout most of the United States; however, quantities are limited in some locations. The 2006 Coal Combustion Product (CCP) Production and Use Survey compiled by the American Coal Ash Association (2008) reports 65 Mtonnes of fly ash were generated in 2006, of which, approximately 45 percent were recycled and 35 percent were placed in landfills. Of fly ash produced, 17 Mtonnes, or 26 percent, was used in concrete products and cement. Not all fly ash is useable in concrete. Power plants with high NOx emissions controls are producing fly ash that is ammoniated. Fly ash with ammonia content greater than 100 ppm is considered a health hazard; to protect workers, contaminated ash is not acceptable for use in concrete. Several technological solutions exist that process the ash to remove the ammonia (Malhotra and Mehta 2008).

Benefits — "The use of fly ash in concrete can reduce the environmental impact of concrete and can actually improve the quality of the concrete (Marceau et al. 2002)."

Incorporating fly ash in concrete can enhance the properties of concrete. During placement, improvements to the properties of fresh concrete include the following:

- enhanced workability;
- reduced bleed water;
- resistance to segregation; and
- reduced slump loss.

For hardened concrete, the addition of fly ash provides the following benefits:

- increase long-term strength;
- reduce permeability;
- increase durability;
- reduce potential for sulfate attack; and
- reduce potential for alkali-silica reactivity.

Fly ash concretes generally have a slower rate of strength gain, due to a lower heat of hydration. This is desirable in mass concrete applications and when the atmospheric temperature is high. Lower heats of hydration correspond to a reduction in thermal micro-cracking and thus decreased permeability. As with all concrete constituents, proper use is necessary for successful concrete.

Composition and specifications — When considering fly ash, a structural engineer should understand the following:

Chemistry and mineralogy: Fly ash is primarily amorphous silicate glass containing silica, aluminum, iron, and calcium. Minor constituents are magnesium, sulfur, sodium, potassium, and carbon. Crystalline compounds are present in small amounts.

Physical properties: The relative density (specific gravity) of fly ash ranges between 1.9 and 2.8 and the color is gray or tan. It is useful to recognize, that since fly ash is lower in density than portland cement, replacement on a "per mass" basis increases the paste volume of concrete. This provides better coverage of aggregates and improves the cohesiveness and workability. Further, fly ash particles are spherical, which helps "lubricate" a mix during hydration; in effect increasing slump without increasing the w/b ratio. By holding slump and paste volume constant, these characteristics (shape and density) can be used to decrease the cement and water content of a mix, without lowering strength.

Class F fly ash: This type is a by-product of burning bituminous coal, which is generally found in the eastern portion of the United States. Class F materials are high in iron, silica, and alumina, but low in calcium (less than 10 percent CaO). Carbon contents are usually less than 5 percent.

Class C fly ash: This type is a by-product of burning the sub-bituminous coals and lignites found in western states. Class C materials are higher in calcium oxide (10 to 30 percent CaO) with carbon contents typically less than 2 percent. Due to the reactivity of the CaO content, Class C fly ashes are considered semi-cementitious. Concrete with Class C fly ash generally develops strength faster than concrete with Class F fly ash. Class C fly ash may be preferred to Class F fly ash where construction schedules demand a fast curing concrete.

Freeze-thaw: Both types vary in composition and carbon content. Fly ash used in concrete subject to freezing and thawing should have low levels of unburned carbon in order to achieve adequate air content — extra air entrainment agent may still be required because it gets absorbed and deactivated by carbon. Specifications typically limit the unburned carbon content to a maximum of 6 percent; however, market forces have typically limited this to less than 1 percent (Marceau et al. 2002).

Particle size: For optimum results a finer particle size is preferred. Particles large than 45μm are generally non-reactive. Pozzolanic activity has been shown to be directly proportional to the amount of particles finer than 10μm (Mehta 1985). ASTM C618-08a allows for a maximum of 34 percent of particles larger than 45μm as retained on a No. 325 sieve. However, it is recommended to limit this to value to a maximum of 15 percent.

Class F and Class C fly ashes meeting ASTM C618-08a, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,* are commonly used for general purpose concrete. ASTM C618-08a provides minimum values for the pozzolanic compounds, limits carbon content and particle size. ACI 232.2-03, *Use of Fly Ash in Concrete*, (ACI Committee 232 2003) provides an extensive review of fly ash.

Use — Fly ash often replaces cement at 15 to 25 percent by mass of binder material, that is, the total of cement, fly ash, and other complementary cementing materials. Replacement rates vary with the reactivity of the ash and the desired effects on the concrete. The amount of fly ash used to replace portland cement should be tailored to the specific constraints and requirements of individual applications, 25 percent is conservative for most applications.

Replacement rates of fly ash more than 25 percent will delay the time of initial set if other admixtures are not used to boost early strength (for example using silica fume, rice husk ash, and ultrafines can offset the slow strength). Delayed set time is often a benefit in warm weather. In cooler weather, accelerators, heated materials or other precautions may be required. Used alone as a cement replacement, fly ash, especially Class F, can cause lower early age strengths. For most common applications early strength is not critical and longer curing times will not impact the construction schedule. For example foundation elements (retaining walls, mat slabs, piers) and shear walls are seldom subjected to high loads in their first two months. Conversely, to be economical, most of the super-structure in high-rise construction requires high early strengths for the fast cycling of forms and post-tensioning of slabs. In these cases, using high portions of fly ash is inappropriate.

For concrete exposed to deicing chemicals, the maximum fly ash content is generally limited to 25 percent. Special provisions for a particular project, along with testing, may increase the fly ash content of concrete for specific applications and needs. The performance of high volume fly ash (HVFA) concrete exposed to deicing chemicals remains a debated subject. While ASTM C672-03 scaling test results are poor, there are several examples of HVFA in service that have done well exposed to these chemicals (Malhotra and Mehta 2008, Bouzoubaâ and Foo 2005).

High volume fly ash (HVFA) — Concrete has been successfully placed using fly ash for over 50 percent of the binder material. In some special applications, such as large mat foundations, concrete has been successfully placed with up to 80 percent fly ash. Strength development is generally slower so construction schedules must accommodate the extra time required before forms and shoring are removed. If above code amounts of fly ash are used, more and/or earlier testing must typically be done to ensure the concrete performance satisfies building codes. This can make HVFA concrete somewhat more expensive for small projects where the cost of testing is not offset by lower material costs. Use of ASTM C1157-08a should be helpful in getting HVFA mixes more generally accepted.

In some cases, the reduced bleed water in HVFA mixes will require that care and attention insure proper curing (Bouzoubaâ and Foo 2005). For example, slabs may require a fog spray or plastic sheeting to retain surface moisture. Guidance on uses of high volume fly ash can be found in Malhotra and Mehta (1996) and (2008).

Fly ash and toxicity — Fly ashes contain minute amounts of arsenic, chromium, lead, titanium, and other heavy metals (Malhotra and Mehta 2008). The amount of heavy metals contained in a particular fly ash varies on the type and source of the fly ash. The presence of these metals in HVFA concrete raised the question of a possible impact on human health; these concerns spurred several investigations. Studies on the possible toxicity of HVFA were conducted at the University of Aachen, Germany, and by Zhang, Blanchette, and Malhotra at CANMET (Canadian Center for Mineral and Energy Technology), Canada. Both studies show that when fly ash was used in good quality concrete the amount of heavy metals that leached from the concrete were either undetectable or well below the prescribed limits for safe drinking water. In general, less than 1 percent of the trace amounts of heavy metals contained in the fly ash were detected to leach out of the concrete. A 30 percent and 60 percent fly ash mix were both tested, with similar results. Based upon the results from the testing there is a relatively low risk of heavy metal contamination to humans or the surrounding environment when fly ash is used in good quality HVFA concrete.

Slag cement

Slag cement, also known as ground granulated blast-furnace slag (GGBFS) or simply slag, is a by-product of the steel industry. It is hydraulic cement formed during the liquification of iron in the blast-furnace. Molten slag is rapidly cooled via quenching to form glassy non-metallic granules. Slag formed from air-cooling is crystalline and will only have weak cementitious properties if very finely ground; some air cooled slags are used as aggregates. The slag used for cement replacement is GGBFS. Slag cement is commonly used as substitute for portland cement in concrete at replacement levels of 65 percent or higher.

The U.S. Slag Cement Association reports 3.62 Mtonnes of slag were shipped for use in concrete in 2006; the U.S. Geological Survey (USGS 2007) confirms this represents domestic use. The demand in the United States increases annually and is up 224 percent since 1996 (U.S. Slag Cement Association 2008). It is worth noting that the availability and use of slag is less than 20 percent of the fly ash market. The USGS reports that the supply of GGBFS from domestic blast furnaces is constrained by the fact that granulation cooling is currently operational at only four blast furnaces in the United States. Furthermore, many blast furnaces have closed over the years for economic and/or environmental reasons and no new blast furnaces are under construction or are planned. Retrofitting existing domestic blast furnaces with granulators is both possible and expensive; however if this is not done, any growth in supply will depend on direct imports of GGBFS or the output of grinding plants that rely on imported GGBFS feed. Currently an undefined portion of the slag used in the United States is a domestically ground, imported product. In fact of the slag suppliers listed in the annual survey by the USGS, nine slag sources used only domestic feed stock, ten used mostly foreign material and two processed both (USGS 2006).

Benefits — Incorporating slag cement in concrete can enhance the properties of concrete while reducing its environmental impact. Slag cement generally improves the following concrete properties during placement:

- workability;
- finishability; and
- pumpability.

Slag cement can improve the following properties of hardened concrete:

- increasing compressive and flexural strength;
- reducing permeability;

- increasing resistance to chloride intrusion and corrosion;
- mitigating moderate to severe sulfate attack;
- reducing the potential for alkali-silica reactivity; and
- increased reflectivity, with a whiter color desirable to reduce urban heat island effects.

Similar to fly ash, slag cement can reduce thermal stress in mass concrete through lower heat generation. The durability enhancements are similar to fly ash but slag is generally about 60 percent as effective at reducing permeability and therefore the exposure of reinforcement steel to corrosive ions. Permeability is the best single indicator of service life in most exposures.

Composition and specifications — When considering slag, a structural engineer should understand the following:

Chemistry and mineralogy: Slag cement is a glassy blend of non-metallic silicates alumino-silicates of calcium.

Physical properties: The relative density (specific gravity) for slag cement is in the range of 2.85 to 2.95. Rapid quenching produces tortuous granular shapes, which contribute to slag's reactivity. The granulated material is normally ground to less than 45 µm, as with fly ash, particles larger than this rarely hydrate. Slag is nearly white in color, which makes it a desirable concrete additive for some architectural concretes, and as a high albedo material for roof tops and parking lots.

Standards: ASTM C989-09, *Standard Specification for Slag Cement for Use in Concrete and Mortars*, classifies slag by its increasing level of reactivity as Grade 80, 100, or 120 (Table 3.2-3). ACI 233R-03, *Slag Cement in Concrete and Mortar* (ACI Committee 233 2003), provides an extensive review of slag cement.

Use — Slag cement has been used as a cementitious material in concrete since the beginning of the 1900s. Slag cement, when used in general purpose concrete in North America, commonly constitutes between 30 percent and 45 percent of the binder material in the mix. Some concretes have a slag component of 70 percent or more of the binder material. Slag cement will tend to delay the time of initial set, which is often a benefit in warm weather. In cooler weather, accelerators, heated materials or lowering the percentage of slag cement in a mixture (as a portion of cementitious material) can be employed to decrease setting time. Early age strengths (through 7 to 14 days) of slag cement tend to be lower while later age strengths will be higher. For the vast majority of applications, the rate of strength gain is sufficient, however for some projects this can affect the construction schedule. Like fly ash, using more than 25 percent slag cement in concrete exposed to de-icing chemicals is controversial (Malhotra and Mehta 2008).

The caveats and benefits of using slag cement are similar to those described for fly ash; refer to earlier sections for more information on specification and use.

Silica fume

Silica fume is a by-product from the electric arc furnace used in the production of silicon or ferrosilicon alloy. Silica fume is commonly used as a partial substitute for portland cement in concrete at replacement levels of 5 to 7 percent. Unlike other CCMs discussed here, silica fume is a premium material in demand and commands a high price.

Benefits — Silica fume is especially useful for projects where high early strength is required. It is used in applications where a high degree of impermeability is needed. Using silica fume can increase the resistance of concrete to chloride ion penetration which increases service life, especially in bridges and parking decks. Because silica fume increases early strength gain it is particularly useful in ternary blends with large proportions of Class F fly ash, which would otherwise have slow strength development.

Composition and specifications — When considering silica fume, a structural engineer should understand the following:

Chemistry and mineralogy: Silica fume, also referred to as microsilica or condensed silica fume, is essentially silicon dioxide (usually more than 85 percent) in non-crystalline (amorphous) form.

Physical properties: The relative density (specific gravity) of silica fume is generally in the range of 2.2 to 2.5. Like fly ash, it has a spherical shape. It is extremely fine with all particles less than 1 μm in diameter and an average diameter of about 0.1 μm, this is about 100 times smaller than the average cement grain. Silica fume has a high specific surface area of approximately 20,000 m^2/kg. For comparison, Type I and Type III cements the surface areas are about 300 to 400 m^2/kg and 500 - 600 m^2/kg, respectively.

Silica fume is sold in powder form, but is more commonly available in a liquid form for ease of transport and handling.

Standards: Silica fume must meet ASTM C1240-05, *Standard Specification for Silica Fume Used in Cementitious Mixtures*. ACI 234R-06, *Guide for the Use of Silica Fume in Concrete* (ACI Committee 234 2006), provides an extensive review of silica fume.

Use — Silica fume's very high specific surface area is the primary reason this material can boost early strength. It also means there is a lot more surface area for the mix water to cover, therefore using silica fume increases water demand. Because of this, using above 10 percent silica fume is not normally recommended. Silica fume is usually used in high-end, high-strength applications and it is normally desirable to keep the w/b ratio low. In order to have a successful mix with good workability and a high percentage of cement grains hydrated, superplasticizers, or high-range water reducers should be used. Silica fume should be used (where economically possible) to increase the portion of fly ash that can be incorporated into high strength, high durability concrete.

Rice husk ash

Rice husk ash (RHA) can be used to replace cement. It can enhance early strength gain and is an especially useful addition to mixes with high volumes of type F fly ash. Like coal fly ash, RHA is a pozzolanic material. RHA is not a well-known material; however, due to its performance abilities and its quantities, RHA is considered by concrete technologists and the materials industry as the next frontier in CCMs. In fact, rice husk ash is the international term for this material; in the United States it is more commonly referred to as rice hull ash. It is important when searching for articles that the searcher include both terms, *hull* as well as *husk*.

RHA comes from incinerated rice husks, which are an abundant agricultural waste product. The husk is around 20 percent of the weight of dried rice paddy (Mehta and Monteiro 2006). Controlled burning produces ash that is 20 percent of the weight of the husk (Malhotra and Mehta 1996). Rice husks contain approximately 50 percent of the energy value of coal (Malhotra and Mehta 1996) and are economical and suitable for use as a fuel for power generation. According to the International Rice Research Institute, 645 Mtonnes of rice was harvested globally in 2007 (International Rice Research Institute 2007). This corresponds to a potential global supply of 25.80 Mtonnes of RHA that could be made available for use as a CCM. If this RHA were to replace 10 percent of portland cement it would produce 1,722 Mtonnes of improved concrete, resulting in 25.8 tonnes of avoided CO_2 emissions.

Clean development mechanism (CDM) is an economic, development and climate policy instrument that provides financial incentives to clean technologies via a carbon credit and offset model. There are a number of "CDM" plants in the developing world using rice husks as fuel, but this has yet to realize its potential. Creating a market for rice husks has the further environmental benefit of providing incentives to rice farmers against crop burning and waste dumping — sources of CO_2 and CH_4 emissions and atmospheric pollution. Biomass dumping is environmentally harmful because as husks ferment they release methane (CH_4), which has a CO_2E value of 21. Controlled combustion in a power plant does useful work while providing filtration of particulate emissions. For power or heat generation with rice husks, the main technology issue is implementing appropriate and standardized burning practices so that a value added waste ash product results. Recent projects in Thailand are hopeful signs that this waste resource is being developed with material products in mind. It is possible that the United States will soon start to see silica fume-quality RHA imported from south east Asian countries.

There are two known RHA producing power plants in the United States: Enpower Corporation in Wadham, Calif., and Agrilectric in Lake Charles, La. Agrilectric is known to supply RHA of a higher and more consistent quality, because (according to Dr. WenPing Li, director of research and development at Agrilectric) it is produced with greater quality controls and burned at lower temperature (800°C maximum). Enpower, operator of the Wadham plant, has been seeking to improve the quality of its RHA, but as of this writing it is not known when this will occur.

Benefits — Pozzolans are well known to significantly improve the durability of concrete while also increasing long-term strength. RHA is a highly reactive pozzolan and has similar benefits to fly ash, only the improvements are enhanced. RHA improves durability mainly by forming an efficient network of C-S-H in the paste matrix and around aggregates in the interfacial transition zone (ITZ) resulting in an almost impervious concrete. Like silica fume, high quality RHA can enhance early strength gain.

Composition and specifications — When considering rice husk ash, a structural engineer should understand the following:

Pyro-processing: Rice husks must be incinerated or gasified under controlled conditions for the resulting pozzolanic ash to be sufficiently reactive. The temperature should be relatively low, in the range of 500°C - 800°C, depending on heat exposure time (Cook 1984). The objective of combustion is to remove the cellulose and lignin while retaining amorphous properties of the silica and the cellular structure of the husk particles (Fig. 3.2-4).

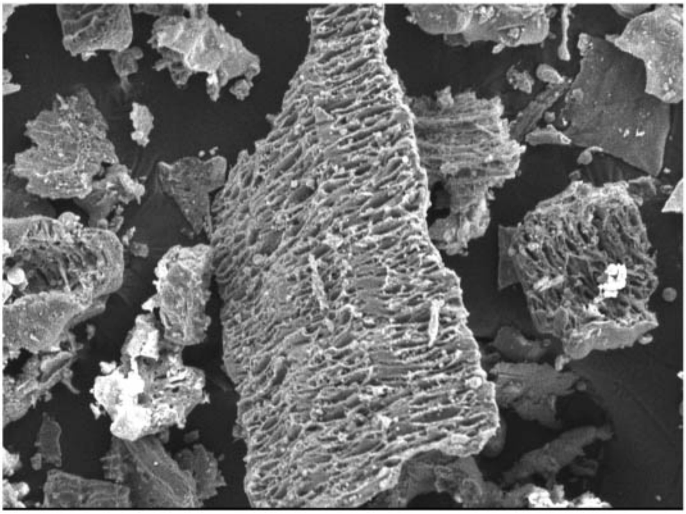

Figure 3.2-4. SEM image of unground RHA
(Image copyright 2005 The Agrilectric Companies, used with permission)

The unique inverted corncob shape of RHA has an enormous specific surface area, which helps boost early strength development in concrete mixes. The combustion conditions also affect the form of silica obtained; generally, temperatures above 850°C will produce the relatively inert, crystalline forms: cristobalite and quartz. As with other CCMs, a glassy, amorphous, non-crystalline form of the SiO_2 content is required for reactivity. As with coal fly ash, low unburnt carbon content (preferably less than 5 percent) is required for good performance. Gasification is very effective at producing highly amorphous ash, but the product must undergo pre- or post-processing to remove the high content of unburnt carbon.

Chemistry and mineralogy: Good quality RHA typically contains well over eighty-five percent amorphous silica (SiO_2), which classifies it as a highly reactive pozzolan (Mehta 1992).

Physical properties: The mean particle size of unground RHA is typically around 120 μm. For use in cement replacement, RHA should be ground to a mean size of less then 10 μm, as shown in Figure 3.2-5. This is still over 100 times greater than the tiny spheres of silica fume, yet due to RHAs shape, its specific surface area is much larger (40,000 to 60,000 m^2/kg). The reactivity and rate of early strength gain increases with an increase in specific surface area (Nehdi et al. 2003; Barbhuiya 2006) and amorphous content.

Figure 3.2-5. Rice husk ash ground to 9 μm. (Meryman 2007)

Use — Currently, there is no standard or guideline for the proportioning of RHA in concrete mixes. Designers should bear in mind that due to RHA's large surface area, it typically causes a slight increase in water demand. Quality RHA can influence the rheological and physiochemical behavior of concrete in a manner similar to silica fume. Therefore, the proportioning of RHA should generally not exceed 20 percent by weight of the binder mix. Appropriate amounts, and those showing good performances in studies, range from 10 to 20 percent.

For any RHA source quality should be confirmed by the batch with information stating the specific surface area to be tested by the BET nitrogen adsorption method (ASTM C1274-00), carbon content (measured as loss on ignition or LOI) and chemical analyses (by x-ray diffraction or XRD) indicating percentages of amorphous and crystalline silica. After grinding to a maximum size of 10 μm, the ash size should be confirmed by particle size distribution (using laser diffraction) and the specific surface area (by BET) should be retested to insure over-grinding and crushing did not occur.

RHA in multiple binder concretes: Binary, ternary and quaternary blends — A considerable amount of research exists on binary and ternary blends of cementing components; some even include RHA. Published investigations into quaternary blends are extremely sparse. The departments of transportations in several states are studying quaternary blends, but these normally include fly ash, slag, and silica fume. A common ternary mix uses fly ash and includes silica fume to mitigate early strength loss. The benefits of RHA are best exploited by using it in ternary and quaternary blends. In simple binary mixes where RHA replaces a percentage of portland cement and in ternary mixes where fly ash and RHA supplement portland cement, the inclusion of RHA results in a higher quality product. RHA has been shown to improve the strength gain and durability of concrete (Malhotra and Mehta 1996). Good quality RHA contributes to early as well as later strength gain. In a quaternary blend with fly ash and ultrafines, the early strength loss due to fly ash is offset by the RHA and the ultrafines. The later strength loss associated with the ultrafine portion is then offset by the later pozzolanic strength gain of the RHA and fly ash.

Mineral ultrafines

Particles less than 5 microns are known as "ultrafines," powders, or flours. Ultrafine minerals are generally a by-product of stone cutting and crushing operations such as architectural stone and aggregate production. Limestone ultrafines are produced as a by-product of cement manufacturing. These materials are commonly known as "baghouse fines" as they are recovered from the filters in dust collectors called baghouses. Any powder from a parent rock suitable for aggregate can be used in concrete as an ultrafine addition. In small proportions, 5 to 15 percent of total binder content, ultrafine powders are known to enhance early strength development of concrete.

The first major study on ultrafine powders was conducted by Soroka in the mid-1970s. It was established that the primary strength improving mechanism attributable to non-pozzolanic ultrafine powders was their ability to enhance cement hydration (Soroka and Setter 1977). This effect, which includes nucleation of cement hydration products, is fundamentally surface oriented: the ultrafine particles present host sites on their surfaces for hydration products to nucleate. It has been shown that accelerated hydration indeed increases with an increase in the fineness of the filler material (Soroka and Setter 1977). Therefore, it was established that heterogeneous nucleation depends on specific surface area (m^2/kg) of the filler (Lawrence et al. 2005).

Benefits — Ultrafine minerals are currently well below the cost of cement (approximately $20 tonne in the western United States). Ultrafine additions increase the efficiency of the cement used by helping to hydrate cement grains. In low water/cement ratio concrete it is typical that over 35 percent of the cement grains remain unhydrated and act as an expensive, energy-intensive filler (Bonavetti et al. 2003). The hydration enhancement contributes to early strength gain without an increase in cement, or use of expensive admixtures like silica fume. Due to the particle packing effect, the permeability of hardened concrete is reduced.

Composition and specifications — When considering ultrafines, a structural engineer should understand the following:

Chemistry and mineralogy: The most common inert ultrafines include crystalline minerals such as quartz. Functionally inert fillers include limestones and dolomites. Until recently, the role of limestone ultrafines in cement mortars and concrete received little attention. The mechanism behind the early strength gain associated with the inclusion of limestone ultrafines has been a subject of debate. The question is this: is the calcium carbonate in the limestone filler inert or does it react chemically with cement minerals, and if so, is this significant, and does it affect strength? On the other hand, strength gained from enhanced hydration is well documented. While the mechanism question is by no means closed, current studies comparing quartz and limestone fillers show that any effect other than hydration enhancement that might be attributable to the calcium content of limestone is relatively insignificant (Lawrence et al. 2005; Bonavetti et al. 2003).

Physical properties: The specific gravity of an ultrafine is the same as its parent rock and thus similar to the values for common aggregates (2.6 to 2.8). Typically, baghouse fines are all smaller than 75 μm (No. 200 sieve) and nearly all particles are finer than 45 μm (No. 325 sieve); however, only the portion less than or equal to 5 μm should be considered as the ultrafine material. Unlike ashes, these inert materials are only distinguished by size and to a lesser extent shape, as it influences surface area. Therefore these materials are relatively uncomplicated to characterize and do not expose the user to the uncertainty associated with highly variable materials.

Use — To benefit strength gain, the proportioning of ultrafines must balance the enhanced hydration against an effectively increased water-binder ratio. Since ultrafines do not have cementing or pozzolanic reactions, their inclusion in the binder mix is akin to increasing the water-binder ratio (Nehdi et al. 1996; Bonavetti et al. 2003), also known as the "dilution effect." Therefore, for ultimate performance the dilution effect must be considered along with hydration enhancement. Proportions in the 5 to15 percent range have shown the most favorable results (Cyr and Ringot 2006; Nehdi et al. 1996).

To increase early strength gain the specific surface area should be maximized by increasing the fineness of the particles used. Material with all particles less than 5 μm may not be available and it is not usually practical to sort out the larger particles. To work around this, the amount of material can be increased so that the portion meeting the 5 μm size criteria constitutes the desired percentage of the binder component (5 to15 percent). The portion of the material larger than 5 μm would then be considered as part of the fine aggregate, which would be adjusted accordingly. This adjustment requires particle size distribution data (by laser diffraction) for the material.

Due to the dilution effect, the use of ultrafines to replace a portion of the cement or pozzolanic binder results in a proportionally lower ultimate strength for the concrete. For most projects, the structural requirements can be met even with the lower ultimate strength. For other cases there are two approaches that can be taken: first, using pozzolans such as fly ash and RHA will provide higher ultimate strengths to offset any loss due to fillers; and second, the 5 to 15 percent of binder component can be used as a guide for the weight of the ultrafine component, but the ultrafine can be added as part of the fine aggregate, thereby removing the dilution effect all together. This method is only recommended if pozzolans are used in the binder components, otherwise the use of ultrafines does not offset cement use, which remains the goal.

Blended cements

Blended cements are produced by intimately and uniformly blending or intergrinding two or more types of fine materials. The primary materials are portland cement, slag cement, fly ash, silica fume, and natural pozzolans. Blended cements are used in all aspects of concrete construction in the same manner as portland cements. Blended cements are often used in combination with other CCMs added at the batch plant.

In the United States, ASTM C595-08a, *Standard Specification for Blended Hydraulic Cements*, provides the standard requirements for blended cements. For pozzolan blended cements (Type IP) the pozzolanic content (fly ash, rice husk ash, or natural pozzolans) is limited to 40 percent by mass. For slag blended cements (Type IS) the slag content can be up to 95 percent by mass. Another option is to follow ASTM C1157-08a, *Standard Performance Specification for Hydraulic Cements*. Blended cements meeting the requirements of ASTM C1157-08a meet performance test requirements without prescriptive restrictions on ingredients or cement chemistry. This allows the cement manufacturer to optimize strength and durability properties through use of a variety of materials, such as portland cement, fly ash, slag, silica fume, and other pozzolans.

In Europe the Cement Specification EN 197/1, issued in 2002, contains three blended portland cements with low clinker factors (0.35 to 0.64). The CCM contents of these along with the ASTM standard blends are summarized in Table 3.2-2.

Selecting and specifying binders

When specifying binder materials (cements and CCMs) for a project, be sure to check the availability; keep in mind that some contractors and concrete suppliers that have not used a particular CCM are inclined to respond that it is not available. The structural engineer may be required to do a little product research and inform the contractor. Reaching out to structural engineers, or other professionals, that have

Table 3.2-2. CCMs in blended cements

	Slag (GGBFS) blends		**Pozzolan blends**	
Standard	**Designation**	**Description**	**Designation**	**Description**
ASTM C595 (U.S.)	Type IS (<70)*	Max. 70 % slag	Type IP(X)	X = specified amount, Max. 40 % pozz
ASTM C595 (U.S.)	Type IS (>70)*	Min. 70 % slag, Max. 95 % slag		
ASTM C1157 (U.S.)	Type IS (X)	Performance based, X = specified amount	Type IP(X)	Performance based, X = specified amount
EN 197/1 (Europe)	Type IIIA	Min. 36 % slag, Max. 65 % slag	Type IV B	Min. 36 %, Max. 65 % pozz.
EN 197/1 (Europe)	Type VA	Min. 18 %, Max. 30 % slag + pozz	Type VA	Min. 18 %, Max. 30 % pozz + slag

* Any percentage of slag less than 95 percent may be specified; these are shown because C 595 identifies different physical requirements for below and above 70 percent.

experience using the CCM in question is highly recommended. Specifications should allow flexibility in selection; limiting a project to only one or two binder materials, one brand, or one standard cement specification can result in project delays, increased costs, and it may not allow for the best use of CCM materials. Binder materials with special properties (such as silica fume or Type III portland cement) should not be required unless special characteristics are necessary. The project specifications should focus on the needs of the concrete structure and allow use of a variety of CCM materials to accomplish those needs. A typical specification may call for portland cements meeting ASTM C150-07 or ASTM C1157-08a, or for blended cements meeting ASTM C595-08a or ASTM C1157-08a.

CCMs are often used to improve a particular concrete property such as resistance to alkali-aggregate reactivity or reduce permeability. The optimum amount to use should be established by testing to determine the amount that achieves the desired concrete property. Due to mineral variations in cement, CCMs react differently with different brands of cements. Trial batching and testing for desired properties is recommended when there is no prior history of successful use.

Traditionally, fly ash, slag cement, and silica fume were used in concrete individually. Today, due to improved access to these materials, concrete producers can combine two or more of these materials to optimize concrete properties. Ternary mixtures using three binder materials are becoming more common. The optimum amounts of CCMs (using the project materials) can be determined by trial batching and testing to insure the mix meets the project requirements. Consideration should be given to the relative cost and availability of the materials and the environmental goals of the project. Table 3.2-3 lists the applicable specifications for fly ash, slag cement, and silica fume.

Table 3.2-3. Specifications and classes of complementary cementing materials

Ground granulated blast furnace slags: ASTM C989-09 *Standard Specification for Slag Cement for Use in Concrete and Mortars*	
Grade 80	Slags with a low activity index
Grade 100	Slags with a moderate activity index
Grade 120	Slags with a high activity index
Fly ash and natural pozzolans: ASTM C618-08a, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*	
Class N	Raw or calcinated natural pozzolans including: • Diatomaceous earths, tuffs and volcanic ashes or pumicites. • Calcinated clays, including metakaolin, and shales
Class F	Fly ash with pozzolanic properties
Class C	Fly ash with pozzolanic and cementitious properties
Silica fume: ASTM C1240-05, *Standard Specification for Silica Fume Used in Cementitious Mixtures*	
Rice husk ash: not standardized, see paragraph this section	
Ultrafines (reclaimed quartz, dolomite, or limestone): see ASTM C1240-05 for guidance	

Aggregates

Aggregate, combined as fine and coarse, makes up the bulk of concrete, measured either by weight or by volume. A typical concrete mix may have on the order of 1,360 kg of aggregate, 225 to 375 kg of cementitious material (cement plus CCMs) and 170 kg of water per 0.764 m^3. Quantities of each will vary with each concrete mix and intended use, and by geography, as the aggregate's properties vary with geography.

Aggregate gradation that includes a range of sizes so as to maximize particle packing and concurrently reduce space between aggregate particles will reduce cement and water volume requirements. Aggregate compressive strength exceeds that of cement mortar and it is the aggregates that make the largest contribution to concrete compressive strength. Well designed concrete mixes intended to achieve specified strengths, reduced permeability, and enhanced durability, will maximize aggregate volume and minimize cement and water content. Thus an understanding of aggregate gradation can contribute to sustainable design.

Recycled aggregates — The environmental attributes of concrete can be improved by using aggregates derived from industrial waste or using recycled concrete as aggregates. Blast furnace slag is a lightweight aggregate with a long history of use in the concrete industry.

Recycled concrete, or crushed waste concrete, is a feasible source of aggregates, particularly the coarse portion, and an economic reality where good aggregates are scarce. Conventional crushing equipment can be used, and new equipment has been developed to reduce noise and dust.

The Federal Highway Administration (FHWA) reports that eleven states use recycled concrete aggregate in new concrete. These states report that concrete with recycled aggregate performs equal to concrete with natural aggregates. When using the recycled concrete as aggregate, the following should be taken into consideration:

- Recycled concrete as aggregate will typically have higher absorption and lower specific gravity than natural aggregate and will produce concrete with slightly higher drying shrinkage and creep. These differences become greater with increasing amounts of recycled fine aggregates.
- Too high a percentage of recycled fines content can also produce a harsh and unworkable mixture. Many transportation departments have found that using 100 percent coarse recycled aggregate, but only about 10 percent to 20 percent recycled fines, works well. The remaining percentage of fines is natural sand (Obla et al. 2007).
- In crushing the concrete, it is difficult to control particle size distribution, meaning that the "aggregate" may fail to meet grading requirements of ASTM C33-08, *Standard Specification for Concrete Aggregates*.
- The chloride content of recycled aggregates is of concern if the material will be used in reinforced concrete. This is particularly an issue if the recycled concrete is from pavements in northern climates where road salt is freely spread in the winter. The alkali content and type of aggregate in the system is probably also unknown, and therefore if mixed with unsuitable materials, there is a risk of alkali-silica reaction.
- The durability of products with recycled content materials should be carefully researched during the design process to ensure comparable life cycle performance. There would obviously be a net negative impact if a product offering a 30 to 60 percent recycled content had only half the expected service life of a product with a lower or no recycled content.
- It is worth noting that recent research (Abbas et al 2008; Fathifazl et al 2009) has led to the development of a new mix design method, which accounts for the volumetric ratio and properties of the residual mortar and the natural aggregate particles in the recycled aggregates. The research included the testing of a large number of concrete and reinforced concrete specimens with and without recycled aggregates to investigate their material, mechanical, and durability properties. The new mix design method resulted in the production and performance of recycled-aggregate concrete that rivaled concrete made with fresh natural aggregates for structural application. The reader should keep in mind that this mix design method has not been adopted by commercial concrete batch plants, nor is there any history of use of concrete batched using this design method.

Considering all of the above, care should be exercised if recycled aggregate is to be used, particularly for structural purposes. It is recommended that mixes use only coarse recycled aggregate (no fines) and that recycled aggregate not exceed 30 percent of the coarse fraction by volume. Mixes should be qualified by trial batching per Chapter 5 of ACI 318-08 if mix properties have not been established by field testing. Recycled aggregate is not advisable for concrete intended to have low permeability, or where low shrinkage is desired.

Recycled glass is not currently recommended for use as a replacement for natural aggregate: glass consists primarily of silica, which may cause an alkali-silica reaction in the concrete. Meyer (2003) reports that grinding glass to at least mesh size #50 minimizes mortar expansion, as do certain compounds used to give glass color, and suggests that recycled glass has the greatest potential for use in architectural concrete products. At the time of this writing there is not sufficient research or field experience to recommend using recycled glass in either architectural or structural concrete.

Water

When considering sustainable design practices, structural engineers should be aware of options for recycling water.

Recycled wash water in concrete production — Re-use of ready mix waste water is a sustainable construction practice. Sources of waste water in concrete operations include water from truck drum wash out, water used in reclaiming sand and gravel from returned concrete, water used to control dust or wash down equipment during batch plant operations, and storm water run off from the batch plant. Waste water is typically collected in wash-out pits or mechanical reclaiming units at the batch plant where a variety of strategies, including reuse, are employed to dispose of the water (Chini and Mbwambo 1996). The Environmental Protection Agency regulates the disposal of concrete waste water, and disposal onto the open ground or into storm sewers is prohibited.

According to Robert Garbini, president of the National Ready Mix Association, "The peak production of ready mixed concrete hit 456 million cubic yards [349 m^3] in 2006, it will hit 650 million cubic yards [497 m^3] in 2030 (Faulkner 2008). Approximately 570 to 1,140 liters of water is required to clean out the drum of a 10-yard ready-mix truck (7.65 m^3) at the end of each day" (Master Builders Technology 1988). Assuming a 10-yard concrete truck can deliver 45 m^3 during the course of a day, an additional 841 to 1,682 billion liters of water are required annually to clean concrete trucks. Estimates of the amount of waste water from other sources are not available, but their inclusion can only add to the total estimated amount of waste water from concrete operations produced annually in the United States.

Waste water from concrete operations contains cement particles and dissolved solids including sulfates, hydroxides, and chlorides. The fine particles in waste water tend to reduce concrete slump. Compressive strengths can be slightly increased, decreased, or unchanged for a given mix, and permeability is decreased. Tests of mortars using wash water with ages varying from 15 minutes to 48 hours found that wash water 8 hours and less in age produced concrete with higher compressive strengths, suggesting that this is the result of un-hydrated cement particles in the wash water that become additive to the total cement content of the concrete mixture (Borger et al. 1994; Lelih et al. 2003; Sandrolinie and Franzoni 2001).

ASTM C1602-04, *Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete*, permits a concrete producer to qualify water for use in concrete through testing as follows:

- When compared to the same concrete made with potable water, concrete made with non-potable water must achieve 90 percent of the seven day compressive strength.
- Time of set must not be earlier than 1 hour or later than 1.5 hours.

ASTM C1602-04 includes an optional requirement that limits the amounts of sulfates, hydroxides, and chlorides as well as total solids in the recycled water. The Portland Cement Association recommends that total solids by mass in the concrete mix water not exceed 50,000 parts per million, consistent with ASTM C1602-04 (Portland Cement Association 2005). "Standards for Mixing Water Concrete," by the National Ready Mixed Concrete Association, provides more information on the specification.

In practice the specifying engineer can permit the use of reclaimed waste water from concrete operations in the production of fresh concrete. Recommendations include requiring the following:

- Conformance to ASTM C1602-04, including limits on water chemistry and solids noted above.
- Limiting the use of water reclaimed from concrete operations to 50 percent of the total water used in the concrete and requiring that a minimum of 50 percent of the mix water be potable.

Local materials

The use of local materials reduces the transportation required to ship heavy building materials and the associated energy and emissions. Cement, cementitious materials, and aggregates are voluminous and expensive to ship so local materials are generally used when available. However, domestic demand for cement continually outstrips supply. In 2006 the United States imported 24 percent of all cement used (USGS 2008). Most ready-mix plants are within 80 kilometers (50 miles) of a building site and most precast concrete plants are within 320 to 800 kilometers (200 to 500 miles) of a building site.

Construction

Material specific considerations for concrete include construction waste; several issues should be considered during construction for materials associated with concrete.

Waste and construction methods — In traditional concrete construction, concrete is ordered and placed in situ. After placement equipment is typically washed down on site. Many municipalities require proper disposal of wash water, thus it is often collected in basins where it evaporates, or is returned to the truck drum and returned to the ready mixed concrete plant for recycling. Left-over concrete is often returned to the ready-mix plant where it is recycled or used to make jersey barriers or retaining wall blocks. Additionally, it can be washed to recycle the coarse aggregate, in such cases retarding admixtures must be added to the return concrete to allow for transport and handling.

Concrete formwork — With the exception of foundations, which are often placed against earth excavations, poured concrete requires on-site formwork to give shape to individual concrete elements. Plywood and milled lumber are most commonly used for forms, and their disposal after removal of the forms creates a large amount of construction waste, as well as impacts on timber harvest and processing. Options to reduce such impacts include the following (Ecological Action 2008):

- Using steel or aluminum forms, which may be reused many more times than wood forms, reducing overall construction waste.
- Determine when precast systems can be used to reduce waste, including options such as insulating autoclaved aerated concrete (AAC panels).
- Permanent formwork such as steel deck and hybrid precast systems.
- Consider using construction-grade lumber and exterior-grade plywood for forms, which have higher durability and enable more reuse at the site.
- Specify lumber and plywood certified as harvested from sustainably managed forests. For smaller projects or those with wood demolition on site consider specifying reclaimed lumber and plywood.
- Use adjustable steel kickers for bracing of forms, which reduces damage to formwork and allows for more reuse.
- For foundation elements, use fabric-based form systems.
- Specify use of non-toxic form-release agents.
- Consider insulating concrete forms (ICFs), which eliminate formwork at the site and have increased thermal performance.

Form-release agents — The majority of concrete used in the United States is poured into formwork or molds. To remove the forms, a form-release agent is typically employed to facilitate the removal of forms. These are typically petroleum-based, low-viscosity oil, which is made available by most oil companies. Another common alternative is used engine oil or a mixture of diesel oil and used engine oil as a form-release agent. This alternative may be cheaper, but is also strongly discouraged due to the contents of the used oil. Sulfuric acid content can harm the forms and concrete, and used oil also may contain heavy metals and, in the case of industrial oil waste, toxins such as PCB, a permanent source of pollution. Conventional form-release agents are typically a high source of VOCs, and contaminate soils at the construction site.

There are low VOC form-release products available. These products have VOC levels ranging from zero to only a fraction of the federally permitted limit for concrete form-release agents. These non-petroleum, biodegradable form-release agents come from soy and other biologically-derived sources. They do not cost more than conventional agents, and are being made increasingly available. Health risks to construction staff and occupants are reduced with these new alternatives, and finishes and sealants are often easier to apply afterward (Malin 1997).

Concrete curing agents — Concrete curing agents are surface coatings or admixtures that aid the set and cure of freshly poured concrete. They generally use chemicals, referred to as combining agents, to retard evaporation while fresh concrete's high temperatures are present. Conventional products use a petroleum hydrocarbon resin base. More environmentally benign concrete curing agents now exist that are made with bio-based materials. These are low-solvent, low to zero VOC, water-based products. Simple tried-and-true alternative methods include using plastic sheeting, water saturated burlap, or mist spraying. These moist-curing methods can be low impact solutions.

Low-emitting — Concrete construction releases negligible VOCs when low-VOC materials for form release agents, curing compounds, damp-proofing materials, wall and floor coatings and primers, membranes, sealers, and water repellants are used.

Insulated concrete forms (ICFs) — ICFs are hollow "blocks" or "panels" made of expanded polystyrene insulation (EPS) or other insulating foam that construction crews stack into the shape of the walls of a building. The workers then fill the center with reinforced concrete to create the structure. There are over 20 brands of ICFs in North America, each with some variations in design and materials.

ICF construction sandwiches a heavy, high-strength material (reinforced concrete) between two layers of a light, highly insulated one (EPS or foam). This combination creates a wall with desirable properties: air tightness, strength, sound attenuation, insulation, and mass.

Demolition/Deconstruction

There are a few topics for structural engineers to consider in regard to demolition of concrete.

Design for deconstruction (DfAD) — Concrete, particularly cast-in-place, is a challenging structural material to design for adaptability and reuse. Reasons for the difficulty of deconstructing and modifying cast-in-place concrete include the following:

- Concrete structures are continuously whole with few if any joints between members. Removal of individual beams or columns becomes involved and the result is not a clean cut member for reuse.
- Members are heavy and difficult to move.

- Members are generally custom-designed for particular applications, making them unlikely to fit the needs of other projects.
- Contractors cannot see reinforcing bars from the exterior, so without as-built or original structural details it becomes difficult to evaluate a given portion of the structure for future adaptation and reuse elsewhere.
- The absence of tried-and-true fastening methods makes members hard to reuse.

While cast-in-place concrete presents major obstacles for DfAD, precast concrete offers some future promise for adaptability for reuse. This can be done if standardized shapes and reinforcement options become more common. Precast concrete panels and slabs can be reused in any application where the size of available, reusable, components is taken into consideration early on the design process. Many precast elements such as hollow-core plank and double-tees are already standardized. These parts can be joined with mechanical fasteners, both in the first-time use and afterward, so as to provide a means for clean disassembly. Current precise detailing conventions present difficulties because connections tend to be grouted or covered with cast-in-place concrete. Non-structural additions must also take disassembly into account. For example, a topping slab over precast floor panels would render mechanical connections ineffective when disassembly is attempted. In high seismic zones, reinforced topping slabs are used to provide continuity and ductility in diaphragms, as well as to make connections to shear walls. This effectively precludes disassembly of precast floor elements, and alternative details addressing seismic performance without topping slabs have not yet been developed.

Several strategies for enabling DfAD are listed below, refer to Section 2.4 — Design for Adaptability and Deconstruction for more information:

- Avoid cast-in-place concrete.
- Fasten precast parts with durable, removable, mechanical fasteners.
- Develop new methods for installing precast plank and tees without topping slabs.
- Indelibly label members with concrete strength, reinforcement details, and other important properties, to allow future engineers to evaluate whether a given member can be applied in a new structure.
- Consider avoiding deep foundations and using precast concrete to construct basements where possible, since deep footings and monolithic concrete foundation walls are likely not salvageable.

Options for recycling: Demolition and disposal of concrete reinforcement — Essentially all domestic producers of steel reinforcing bars use 98 to100 percent recycled steel. This percentage is typical of the electric arc furnaces used to manufacture heavy structural steel. Steel reinforced concrete is demolished using the common practice of magnetic separation, which allows for almost 100 percent of steel from old concrete structures to be recycled or used in the production of new steel. When used, fiber-reinforced polymer (FRP) reinforced concrete cannot be easily separated during demolition and all FRP bars are sent to landfill. Because dividing the concrete and FRP is difficult, the amount of quality concrete aggregates obtained is significantly reduced as well. The environmental load at the disposal stage of FRP reinforced concrete is higher than the load from standard steel reinforced concrete. However, despite the inability to recycle or reuse FRP reinforcing, the overall environmental load of FRP from cradle to grave may not necessarily be higher than its steel counterpart. This is essentially because of reduced maintenance required during the lifetime of the concrete related to steel corrosion, and a reduction in embodied energy by replacing steel content.

Implementation techniques

There are several material-specific implementation techniques for structural engineers to consider for sustainability for concrete including construction, building synergies and durability:

Sustainable concrete construction

Many techniques have been developed to achieve a higher level of sustainability in concrete construction.

Portland cement content — Reducing portland cement content in the mix design should be the first technique to designing for sustainability. Mix designs can be optimized to reduce portland cement by maximizing aggregate content and minimizing water content, and by replacing cement with CCMs. Often times the best mix design for a given use is not the design that contains the most cement. Please refer to Engineering Solutions, above, for a more in-depth discussion of mix design and reducing cement content.

Concrete as finish — Covering concrete with cosmetic layers can increase environmental and financial costs over the lifespan of a structure. Consider the following instead:

- Leave concrete exposed and using it as a finish material.
- For color, consider relatively benign concrete stains, which are often less expensive than embedded colorants or acid stains. For example, the common plant fertilizer iron sulfate (also called ferrous sulfate), can create tones ranging from yellow to rusted umber. Leftover ferrous sulfate is a useful soil amendment. However, embedded color is the most durable finish option, reducing long-term waste and maintenance.
- Stamping slabs can add a variety of textures to concrete finishes. Inlayed materials such as pebbles can add additional color and texture.

Concrete reinforcing — One way to reduce the amount of steel material required in concrete structures is by using higher grade reinforcing steel rather than Grade 60 (60 ksi, 400 MPa) reinforcing steel. High-strength steels (HSS) having desirable formability and tensile yield strengths ranging from 500 to 800 MPa (73 - 116 ksi) are emerging more into the commercial market as manufacturing techniques become more commonplace in practice. This steel has been successfully used in high rise construction in high seismic zones, where seismic design requires closely spaced column and beam ties, the steel's higher strength permits greater tie spacing. As of press time, one domestic manufacturer, MMFX, produces 690 MPa (100 ksi) steel in the form of concrete reinforcement bars ranging in size from #3 to #14.

While HSS can reduce the amount of steel in a structure, its use will not address considerations of stiffness and deflection, which are principally determined by element geometry. Where stiffness and deflection govern design considerations, concrete volume will not be reduced by the use of HSS.

There are applications where reinforcement is not required, such as at sidewalks and residential driveways. In such cases slabs should be of the appropriate thickness for the anticipated loads, and appropriately jointed to control crack location.

Schematic planning — When beginning a project, a little planning goes a long way. Consider the following:

- Avoid upturned beams where possible. Buildings with upturned beams lack flexibility in the interior layout. Even if a change of use is not foreseeable, a building that does not cater to occupants' needs will inevitably depreciate in value and runs the risk of being replaced far before the lifetime of the building runs its full course.
- Layouts with no beams (flat plate) – these give lots of flexibility in layout as services can easily be re-routed, if layouts change there are not beams going through the centre of rooms etc.
- If DfAD is possible, use typical-size precast members and avoid permanent connections.
- Sequence construction work to accommodate high volume SCMs cure rates.

Precast concrete — Precast concrete elements are usually efficiently shipped because of their large, often repetitive sizes and the ability for the fabricator and contractor to plan their shipment during the normal course of the project. Efficient shipping practices reduce the energy and emissions associated with trucks or barges. Construction incorporating precast concrete has many inherent benefits, including:

- Less material is required because precise mixture proportions and tighter tolerances are achievable;
- Insulation can be placed within the precast concrete sandwich panel walls during its manufacture;
- Less concrete is wasted because of tight control of material quantities;
- Waste materials are more likely to be recycled because concrete production is in one location; in fact, gray water is often recycled into future mixtures, hardened concrete is recycled (about 5 percent to 20 percent of aggregate in precast concrete can be obtained from crushed recycled concrete), sand and acids for finishing surfaces are reused, and steel forms and other materials are reused;
- Less dust and waste is created at the construction site; there is no debris from old wood formwork and associated fasteners;
- Fewer trucks are required for precast construction; this is particularly beneficial in urban areas where minimal traffic disruption is critical and congestion can mean trucks spend more time idling; and
- Precast units can be designed for future deconstruction.

Synergies with building systems other than structural

Innovative practices exist for increasing sustainability for the entire project while specifying concrete.

Pervious concrete — Pervious concrete has a 15 to 25 percent void structure, allowing for 118 to 323 liters of water per minute to pass through each square meter. By allowing rainwater to seep into the ground, pervious concrete is instrumental in recharging groundwater, reducing storm water runoff, and meeting U.S. Environmental Protection Agency (EPA) storm water regulations. This paving technology creates more efficient land use by eliminating the need for retention ponds, swales, and other storm water management devices. Pervious pavement integrates hardscape surfaces with storm water management.

Pervious concrete is made from controlled amounts of water and binder materials to make a paste that forms a thick coating around aggregate particles. The mixture contains little or no sand, creating the substantial void content noted above. Using sufficient paste to coat and bind the aggregate particles together, on the order of 712 kg of binder material per cubic meter of permeable concrete, creates a system of highly permeable, interconnected voids that drains quickly. Up to 25 percent fly ash, and 50 percent slag can be substituted for cement, though slag content should be reduced to 30 percent where ambient temperatures fall below 10°C. The high porosity reduces strength compared to conventional concrete, but sufficient strength is readily achieved for many applications.

The advantages of pervious concrete include the following:

- Integrated paving and drainage;
- Reduced storm water runoff;
- Reduced pollutants from storm water runoff;
- Reduced heat island effect; and
- Recycled content, by using a partial replacement of fly ash or slag cement for portland cement, as can be done with most other concrete.

The properties of pervious concrete vary with design and depend on the materials used and the compaction procedures. The following are general guidelines:

Permeability: Typical flow rates for water through pervious concrete are 118 to 323 liters per square meter per minute, but can be double that amount.

Compressive strength: Pervious concretes can develop compressive strengths in the range of 4 to 27.5 MPa, which is suitable for a wide range of applications.

Flexural strength: Flexural strength of pervious concrete ranges between 1 and 3.8 MPa.

Shrinkage: Drying shrinkage of pervious concrete develops sooner but is much less than conventional concrete. Many pervious concretes are made without control joints and are allowed to crack randomly.

Freeze-thaw resistance: Freeze-thaw resistance depends on the saturation level of the voids in the concrete at the time of freezing. In the field, it appears that the rapid draining characteristics of pervious concrete prevent saturation from occurring. Where substantial moisture and freeze-thaw conditions are anticipated, pervious concrete should be placed on a 150 to 450-mm-thick (6 to 18-inch-thick) layer of drainable rock base such as 1-inch crushed stone.

Abrasion resistance: Because of the rougher surface texture and open structure of pervious concrete, abrasion and raveling of aggregate particles can be a problem, particularly where snowplows are used to clear pavements. Surface raveling in new pervious concrete can occur when rocks loosely bound to the surface pop out under traffic loads. This raveling is reduced considerably after the first few weeks.

Maintenance: Permeable concrete surfaces can clog over time with fines and/or landscape and other debris, requiring scheduled vacuuming to unclog.

Concrete in use: Durability and maintenance

The number one cause of deterioration of concrete is corrosion of reinforcement. Corrosion results in rust-jacking, which can cause large portions of concrete to spall off. However the corrosion of reinforcement is really just a symptom of concrete that is cracked or permeable. To improve the protection of reinforcement in exterior concrete elements, consider the following:

- Adding above code required cover concrete;
- Avoiding protruding and post-installed metallic elements other than stainless steel; and
- Reducing the permeability of the mix design and lowering the heat of hydration to reduce thermal cracking. For tips on improving the durability of concrete through proper mix design, please refer to Engineering Solutions above.

When properly detailed and maintained, concrete exterior walls provide a long service life. Yearly maintenance should include inspection and, if necessary, repair of joint material. Exposed finish concrete can be protected by using low- or no-VOC cleaners, waterproofing admixtures and sealants.

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3.3

MASONRY

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Masonry is one of the oldest and most common building systems, comprised of pre-formed units, usually of standardized sizes, that are stacked and bonded with mortar by hand. The predominant structural units used are concrete masonry (CMU), clay masonry (brick), and aerated autoclaved concrete (AAC), and are the focus of this Section. Although many other types of masonry products, systems, and construction practices are used based on regional availability and project demand, they are not individually discussed here as a result of their current lack of widespread use as a structural elements. However, the practices and considerations discussed in this Section and the Guide are applicable to their employment.

Examples of other masonry units include:

- Indigenous systems including adobe, rammed earth, cobb, stone, and straw bale which are addressed in Section 3.7 — Natural Building Materials;
- Products using recycled materials, such as Integrity Block or Redi-Maxi-Max cement products; or use alternative materials, such as Lakewood Brick and Tile hemp-based masonry;
- Veneer systems such as natural stone.

CMU — CMU systems are used for walls, either load bearing or non-load bearing, and can act either as stand-alone walls, or backup for a veneer system. They are also frequently used for foundation walls, retaining walls and other site structures. CMU construction is economical, energy efficient, fire-resistant, and involves minimal maintenance. The most common concrete masonry unit is a rectangular 8x8x16-inch nominal size comprised mainly of portland cement or other cementitious materials, coarse and fine aggregate, and water. Like concrete, the mix may also contain admixtures such as air-entraining agents, coloring pigment, and water repellent. During the manufacturing process, a machine molds moist, low-slump concrete into the desired shapes. These blocks then undergo an accelerated curing process at elevated temperatures inside a special chamber. This is generally followed by a storage or drying phase. The component materials are common to concrete, so more detailed information on the material properties can be found in Section 3.2 — Concrete.

Brick — In modern applications, brick masonry is most often made of clay or other ceramic material and is found as a wall veneer. Bricks are not as commonly used in load bearing applications compared to CMU because they require a more labor-intensive process given their smaller 4x4x8 inch common nominal unit size. However, older structures frequently employed brick masonry as a load bearing element. The performance of structural renovations involving brick masonry must be carefully considered with regard to compatibility with the original materials. This includes such measures as specifying original lime-based mortar for patching and re-pointing to avoid stress concentrations engendered by more rigid cements.

AAC — A relative newcomer to masonry in the US, AAC is a somewhat more "high-tech" structural material, with a number of different applications due to its workability Typical uses include plank applied as floor and wall units, and block laid up vertically, in a similar manner to more traditional masonry. AAC is comprised of thousands of homogeneous and totally independent air cells that provide its superior thermal insulation and fire resistance, which can only be achieved in traditional systems through the combination of different materials or the exaggerated thickness of more conventional materials. Besides insulating capability, one of AAC's advantages in construction is its quick and easy installation since the material can be routed, sanded, and cut to size on site with hand tools. AAC is produced from five raw materials: silica sand, lime, cement, gypsum, and water, combined with an expansive agent of aluminum powder (in 5 to 8 percent in volume), which make a product having desirable structural properties such as strength, lightness, thermal insulation, and fire resistance.

To produce AAC, the sand, quartz, lime, and cement are blended and mixed with water and the expansive agent, then cast in molds. The expansive agent reacts with the elements, creating the bubbles and causing the expansion. If reinforcing in the AAC is required, for example in planks, the rebar cages are coated with an anticorrosive before casting. Next, during the pre-curing process, the product reaches the required consistency to be manipulated and cut. At this point, the resulting semi-row block are machine-cut (using a steel-wire saw) to form the different AAC products. Final phase is the curing of the material in autoclaves at controlled temperature, moisture, and pressure conditions. AAC products are cured for 12-hours and are packed and transported to the finished products warehouse.

Environmental impact

Masonry components impact the environment in ways that are similar to concrete.

Sustainability considerations

Primary sustainability considerations are similar in many respects to those for concrete. Largely mineral-based, all masonry systems and components rely on excavation, which include impacts such as mining of aggregate, erosion, and habitat loss. Additionally, masonry products (CMU, mortar, and grout) typically contain portland cement. As discussed in Section 3.2 – Concrete, the production of portland cement is an energy-intensive process, as well as one of the greatest producers of carbon dioxide (CO_2). However, like most manufacturing processes, it has potential for manufacturing efficiencies such as waste water reuse and use of recycled materials. The use of clay based bricks and lime based mortars may lower the overall CO_2 footprint. Also, the use on masonry as the wall veneer is a significant parameter in the envelope's energy equation.

Transportation — Impacts of transportation are discussed in Section 2.2 — Local Sourcing and Local Manufacturing. Although masonry block is typically produced locally in small manufacturing plants, this varies greatly, and depending on the specialty block, it can require significant transportation. Quite often, masonry is manufactured in close proximity to metropolitan areas, although this is more common with CMU than with brick. AAC manufacture is limited to a few locations in North America; however its lighter weight may reduce transportation-related energy use when compared to hauling heavier materials that may be closer to the project site.

Stormwater — Pervious paving units are frequently used to reducing impervious surface, and can be part of a strategy to reduce stormwater volume from a site.

Durability — Long lifecycle, resistance to weathering, reduced maintenance, bricks and other masonry systems generally do not require outside painting but may require re-pointing over the long term. CMU and AAC are usually specified to have additional parged coatings when used as an exterior, exposed surface.

Recyclability — Masonry is frequently crushed and used as aggregate for a sub-base or backfill. Steel joint and wall reinforcing, as well as veneer wall ties can be recycled.

Reuse — Maybe disassembled, and with higher-value unit such as brick, are commonly resold for use, albeit, subject to usual concerns about material consistency in structural applications. See Section 2.4 — Design for Deconstruction and Adaptability for more details.

Refining and manufacture

Basic raw materials are naturally occurring, abundant, and require relatively little refinement or processing. However, environmental impacts of the methods used to obtain these can vary greatly by locale and material manufacturing of portland cement has high energy-use and the CO_2 impacts well documented (see Section 3.2 — Concrete for more details). Alternatives include Portland cement replacement strategies similar to those for concrete, such as using fly ash or slag. Few CMU block manufacturers are currently employing these techniques, and if they are, they may not be advertising them. Engineers are encourages to work with a contractor and a block manufacturer to ensure recycled content if specified.

Mortar is more commonly available with cementitious (pozzolanic) materials as Portland cement replacement. Similarly, grout can be manufactured with cementitious options.

It is possible to use aggregates from other sources, but this practice is uncommon in structural applications. However, manufacturers can be found advertising the recycled content in a product that meets ASTM C90 (2009) standard for CMU. One example, Emco's Versalite (www.emcoblock.com/assets/versalite-spec.pdf) is manufactured with a minimum of 35% "agglomerated fly ash."

Proprietary CMU block that are manufactured with sustainable properties are becoming more common. , but their expense and/or the project team's lack of experience and the product's lack of satisfactory long term performance are limiting their application.

Other topics to consider of the manufacturing practices include energy reclamation, water reclamation, conservation, changes in manufacturing efficiencies (materials and energy), low chemical content (non-toxic), and choice of fuel sources.

Engineering solutions

Structural engineers can affect how masonry components are used on a project and how the material contributes to sustainable design goals.

Construction and design (material specific considerations)

The following lists many benefits of masonry for construction on a project:

- Inherent to masonry are the smaller, modular units which are likely to reduce construction waste. However, design and detailing at connections, interfaces with adjoining structure (e.g., columns) requires forethought to avoid waste due to excessive cutting. However, this can be considered normal economical design.
- Specifying material component strengths based on structural demand. For example, on interior walls, mortars requiring higher cement contents for durability on an exterior wall may not be needed. Or, when grouted cells or wythes are required for "holding" flexural reinforcing only, cement percentages may be reduced.
- Reinforcing is often required for seismic requirements or system strength and can greatly increase the masonry overall system and localized strength capacity. The use of tie beams and tie columns is both traditional and streamline connections that might otherwise require additional structural materials or obviate masonry as a material (Fig. 3.3-1). Although more predominant in CMU buildings, tie elements can be used in brick construction as well, with a grouted, reinforced cavity between wythes to achieve continuities. In AAC walls, the tie elements can create the require ductility by surrounding vertically unreinforced panels, in lieu of costly coring for reinforcement.
- Sealants, finishes are frequently VOC contributors, but they can be specified to avoid this, as discussed in Section 3.2 — Concrete.
- Material-handling is relatively minimal low impact; units are normally delivered by truck and distributed by small lifts. The units and mortar is typically mixed by hand or machine in small batches. Grouting is placed by hand or small line pumps.
- Some of the uses advertised by the Portland Cement Association for masonry are: Mitigation of the urban heat island effect through use of light color pavers or grass-pavers. If employed as part of a properly designed thermal-mass system, they can be used to store thermal energy.

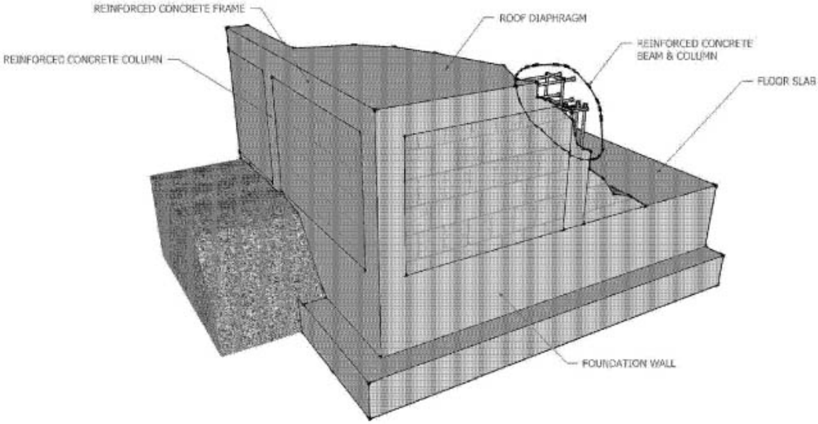

Figure 3.3-1. Unreinforced masonry system with concrete frame (Robert Silman Associates, 2009)

In use

The following lists many benefits of masonry when used on a project:

- It is possible to reduce finishes both interior and exterior due to the durable, maintainable surface of masonry, as well as its many aesthetic options.
- Thermal comfort is a beneficial property of masonry. Concrete masonry has high thermal mass and specific heat; additionally, it provides very effective thermal storage as well as enhancing, acoustics, air quality, and fire resistive properties.
- Small units enable its use in compact urban spaces with limited space for staging areas.
- Improvement to indoor air quality due to the reduced potential for mold growth (concrete masonry does not provide a food source for mold) and ease of cleaning should mold growth occur.
- Masonry walls remain warm or cool long after the applied heat or cooling is no longer applied. This, in turn, can effectively: reduce heating and cooling loads; improve occupant comfort by moderating indoor temperature swings; and shift peak heating and cooling loads to off-peak hours.
- The reflective properties of concrete pavers may allow designers to reduce energy requirements for lighting in parking areas.
- Masonry is an exceptionally durable material, with low maintenance requirements and a life cycle measurably longer than many other building envelope products.
- Adaptability: Masonry construction provides the opportunity to refurbish the building should the building use or function change, rather than tear down and start anew. Masonry also resists weathering and vandalism. The durability and minimum maintenance extend a building's useful life, providing an enduring, high-quality appearance.

- AAC has insulative properties; CMU can incorporate insulation as can CMU/brick veneer systems. Other proprietary masonry systems have insulative properties, as well.

Demolition and deconstruction

When using masonry on a project consider the longevity of the material. If considering design for deconstruction techniques, the use of Portland cement in mortar for bricks often reduces the ability to disassemble economically. Unfortunately, mortars that do not contain Portland cement may not provide the strength required for veneer applications prevalent in the commercial application of brick. If you are considering options for reuse, the following are some developed best practices.

Concrete masonry can be disassembled for reuse, and in unreinforced masonry structures, this may be feasible, however the low value of the units typically does not make this a market-driven choice. Furthermore, grouting and reinforcing common in concrete masonry makes this even less feasible. First, the Portland cement based mortars are often stronger than the base unit, especially when it is partially or fully grouted or if it is reinforced with vertical steel. (Webster and Costello 2005)

Brick is more frequently disassembled for reuse. Local market prices for aged brick masonry is often high enough to make it cost effective to engage the labor required to remove the traditional lime-based mortars which remain after disassembly. However, if portland cement based mortar strength of modern portland cement based mortars is often great enough that the brick unit will be damaged during its removal. (Webster and Costello 2005)

CMU can be recycled into aggregate for road bases or other concrete products, pipe bedding, or construction fill. This occurs when buildings with concrete masonry are demolished or — in new construction — when saw-cut scraps and broken pieces of concrete masonry are crushed and reused. In addition, intact and unused concrete masonry units can be redirected to other projects or donated to charitable organizations such as Habitat for Humanity

If disposed of as waste, the units are inert and are often crushed and used as fill. Problems arise when bonded with insulation, gypsum board, or lead paint.

Implementation techniques

There are several material-specific implementation techniques for sustainability for structural engineers to consider for masonry design and construction.

Specifications — Strategic use of a project's specification can enable sustainable use of masonry. The reduction of CO_2 intensive materials, again primarily portland cement contents can be effective for LCA reductions. Researching and specifying recycled contents in locally available masonry products, as well masonry wall accessories, such as steel reinforcing or ties.

Techniques to achieve sustainability — Careful use of admixtures, non-potable water, recycled aggregates, AAC, insulation in block voids, or full building integrated design can lead to more sustainable designs.

Synergies — Some masonry products can be incorporated in a Trombe Wall. This wall design involves careful coordination with mechanical systems and architecture to achieve a system which stores heat from the sun accumulated during the day, and releases it at night to reduce load on mechanical systems. The mass of masonry, similar to concrete, can be used to its benefit as a storage device.

Code considerations — Areas requiring special consideration could include AAC; design of which is in the latest ACI 530/530.1-08, *Building Code Requirements and Specification for Masonry Structures and Related Commentaries*, (ACI Committee 530 2008), indicating, perhaps, increased acceptance.

Metrics systems — LEED credits can potentially include recycled content, local sourcing, permeable surface pavers, and high reflectivity with light colored pavers.

State of the art / industry research / knowledge base — Several organizations and individuals are working to advance the state of the art for masonry including the Portland Cement Association (PCA), The National Concrete Masonry Association (NCMA), and the Slag Cement Association.

Conclusion

Use of masonry products can offer many environmentally "green" attributes and opportunities to contribute to environmental benefits. The use of masonry building products can increase the thermal mass of a building, giving increased comfort in the heat of summer and the cold of winter and can be ideal for passive solar applications. In addition most of these systems will not require painting and so can provide a structure with reduced life-cycle costs when properly detailed and constructed. In addition, each of the component parts of masonry: cementitious mixes, aggregates, water, reinforcing bars, and admixtures, has approaches which can increase their sustainability.

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3.4

STEEL

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Steel has long been utilized in building construction in the United States. The steel used in construction consists of many different types of end products that are produced using different production technologies. The two major processes for producing steel are the integrated basic oxygen furnace (BOF) and the electric arc furnace (EAF). BOF and EAF technology differ in feedstock material, energy consumption, and environmental impacts. To understand this difference it is necessary to step back and review the historic developments surrounding the production of steel.

The United States has historically been one of the largest steel producers in the world with approximately 13 percent of total world steel production. Structural steel represents about 15 percent of the total production and consumption of domestic steel (DOE 2000). Steel production has changed considerably over the past 50 years from the large integrated steel mills of the past to the smaller mini-mills of today. Due to large demands for high-quality steel in the 1950s and 1960s and the limited flexibility of large integrated steel mills that take iron ore from start to finish, the industry started to shift from the BOF to the EAF process.

The steps in the BOF steel-making process consist of coke-making, iron-making, and steel-making. *Coke-making* is the process of cooking coal in order to drive off volatile impurities that would interfere with the subsequent iron-reduction step. The coke lumps that form during this process help maintain the proper conditions for the iron-reduction steps.

Iron-making, the next step, reduces the metallic iron from the oxide. Oxygen is transferred to carbon supplied by the coke. The resulting product is commonly referred to as pig iron. This process is carried out in a blast furnace with extremely high temperatures. The furnace must be operated in a continuous mode because it is very wasteful to allow the system to cool and then have to reheat it. The design of the blast-furnace process dictates certain environmental impacts that are difficult to avoid. The furnace itself is a large source of carbon monoxide that can leak from the furnace at various openings. The furnaces also generate large quantities of slag, a waste product composed of impurities that are skimmed off the surface of the molten metal.

Steel-making is the last stage of refinement that reduces the amount of carbon and other impurities. In this step of the process, various alloying elements are added to give the finished material the combination of properties desired.

During the energy crisis of the 1970s, the BOF mills increased thermal efficiency through the use of continuous casting methods. Keeping blast furnaces continually fed with iron ore, heat is used more efficiently. Environmental concerns grew in importance in the 1980s and 1990s, bringing more robust environmental regulations. During this period competition increased, including from foreign steel production plants. As a result, just-in-time technology became more prominent and integrated steel plants were being replaced by smaller plants, called mini-mills. These facilities utilize EAF technology and rely on steel scrap as a base material rather than ore.

Comparison of BOF and EAF processes —The BOF process uses coke, iron ore, and roughly 25 percent steel scrap, while the EAF process relies on electricity and incorporates approximately 95 percent recycled steel scrap. Structural steel products consisting of hot-rolled sections (WF, H piles, angles, and channels) and rebar are produced in EAF furnaces. HSS sections and decking are produced using either EAF or BOF processes.

As with all metals, the key environmental trait of steel is its recyclability. The material can be recycled over and over, and as it is recycled the physical properties of the material are maintained, and often improve. Recycling has become a required part of modern steelmaking. In fact, because nearly all steel products are manufactured with some percentage of recycled content, finding products manufactured entirely from virgin ore is rare in today's market.

Steel production supply chain

Currently, the supply chain for structural steel is a closed-loop production cycle allowing the discussion of its production cycle to start at any point along the chain of its use. Most often though, it is best to begin with what many life-cycle analysis programs use as the starting point for today's steel — the scrap collector.

Found in every state, scrap collectors have a vested interest in your car, your refrigerator, your steel office building and your steel cans. Scrap steel has a high value as a commodity, and because of this, an entire network of collection and processing facilities has been developed to capitalize on this value. Recycled scrap is the main ingredient and the commodity that most significantly influences the price of the structural steel. A general rule of thumb is that a ton of scrap purchased from a scrap vendor is worth about 10 to 20 percent of the value of a ton of milled and fabricated structural steel.

The vocabulary of steel recyclers is somewhat different than that which a structural engineer or architect may be accustomed. Keep in mind that scrap dealers tend to look at the world as one big farm for future recycling, where even the Golden Gate Bridge is a crop that they someday plan to harvest. The steel producer will speak of recycled steel in terms of "home scrap" or "prompt scrap". Home scrap refers to steel that is produced in the mill, but for one reason or another does not make it into the final steel product that is sold to a fabricator, such as the ends of members cut off for length. Prompt scrap refers to material that is purchased from a scrap vendor by a mill, and is used in the production of new steel. It is promptly available for purchase. Some scrap vendors break this distinction down further and distinguish between prompt scrap that is the result of construction processes, and obsolete scrap that has been reclaimed from the end of life of another product, such as a car.

From the scrap dealer, the scrap is sent to a local steel mill. Generally, steel mills collect scrap from within about a 300-mile radius of their location, as this reduces transportation costs. It is important for structural engineers to understand that while wide-flange steel beams are only produced domestically in a few locations (currently Indiana, Texas, Virginia, and Arkansas for larger shapes, with additional producers in South Carolina and Georgia that are limited to producing smaller wide flange shapes) various other steel products are produced in more locations around the United States. Since all of these operations rely on scrap, recyclers tend to feed their supply to the mill that is closest to them. Some mills have existing contacts with scrap vendors that supply the majority of their scrap. Upon request, most mills will supply a designer with documentation indicating the origin of their steel scrap. In some cases this can be tailored to the project site, and for a given project, mills can cite how much of their scrap came within a certain distance of a project site. Readers may refer to the AISC shapes availability tool for more information on where steel shapes of various sizes are produced.

At an EAF mill, the steel scrap is melted in an electric furnace and small amounts of other chemicals are added to the molten scrap to create the proper metallurgical makeup for the appropriate chemical and structural properties. The steel is then cast continuously into blanks and billets from which the products will be produced. Hot rolled structural shapes are produced by passing these beam blanks back and forth through a series of rollers until the beam reaches the proper dimensions.

Depending on the size of the order, the steel is either shipped directly from the mill to a steel fabricator, or is shipped to a service center, which is essentially a warehouse for steel members. Service centers are typically located near structural mills, and at times are located on adjacent properties. Service centers allow fabricators to purchase steel on a piece-by-piece basis, to fill their orders.

Once the steel members arrive at the fabricator, they are cut, drilled, punched, and prepared for construction. In so far as is possible, connections are made to the members, and pieces are bundled and then sequenced for delivery to the site to make erection at the site as simple as possible. After the steel is installed, and if properly enclosed, the building or other structure can stand for hundreds of years, as in most cases the steel members, unless part of a bridge system, will not be subjected to any significant fatigue stresses.

Environmental impacts

The impact that steel has on the environment will be discusses as it relates to greenhouse gases, recycling, foreign steel producers, and construction waste.

Greenhouse gases and wastes

The primary environmental impacts of the steel industry are air emissions, greenhouse gas emissions, wastewater, and solid wastes.

Every stage of the steel-making process has air emissions issues, but coke-making and blast furnace operations impact air quality most heavily. Blast furnace operations generate large quantities of sulfur, nitrogen oxides, and carbon monoxide. Casting and rolling processes that are downstream events of steel-making can release significant quantities of sulfur oxides as they are liberated from the surface. The environmental impact of the BOF comes mostly from the carbon monoxide that escapes the melt and the particulates that are generated. Current regulations for air quality in the United States result in most of the air emissions being bag-housed and particulates removed; the solid wastes are sold to secondary markets.

As described above, the EAF process used by mini-mills skips the coke-making and iron-making steps; consequently, EAF mills produce fewer emissions than mills using the BOF process. However, EAF is not without environmental impacts of its own. EAF uses electricity as the major heat source. It is cleaner at the point of use, but converting heat energy into electricity only to turn it back to heat is inefficient. For every calorie of energy consumed by the electrodes in the EAF, about three calories of heat are expended at the power generator. If the heat comes from fossil fuels, the greenhouse gas impact from the EAF is correspondingly three times greater than the impact from furnaces burning carbon directly (NCMS 2004).

Greenhouse gas emissions from a number of energy-intensive sectors have been calculated by the National Center for Manufacturing Sciences (NCMS) based on 1998 fuel consumption data. According to the Greenhouse Gas Estimates for Selected Industry Sectors, the steel sector is one of the most significant contributors to greenhouse gas emissions of all industry sectors. The U.S. Steel Industry has reduced its energy intensity per ton of steel by approximately 33 percent since 1990. This is based on blended values or industry average for both EAF and BOF processes combined.

In addition, approximately 75,000 gallons of water are needed to produce a ton of steel. Most of this water is used for cooling and for wet scrubbers used for pollution control. However, this figure includes recycled and reused process and cooling water. With high-rate recycling, typical steel-making "fresh" water requirements range between 13,000 and 23,000 gallons per ton of product through all stages of production (Ellis et al. undated). EAF facilities typically use closed loop systems to remove water discharge and reduce water consumption.

The iron and steel sector generates tens of millions of tons of solid wastes and residues annually — 39 million tons in 1997 (NCMS 2004). Blast furnace slag was the single largest contributor to this waste with 13 million tons. The volume of wastes generated is much more of an issue than the hazard they represent. Most of the waste produced in the steel sector is relatively benign. The majority of slag is used as roadbed material or processed as a substitute for cement; see Section 3.2 – Concrete for a discussion of the use of slag in concrete.

Resource utilization

The recycled content of steel varies, depending on the process by which it is produced. Likewise, the process used for production varies, depending on the type of steel product being produced. Products made by EAF mills include all wide-flange shapes, channels, angles, and rebar. Other products such as some HSS members, plate, deck, and cold-formed steel framing products are produced in both EAF and

BOF mills. Products manufactured in an EAF process have, at a minimum, approximately 57 percent post-consumer recycled content and 33 percent post-industrial recycled content. BOF products have a minimum of approximately 24 percent post-consumer recycled content and 12 percent post-industrial recycled content. The percentages of recycled content are determined annually by the Steel Recycling Institute on an industry-wide basis. For updated information on levels of recycled content, refer to the Steel Recycling Institute website, www.recycle-steel.org. The U.S. Green Building Council requires the project team to submit the actual recycled content of the steel used in the project if it wants credit for more than the default value of 25 percent post-consumer.

Many designers are tempted to specify steel with the highest attainable level of recycled content in order to maximize the credit they can get in a LEED project or other green certification. While steel always has a certain level of recycled content, and specifying steel over non-recycled materials has a positive environmental effect. However, shopping around for the highest percentage of recycled content can potentially have an adverse effect on the environment, because all of the scrap available for consumption in the United States is already consumed. For instance, if a project is located in Flint, Michigan, and a designer finds that steel from Indiana has 90 percent recycled content, while steel from Texas has 97 percent recycled content, it is actually more environmentally responsible to specify the lower recycled content material from the closest available steel source. If the mill in Indiana were to ship in additional scrap material to raise their level of recycled content, this would only add to the impact of shipping materials and would lower the recycled content of the material produced by the mill in Texas.

Economy of recycling

Because of steel's value, a large recycling market has emerged. Nearly all steel beams get recycled at the end of their useful lives because of their high inherent value. This recycling market is important because it has generated an economically sustainable model to reclaim the material. However, this directly hinders the economic benefits of reusing salvaged steel beams on future project applications.

Foreign steel

Certain grades of steel, such as ASTM A913 (2007) Grade 65 steel, are not produced domestically. In this case, the steel must be imported from other countries, and the impact of the import operation increases the material's environmental footprint. When a certain grade of steel is not available domestically, the designer must weigh the environmental impact of importing the material against the savings of material on the project in order to determine the appropriateness of the design decision.

About one-fifth to one-quarter of all steel used annually in the United States is used in construction. Global steel production in 2005 was up 6.1 percent over the year before, sustained by China where production increased by 25.5 percent and India which increased by 16.6 percent. In the United States, the steel industry has been reducing pollutants and greenhouse gases through regulations and voluntary programs. If a structural engineer is designing a steel project, they should consider the impacts of specifying steel products only available from foreign sources. In developing countries, environmental regulations may not be as restrictive as in the United States.

Construction waste management

With respect to structural steel and construction waste management, there are a few factors to consider. First, structural steel is fabricated offsite, so there is little to no waste created onsite. This cuts down on the waste produced, reduces the cost of tipping fees for the project, and helps to reduce site disturbance in the erection of the structural frame. Additionally, any waste that is produced on site or at the fabrication shop has value, and there is a large incentive for the contractor or fabricator to collect this material and sell it to a scrap dealer. Thus, when constructing a steel frame, there is no appreciable amount of waste steel produced. Additionally, the use of controlled offsite fabrication processes allows the frame to be erected with a minimal amount of associated labor, so the transportation impacts associated with the travel of labor for the construction of the steel frame is low.

Engineering solutions

The primary considerations when using steel as a sustainable product are its recycled content, its high strength-to-weight ratio, the proximity of the material to the project site, off-site fabrication (and its impact on reducing both on-site and off-site waste), and its ability to be designed for deconstruction and reusability of members

Design for deconstruction and strategies for reuse

Design for deconstruction is an approach to design that is not new, but has become more popular with the proliferation of green design throughout the market. Design for deconstruction refers to the act of designing a structure such that the members can be reclaimed, refabricated, and reused on a future project, without expending the energy involved in recycling the members. Steel is a very logical candidate for this process, as the material is not monolithically cast into a structure, but rather is brought to site in prefabricated assemblies that are erected in piecemeal form. Thus, with design for deconstruction, the less intrusive the field work, the more plausible the use of reclaimed members in the future. For example, by making use of bolted field connections rather than welded ones, the act of separating the materials is greatly simplified; the demolition contractor need only remove the bolts, rather than going through the act of gouging out welds. The corollaries between prefabrication and design for deconstruction have been documented (Pulaski et al. 2004). Several projects have, in the past, found it reasonable to anticipate the deconstruction of the building itself. The up-front costs associated with this are most often justified when the future use of a project is anticipated ahead of time. For instance, this approach to design is often used for festival structures that are intended to stand in one location for only a short period of time.

The American Institute of Steel Construction (AISC) has an appendix devoted to the retrofit and rehabilitation of buildings and members within the AISC Specification. In most cases, structures that are designed for deconstruction are made from steel, and sometimes precast concrete or wood members, as these members arrive on site in their near-final dimensional form, making them more open to future adaptation and deconstruction. Refer to Section 2.4 Design for Adaptability and Deconstruction for additional information.

Material efficiency

As with any material, if the same result can be achieved with less material, there is reduced impact on the environment. Common strategies to economize on the amount of structural steel used include cantilever construction for roof framing, composite floor beam construction, and partial end fixity for floor purlins. In addition, Grade 50 steel is commonplace today for wide flange members. As technologies advance, higher grade steel is becoming more common and can be incorporated into the structural engineer's designs to reduce materials. Additional study is required to determine how an increase in manufacturing energy for such processes as reheating and tempering to achieve higher strength compares to the resultant material savings. In some cases, adding alloys such as vanadium can increase the strength of steel with little change in production process, thereby ensuring that any reduction in material is accompanied by a similar reduction in environmental impact.

Thermal properties: Steel in the building envelope

A consideration in the design of steel that needs to be properly addressed when it is used in building applications is its very high thermal conductivity. Its use in a building's exterior envelope needs to be carefully considered, with details that create minimal thermal bridging across the insulation layers.

The low resistance to heat flow of steel makes it act as a heat conductor, rather than an insulator. In the United States, a material's resistance to heat flow is defined as its R-value, and is measured in degrees Fahrenheit, square feet hours per Btu, (ft^2•°F•h/Btu). The R-value of steel is approximately 0.003 per inch, as compared to other construction materials such as wood (average R-value of approximately 2.5 per inch) and normal weight concrete (average R-value of approximately 0.1 per inch). Any steel element that interrupts and passes through the insulated building envelope represents a significant path for building heat energy loss to occur during cold regions in cold seasons, and for exterior heat gain when the exterior is warmer than the interior.

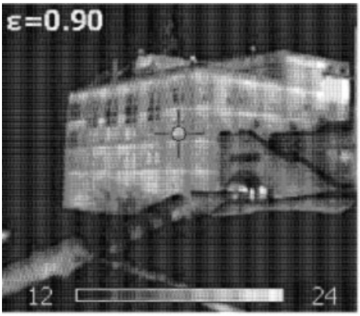

Figure 3.4-1. Heat loss photo of a steel-framed building (J. D'Aloisio 2009)

Steel beams and columns that extend into the exterior insulation plane can cause thermal bridging. This can also be true at roof edge angles, brick shelf angles, and continuous steel angles. This heat loss can be dramatic: a continuous 1/4-inch thick steel plate that extends across a plane of rigid insulation at every floor level can reduce the total effectiveness of the wall insulation by 67 percent or more. Figure 3.4-1 shows the heat loss from a steel-framed building. Support conditions for steel-framed balconies and canopies can also create significant thermal bridging, as can steel columns that pass through to the exterior of a building, and steel rooftop grillage systems.

For example, a brick shelf angle consisting of a 1/4-inch continuous thickness of steel angle that bridges across a layer of two-inch rigid insulation at each floor level, 12 feet on center, comprises (0.25 in.) / (12 ft × 12 in./ft) = 0.0017, or 0.17 percent of the wall area. Although this is small, the thermal conductivity (known as U-value) of two inches of expanded polystyrene insulation (the inverse of the R-value) is:

$$U_{INSULATION} = \frac{1}{(3.7 \times 2)} = 0.135,$$

while the U-value of two inches of steel is approximately:

$$U_{STEEL} = \frac{1}{(0.031 \times 2)} = 160.$$

Roughly speaking, steel conducts heat approximately 1,200 times more than the rigid insulation. In a steady-state condition, and assuming that there are no heat flow restrictions in delivering or dissipating heat from the assembly, the total heat transfer across an area comprised of different materials parallel to the heat flow can be calculated as the algebraic sum of the U-value times the area of each material. So using this methodology, the steel conductivity would account for about:

$$\frac{(0.0017 \times 160)}{[(0.0017 \times 160) + (0.9983 \times 0.135)]} = 0.67,$$

or 67 percent of the total amount of heat that moves through this section of wall. This makes the effective R-value of this section of wall:

$$R_{EFFECTIVE} = (0.67)(0.0062) + (1\text{-}0.67)(7.4) = 2.4,$$

which is a 67 percent reduction from the 7.4 R-value of the insulation alone. However, since most building conditions do not fully meet these assumptions, this approach should be used to determine the maximum possible reduction of R-value, rather than the actual value.

Cold-formed steel studs with insulation infill between the studs have a significant reduction in the system's R-value, as compared to the same thickness of uninterrupted insulation. In addition, the presence of top and bottom stud tracks in a typical exterior wall result in an additional reduction of total insulation value. The total effect is called the "framing factor." For example, a wall with 5-1/2 inch steel studs spaced at 16 inches on center using R-21 fiberglass batt insulation with top and bottom track has a framing factor of about 0.35, making the total wall system's effective R-value approximately 7.4. This assumes no workmanship errors, and that a continuous and effective air barrier is present.

In addition to reducing the building envelope thermal performance, metal stud systems with infill insulation and the commonly used 1/2-inch or 5/8-inch-thick water-resistant gypsum board sheathing at the exterior face (which has an R-value in the range of 0.6) can be subject to condensation in cold climates during the heating season. This moisture in the stud wall cavity can lead to corrosion of the steel, reduced effectiveness of some water-sensitive insulation materials such as fiberglass, and, if food sources are present, the development of mold.

Strategies to overcome the thermal reduction in the effectiveness of the building envelope for steel stud wall construction include the following:

- Providing continuous rigid insulation across the exterior of the studs. Manufacturers have developed boards that consist of structural sheathing material factory bonded to insulation.
- Use of exterior horizontal sub-purlins to attach exterior sheathing, with spray-on foam insulation applied to the inside surface of the sheathing and between the studs. This limits the extent of the steel thermal bridging to the intersection points between the studs and the sub-purlins.
- Use of proprietary studs such as slit-web steel studs, which have been shown to decrease the thermal transfer across the studs while having a fairly minimal effect on the stud strength reduction.

For buildings faced with brick or other exterior masonry cladding, any steel that supports the cladding and passes through the insulated building envelope represents a significant path for building heat loss during heating seasons and for cooling loss during cooling seasons. The following strategies should be considered:

- Steel lintels: Whenever possible, lintels over doors and windows that support the exterior wythe of masonry should not be continuously connected with a steel plate or angle across the insulation plane. Lintel support hangers should be spaced as far apart as practical to minimize the amount of continuous steel across the insulation. Details that incorporate a thermally insulating material in the insulation plane will greatly reduce the heat loss. Loose lintels should not have a continuous plate across the full width of the opening. If closure is necessary across the gap, consider using a thin-gauge cold-formed stud or track, or a fire-treated fiberglass plate.
- Relieving angles: As with lintels, avoid continuous steel between the relieving angle and the structure. Space support clips as far as the angle will accommodate. Six-inch-long reinforced clips spaced 48 inches on center reduce the heat transfer through the steel by approximately 66 percent as compared to a continuously supported relieving angle.

For steel framing details, the following conditions should be carefully reviewed and coordinated:

- Perimeter columns and spandrel beams: The sizes and positions of these members must be coordinated so as to allow the building envelope insulation to pass by continuously. Also, if the steel elements are adjacent to the building envelope's air barrier plane, a slight offset may produce corner details that complicate the proper execution of the continuous air barrier.
- Wall and roof intersections: Details that allow minimal interruption of the insulation and air barrier continuity across this transition is critical to a building's energy performance. When a continuous steel angle is needed at the edge of the roof deck as a component of the structural diaphragm, any roof edge blocking support angle should be discrete, not continuous, and clipped to the continuous angle or spandrel. The air barrier systems of the wall and roof should be detailed (and accommodated by the structural engineer) to ensure continuity, possibly with the use of an adhesive membrane adhered to, and overlapped across, the steel elements.
- Exposed steel columns or posts: These elements are thermally connected to the structural steel frame inside the insulated building envelope, therefore, any steel support elements that pass through unconditioned space should be completely insulated, including, when possible, around the pier foundation support.
- Balconies and canopies: The quantity and size of steel elements that structurally connect across the insulated building envelope and air barrier should be minimized. Discrete point connections, with minimal thermal insulation interruption and carefully detailed air barrier continuity, are much more efficient than continuous connections.
- Stainless steel: The effective use of stainless steel, which has a thermal conductivity approximately one third of carbon steel's, can greatly reduce energy loss due to thermal steel bridging.

Durability

Structural steel, if properly enclosed in a building, is an exceptionally durable material. Steel rebar used on the exterior of a building or in bridge applications needs to be properly protected, or treated with epoxy coatings to ensure its durability. The durability of any structural material, when properly installed and designed to remain elastic is very durable.

Corrosion protection

When enclosed, steel generally does not need to be protected from corrosion. Materials used unnecessarily to protect steel waste materials and labor. For instance, the interior beams of buildings with properly-designed and maintained exterior walls and roofs do not need to be painted because there is no risk of corrosion.

Corrosion protection is important for steel members that will be exposed to moisture. The steel should be properly protected with a coating system designed to prevent water infiltration. Generally, steel that is exposed to the elements needs to be treated or to be of a "weathering" variety. ASTM A588 steel is a specially-designed weathering steel that develops a self-protecting patina to prevent corrosion. There are specific concerns when this material is used, however, such as run off causing staining at the base of the members, and the architect has to be aware of the design challenges before it is used.

Synergies

When a material can be used to serve two purposes, there may be a savings to the environment. For instance, The London City Hall building project utilized steel pipe columns as both a mechanical and a structural element — running the required drainage system through the structure. Such an approach reduces the initial embodied effects of the building, but can hinder future modifications or system replacement, possibly resulting in a net increase in environmental impact over the building's life-cycle.

Structural steel finishes

When the structure itself can be left exposed, there is a material savings since additional finishes are eliminated. Architecturally exposed structural steel is designed to be aesthetically pleasing. Typically the welds are ground smooth to give the structure a more polished look. The architect or interior designer will often specify a painted finish on the material to satisfy their aesthetic objectives. Architecturally exposed structural steel typically costs more than conventionally finished steel, but this cost must be weighed against the cost savings realized by eliminating architectural finishes.

Code considerations and design aids

Each of the major structural materials has code provisions for the retrofit and rehabilitation of the material. For steel, this can be found in Appendix 5 of the AISC Specification. This section of the Specification provides procedures for assessing material properties, performing a structural analysis, and performing load tests, and provides requirements for evaluation reports. If possible on a renovation project, re-using the existing steel will usually be a more sustainable practice than demolishing and replacing with new steel members.

Metrics

Percentages of building material that is recycled is required by many third-party certification programs, including for LEED Recycled Content credit calculations. Following is the current average data (based on 2006 domestic data, dated August 2007) published by the Steel Recycling Institute:

- Basic Oxygen Furnace (hollow structural sections and all cold formed steel)
    Total Recycled Content: 28.9 percent
    Post-Consumer Recycled Content: 22.3 percent
    Pre-Consumer Recycled Content: 6.1 percent
- Electric Arc Furnace (wide flanges, H-piles, plates, angles, channels, reinforcing bars)
    Total Recycled Content: 82.8 percent
    Post-Consumer Recycled Content: 46.2 percent
    Pre-Consumer Recycled Content: 31.1 percent

Note that in the published information, the total recycled content percentages of steel for both manufacturing systems is greater than the sum of the post-consumer and pre-consumer recycled content because a small amount of the "home scrap" at the mills is considered "runaround scrap" and not included in the pre-consumer scrap percentage.

Steel industry and sustainable design practices

Transformation of the market requires new ideas and rethinking ways of designing, manufacturing, and constructing with steel products. The recycling of steel is a very good sustainable practice. The steel industry can improve the environmental impacts that exist by purchasing and producing renewable energy, investing in low-carbon technologies, working to improve energy efficiency, and offering new products and services aimed at reducing emissions. The steel industry is making efforts to encourage the production of electricity from less carbon intensive sources and taking a fresh look at its own processes. This will be critical to reducing its negative environmental impacts.

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3.5

WOOD

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Wood, the most widely used structural building material in the world, is the only one that is renewable and bio-based. Powered by solar energy collected by a tree's leaves, carbon dioxide extracted from the atmosphere is combined with water and nutrients absorbed through the tree's roots to form a composite of hollow cellulose fibers bound in a matrix of lignin by photosynthesis (Fig. 3.5-1). The result is an extremely versatile lightweight structural material that is easily shaped and fastened with common hand tools.

As mature trees are harvested they are replaced by younger trees and the wood resource is renewed. In a well-managed forest this natural renewal can continue indefinitely as long as there is an ample source of water, carbon dioxide and sunlight.

Scientific evidence suggests that increasing levels of carbon dioxide in the atmosphere from the consumption of fossil fuels is the prime cause of accelerated climate change. The only practical technology currently available for extracting carbon dioxide from the atmosphere is the cultivation and harvesting of trees and other crops.

Figure 3.5-1. Wood products begin their life as trees.
(Photo by DeStefano & Chamberlain, used with permission)

A well-managed forest or woodlot will extract a considerable amount of carbon dioxide from the atmosphere. Based on the chemistry of photosynthesis, for every pound of wood grown, 1.47 pounds of carbon dioxide is removed from the atmosphere and replaced with 1.07 pounds of oxygen. Studies show that the carbon content of harvested roundwood varies from about 12 to 20 pounds per cubic foot (pcf) (Skog and Nicholson 2000). However, if a forest is not managed and trees are not thinned and harvested, the forest will mature to a point where the carbon dioxide returned to the atmosphere by the decay of dead trees and forest fires balances that extracted from the atmosphere. To effectively remove carbon dioxide from the atmosphere on a sustainable basis, mature trees must be periodically harvested and milled into building products that will endure for many decades. This is referred to as "carbon sequestration" since carbon becomes a permanent and integral part of the building products (Lippke et al. 2004). When trees are harvested for short duration uses such as paper pulp or in the construction of buildings with a relatively short service life, the carbon dioxide may soon be returned to the atmosphere with less sustained environmental benefit. One key to effective carbon sequestration is building wood structures that will endure for many decades, or even centuries, with wood products.

Studies have shown that wood has low embodied energy compared to most other structural materials (CORRIM 2004 and Edmonds and Lippke 2005). The energy consumed in managing forests, harvesting trees, milling timber and transporting lumber to job sites is relatively small. Wood fares exceptionally well when comparing the manufacturing impacts of building materials such as solid waste generation, air and water quality impacts, and greenhouse gas creation (EBN 1999 and APA 2005).

Sustainable forestry

Responsible forest management is the key to minimizing adverse environmental impacts associated with the extraction of timber from forests. While environmental degradation of forests from irresponsible logging practices continues to be a problem in some locations, most forest owners in recent decades, have become more environmentally sensitive and there has been a trend towards managing forests in a more sustainable manner. Foresters have gained a better understanding of the forest environment. Forest management has evolved into not just maximizing timber yield, but also protecting streams and rivers, minimizing erosion, protecting natural ecosystems, and enhancing wildlife habitats. Modern harvesting practices and equipment enable forest owners to remove timber with less long-term impact on the forest ecosystem (Fig. 3.5-2).

For example, it is important to maintain a riparian fringe of vegetation immediately adjacent to rivers and streams as shown in Figure 3.5-3. The vegetated fringe serves as a natural bio-filter that traps nutrients and eroded soil that would otherwise degrade the waterway. The plant roots stabilize stream banks, the tree canopy provides essential shade for the water, and trees fall into the streams to create stream flow conditions important to many fish and other riparian species.

Figure 3.5-2. Damage to understory plants can be minimized by performing logging operations in winter. (Photo by DeStefano & Chamberlain, used with permission)

Figure 3.5-3. Riparian fringe adjacent to a woodland stream. (Photo by DeStefano & Chamberlain, used with permission)

The science of forest ecosystems and cultivating trees is referred to as *silviculture*. Every forest has a unique combination of species, soil type, elevation, climate, and terrain. For this reason, individual forests require a specifically tailored management strategy to keep the forest healthy, maximize forest growth, and protect against environmental degradation. Foresters have developed a variety of silvicultural tools to assist them in responsible forest management.

Timber may be harvested by selection where individual mature trees are marked and cut. This allows the younger trees to grow more vigorously when competition for water, soil nutrients, and sunlight is reduced. Selection is the preferred harvesting method for tree species that can propagate in the shade of surrounding trees.

Timber may also be harvested by clearcutting, also referred to as even-age forestry. The practice of clearcutting has often been criticized by environmental groups due to its impact on forest ecosystems. When done responsibly considering size, shape, adjacency, water quality protection, erosion control, and wildlife needs, clearcutting can have environmental benefits. It can be very effective in enhancing wildlife habitat since it creates a forest fringe ecosystem that is essential to deer, wild turkey, and many other species of wildlife. It allows for the growth of many plant species that can only propagate in full sun and better mimics natural stand clearing disturbances such as fire and windstorms. Even-age forestry requires that effective erosion control measures be implemented including the proper disposal of tree crowns and limbs (referred to as *slash*) from the harvested trees. In general, shade intolerant species such as Douglas fir, some Pine species and Oaks are best managed by using even-age forestry practices.

Biodiversity must be considered in forestry management. While it is efficient to plant a single species of tree and to grow the stand to harvest at the same age, this can sometimes result in reduced opportunities for wildlife habitat. Special measures must be taken to maintain biodiversity such as planting a diverse understory of plants, and introducing other tree species that seed naturally among the planted trees.

The most important aspect of sustainable forestry is keeping forests healthy and available as a long-term resource. When forest lands are displaced by shopping centers or housing developments, that forest resource is lost forever. Development pressure is by far the biggest threat to forests globally. The economic value generated from sustainable timber harvesting provides woodland owners with an incentive to maintain their forest (Fig. 3.5-4).

Figure 3.5-4. Small-scale sustainable timber harvest.
(Photo by DeStefano & Chamberlain, used with permission)

Forest certification — How does a structural engineer know if the lumber on his or her project came from a responsibly managed forest? There are certification programs that verify that wood products are linked to forests managed under specific sustainable forestry criteria (Fig. 3.5-5). The two best-known forest certification programs in the United States are the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative® (SFI).

The *Forest Stewardship Council (FSC)*, originally created by the World Wildlife Fund, is a non-profit environmental organization devoted to encouraging the responsible management of the world's forests. FSC standards are intended to ensure that forestry is practiced in an environmentally responsible, socially beneficial, and economically viable way. It was originally created to protect tropical hardwood forests in developing nations and has evolved into an umbrella certification program that endorses national and regional FSC programs with emphasis on the protection of ecosystems. Criteria for FSC certification vary by country, and even by region within a country. Much of the FSC certified woods available in the United States are tropical hardwoods imported for millwork and other non-structural uses. FSC-certified dimension lumber, sheathing, and engineered wood products are available for structural use in some geographic regions but the specifier needs to confirm this product availability on a local basis.

The *Sustainable Forestry Initiative*® *(SFI)* standard was initially developed by the domestic wood products industry as a code of conduct for responsible forest management. It has evolved into a fully-independent non-profit organization. The SFI standard is designed to address sustainable forestry issues found in the specific forest conditions of North America. Almost all of the SFI certified wood products available are domestically harvested softwoods for structural applications.

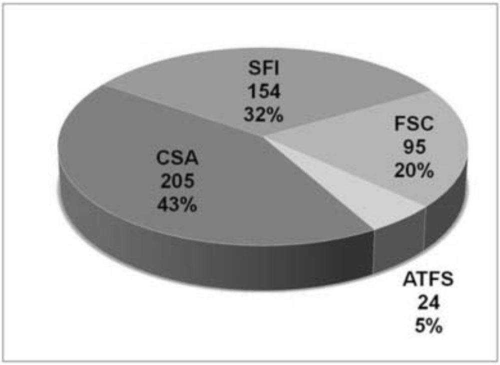

Figure 3.5-5. Certified forests in North America graphed by program: Total = 478 million acres (Data = millions of acres; percent of total) 1 acre = 0.4 hectares

Two other widely-known forest certification programs in North America are the American Tree Farm System (ATFS) and Canadian Standards Association (CSA) (2002) sustainable forest management standard. Founded in 1941, the American Tree Farm System (ATFS) is the oldest sustainable forestry program in North America. ATFS covers predominately family-owned forestland and has nearly 70,000 certified tree farmers. The CSA (2002) sustainable forest management standard was developed for publicly owned forests in Canada.

While there has been considerable debate over which certification program is best (Bland 2005), all four are credible programs. Green Globes and the National Green Building Standard (NAHB 2008), for instance, recognize all four programs. LEED only recognizes FSC at this time, but the USGBC is working on revisions to the wood certification credit that will, if adopted, reward any certification system meeting defined criteria. The CSA, FSC, and SFI programs currently have criteria for on-product labeling of certified wood products. Each has a system for manufacturing facilities to track the percentage of fiber that originates from certified forests. The USGBC and many environmental advocacy groups consider FSC to be the certification system with the highest environmental and social standards.

Less than 25 percent of the structural wood products produced in the United States come from certified forests (Alvarez 2007). Wood that is not certified by one of the four sustainable forestry programs is more likely to have been grown and harvested using less sustainable forestry practices, so specifying wood certified by any of the major certification systems in the place of uncertified wood will likely reduce a building's environmental footprint.

Wood product selection

Each type of wood product available to the specifier will have its own environmental advantages and disadvantages that need to be considered.

Solid sawn lumber — Solid sawn lumber, and particularly dimension lumber, is commonly used in building construction. A major advantage of sawn lumber is its extremely low embodied energy. Specifying kiln-dried lumber rather than green or air-dried lumber will result in an increase in its embodied energy.

Transportation impacts and the associated embodied energy can be minimized by specifying locally or regionally grown species. Typically the dominant structural wood species in various regions of North America are Douglas fir in the West, Southern Yellow Pine in the Southeast, and Spruce-Pine-Fir (SPF) in the Northeast and Midwest.

Figure 3.5-6. Engineered wood products utilize wood efficiently. (Photo by DeStefano & Chamberlain, used with permission)

Engineered wood products — The popularity of engineered wood products (EWP) for structural applications has grown significantly in recent decades. EWPs include the following:

- structural composite lumber (SCL), including LVL, LSL and PSL;
- plywood;
- oriented strand board (OSB);
- prefabricated Wood I-joists; and
- glued laminated timbers (glulam).

The primary advantage of EWPs is their ability to efficiently use smaller trees and underutilized species with very little manufacturing waste. For example, Aspen is often used in the manufacture of OSB and some SCLs. Aspen is a fast growing species that has the ability to naturally regenerate from its live root system after harvest.

Another advantage of EWPs is their ability to span further and use fiber more efficiently (Fig. 3.5-6). For example, a typical wood I-joist requires only 65 percent of the fiber to support the same structural load as a solid section. Offsetting these advantages for EWPs is their somewhat higher embodied energy when compared to solid sawn lumber.

Virtually all composite wood products are manufactured using petro-chemical-based adhesives and resins. However, different types of adhesives are used for non-structural products (typically used indoors) than for structural EWP's. There are valid toxicity and air-quality concerns related to off-gassing from urea-formaldehyde resin in non-structural wood products used in indoor applications such as cabinets and furniture (unless those products are manufactured in accordance with newer low-VOC standards such as ANSI A208.1-2009). Interior use urea-formaldehyde resins are not typically used in the manufacture of structural EWPs since they do not perform as well as exterior-use resins when exposed to the weather. EWPs primarily utilize phenol-formaldehyde (PF) resins which are not subject to any significant detectable off-gassing. In phenol-formaldehyde adhesives, the "formaldehyde is efficiently consumed in the curing reaction" (FPL 2007). Another common adhesive used in EWP is polymeric methylene diphenyl diisocyanate (PMDI). PMDI and the formaldehyde in PF adhesives, while safe in the finished product, are treated as potential health hazards during the manufacturing phase. Reduced quantities of urea-formaldehyde at acceptable emission levels are still commonly used in non-structural wood products used for architectural millwork.

Building components

Precut and prefabricated building components are assembled more efficiently and with less waste than site-built construction. Prefabricated components include the following:

- metal plate connected wood trusses;
- panelized framing;
- structural insulated panels (SIPs); and
- timber framing.

Fabricating wood building components in a factory environment, unimpeded by adverse weather conditions, has proven to result in greater efficiency and productivity which translates into reduced embodied energy.

Structural insulated panels — Structural Insulated Panels (SIPs) have a rigid foam core sandwiched between most commonly OSB skins. Expanded polystyrene (EPS) and urethane are the most common core materials. SIPs can be used as a cladding system on a timber frame structure or as a stand-alone structural system. The panels can be engineered to meet a wide range of structural spans (Fig. 3.5-7).

Figure 3.5-7. SIP roof and wall cladding over structural steel on a school in Cherokee, N.C. (Photo by Panelwrights, used with permission)

Figure 3.5-8. Timber framing has experienced a revival in popularity. (Photo by DeStefano & Chamberlain, used with permission)

Well-built SIPs can produce very energy-efficient structures. They have a high R-value and provide a very low air-infiltration rate. With proper sealing of the panel joints, infiltration rates are typically less than 0.10 air changes per hour. As with any "tight" structural system, SIP-enclosed structures must be mechanically ventilated to prevent indoor air quality problems.

Timber framing — Timber framing, sometimes referred to as post and beam construction, utilizes heavy timbers connected with mortise and tenon style joints that are secured with hardwood pegs (Fig. 3.5-8). This type of construction has been around for thousands of years and has experienced a resurgence in popularity in recent decades for architecturally exposed structures. Benefits of timber framing include the following:

- Timber frame structures tend to have a long service life due to the substantial nature of their construction and aesthetic appeal.
- Structures can be easily deconstructed and re-erected on another site. This is commonly done with old barn frames and antique house structures.
- Timber frame structures are commonly clad with SIP roof and wall panels resulting in very energy-efficient structures.

Salvaged timbers are often used in new timber frame structures. Older timbers from demolished structures can be used in their whole dimension but they are more often resawn into new timbers.

Some timber harvested from standing dead trees is valued for its dimensional stability, although it may contain defects such as excessive shake. There is a significant supply of standing dead timber that has been killed by fires or by parasites. In the western states, large stands of Pines have been decimated by the Pine Bark Beetle. In the northeast, Hemlocks have been killed off by the Wooly Adelgid. While an individual standing dead tree, referred to as a snag, within a healthy forest provides shelter for wildlife, when an entire stand of trees is killed off, wildlife habitats are severely impacted. Harvesting this standing dead timber allows the forest to be rejuvenated.

Advanced framing

Advanced framing techniques, also referred to as optimum value engineering (OVE) (USDOE 2000), involve framing structures with less lumber than would be used with traditional wood framing methods. Advanced wood framing uses wood most effectively when wall studs, joists and rafters are spaced at 24 inches on-center rather than the more common spacing of 16 inches on-center. Joists and rafters are aligned with wall studs and wall studs are aligned from floor to floor. This alignment of horizontal framing members with studs allows the use of single member top plates. Headers are sized for actual loading conditions at structural walls and may be eliminated at non-bearing walls. Redundant studs and floor joists are eliminated on typical details. In addition, advanced framing allows for more effective insulation of exterior walls with fewer studs to interrupt the insulation.

Advanced framing results in fewer pieces of lumber, but sometimes an increase in lumber size. For instance, when wall stud spacing is increased from 16 inches on center to 24 inches on- center, the stud size may need to be increased from 2x4 to 2x6, particularly for the lower stories of multi-story buildings. In colder climates, exterior wall studs are usually 2x6 anyway to accommodate insulation requirements. The wall sheathing and drywall will also often increase in thickness from 1/2 inch to 5/8 inch. When rafters are spaced 24 inches on-center, 1/2-inch roof sheathing is still often used, although some applications may require thicker sheathing to be used.

Implementing advanced framing techniques requires some retraining of carpentry crews. It has been estimated that it takes framing as many as ten house structures for a framing crew to become proficient at executing advanced framing techniques.

Advanced framing results in a more efficient structure than a conventionally framed wood structure. It also results in a less redundant structure which can be a disadvantage when a structure is altered or adapted to a different use. Additionally, the advantages of advanced framing can be limited by other design concerns such as fire and draft stopping, or floor vibrations due to reduced mass.

Design for durability

All efforts to design an efficient structure are of limited sustainable value if the structure has a short service life and is demolished or destroyed after a few decades. If a wood frame structure does not stand for as long a time as it took the trees that went into its construction to grow, then it can be hardly classified as a sustainable building. Sometimes a robust structure that can be easily adapted to new building uses and loading conditions will be the most sustainable design.

The durability of well constructed and maintained wood-framed structures has been proven by the multitude of examples that have stood for centuries. While wood's bio-based attributes can help make it a sustainable building material, those same attributes mean that proper design, installation and detailing are critical to ensure long-term durability.

When wood is used in exposed applications, or in areas where it is subjected to moisture and insects, it must be protected with mechanical barriers, coatings and, in some instances, preservative treatments. Proper design details such as roof overhangs, drip edges and flashing around window and door openings can also protect wood from excessive moisture intrusion.

Preservative treatment

Wood can be impregnated with preservative chemicals to protect it from decay and insect damage. Many preservative compounds are toxic and protect the wood by poisoning decay fungi and insects. Common preservative treatment compounds such as Chromated Copper Arsenate (CCA), Alkaline Copper Quaternary (ACQ), Copper Azole, and pentachlorophenol, require special handling during manufacture and disposal after use. Designers should note that CCA, while available for commercial or industrial applications, is no longer available for residential applications. The advantage of an extended service life must be balanced against chemical toxicity concerns. Preservative-treated wood can leach small amounts of toxic chemicals over time, and can cause adverse environmental impacts if not properly handled and disposed of. Some types of treated wood also accelerate the corrosion of susceptible fasteners that are in contact with the wood, so designers must use care when selecting fasteners and connection details to ensure durability.

Borates are not toxic to humans and other mammals although they are toxic to termites and decay fungus. Most borate treatments are susceptible to leaching and are not suitable for applications where they are exposed to the weather. Their use is limited to applications such as sill plates, crawlspace framing, and other protected framing (Fig. 3.5-9). There are some borate treatments that are non-leaching that can be exposed to the weather but are not suitable for ground contact.

Figure 3.5-9. Borate treatment is an effective non-toxic preservative. (Photo by DeStefano & Chamberlain, used with permission)

An emerging preservative technology uses sodium silicate and seems to combine the benefits of non-toxicity with non-leachability (EBN 2004). Sodium silicate is widely used in products such as laundry detergents, household cleaners, and water treatment plants.

Naturally decay resistant species contain extractives in their heartwood that are resistant to decay and wood eating insects. Redwood, Cedar, and Cypress are commonly used when natural decay-resistance is desired.

Deconstruction and recycling

Within the manufacturing environment, wood waste is either recycled into the production process or used as process fuel.

At the jobsite, wood waste along with drywall scraps can be processed into landscape mulch (Fig. 3.5-10). Studies have shown that mulch made from engineered wood products is suitable for landscape use (APA 2008). Mulch is beneficial to plantings due to its ability to retain moisture in the soil and retard weed growth. Eventually the mulch decays and contributes organic material to the soil.

Demolition debris can be sorted and recycled. Larger structural timbers can be salvaged during deconstruction for re-use in other structures. Sorting and nail removal from light wood framing can be very labor intensive and impractical unless specialized tools or very inexpensive labor are used.

Wood waste can also be used as a boiler fuel. Jobsite waste, demolition debris, manufacturing scraps, and slash from logging operations can all be chipped and used as bio-fuel, displacing the consumption of fossil fuels (USDA 2002).

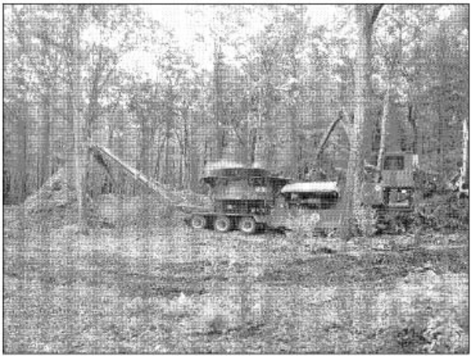

Figure 3.5-10. Wood construction waste is converted to landscape mulch in a tub grinder. (Photo by DeStefano & Chamberlain, used with permission)

Summary

A structural engineer endeavoring to design responsibly with wood should consider the following sustainable initiatives:

- Specify wood products that come from sustainably managed forests.
- Specify wood species that are grown in the same region as the project.

- Utilize wood efficiently. Consider using prefabricated building components, engineered wood products, and advanced framing techniques.
- Design durable structures that are resistant to deterioration and can be altered and adapted to new uses and loading conditions.
- Specify non-toxic preservative treatments when appropriate.
- Require that construction site waste and demolish debris be sorted and recycled or used as biofuel.

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Additional resources

APA – The Engineered Wood Association: www.apawood.org

ATFS – American Tree Farm System: www.treefarmsystem.org

Canadian Standards Association (CSA): www.csa-international.org

Forest Stewardship Council (FSC): www.fscus.org

PATH Advanced Framing Techniques:
http://www.toolbase.org/pdf/techinv/oveadvancedframingtechniques_techspec.pdf

Sustainable Forest Initiative (SFI): www.sfiprogram.org

Structural Insulated Panel Association (SIPA): www.sips.org

Consortium for Research on Renewable Industrial Materials (CORRIM): www.corrim.org

Society of American Foresters (SAF): www.safnet.org

3.6

NATURAL BUILDING MATERIALS AND SYSTEMS

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Natural building materials and systems have their roots in pre-industrial indigenous building techniques. About two-thirds of the world's population lives in buildings made with non-industrial materials such as earth and bamboo. For a variety of reasons, some of which are explored in this section, their use is limited to specific building types, sizes, and geographical regions. Some examples of natural building materials with structural uses are straw bale, bamboo, stone, and multiple techniques using earth. Other related uses are earthen finishes, tree house design, and thatched roofs. There are also hybrid construction techniques that combine natural and modern materials such as steel reinforcing in earthen structures or portland cement used in earthen or bamboo/earthen hybrid buildings. Timber construction is also considered a natural building material.

The amount of information and testing available on natural building techniques is varied, but generally not extensive when compared to modern industrial materials. With the exception of timber construction, there is little industry involvement with these materials so standards for design and quality assurance and sources of funding for research are not easily found. Still, much is known based upon historic empirical knowledge and modern innovations by various organizations, non-profits, and universities. Locating the most relevant information can be a challenge. The majority of knowledge sharing in the United States is occurring at the grassroots level through small organizations that are teaching natural building for use in private residences or garden structures.

Most building codes do not directly address natural building techniques and this may be the biggest hurdle to wider adoption (Piepkorn 2005). There are regional exceptions, some of which are explained further in this section. The development of the *International Performance Code* (IPC) (ICC 2006b) makes possible a performance-based approach to design based on testing and analysis of undocumented systems, given evidence of positive benefits and the absence of excessive risk. Building departments typically are not familiar with design using such materials, so the testing programs required can be costly and time-consuming. David Eisenberg at the Development Center for Appropriate Technology (www.dcat.net) is involved with "greening the codes" and aiding the building department approval process for natural building methods. Eisenberg explains that current building codes focus on the protection of the structure and occupants, and overlook other impacts, such as climate change, toxins created during production, and reuse or disposal of the structure at the end of its life: "The larger, ecologically based risks to public welfare must eventually be seen as risks that demand responsibility for protecting public welfare as much as structural integrity, fire safety, or means of egress." (Eisenberg and Yost 2001). Despite building code hurdles, a greater resurgence of natural building techniques could be fueled by market demand or by market forces such as rising energy and construction costs.

The intent of this section is to provide general information on a few natural building materials and systems. The materials covered are earthen construction, strawbale, and structural bamboo. A list of additional resources is provided at the end of the section.

Earthen construction

There are advantages and disadvantages to all building materials. Following are some general advantages and disadvantages of earthen construction.

Earthen construction advantages:

- naturally abundant;
- non-toxic;
- effective for passive solar design;
- low sound transmission;
- low embodied energy; and
- locally sourced.

Earthen construction disadvantages:

- poor seismic performance if not designed and detailed properly;
- building height limitations;
- durability issues with prolonged water exposure;
- maintenance; and
- labor intensive.

Overview — Earthen structures have seen pervasive use as human shelter on many continents, with the oldest excavated site dating to 8,300 B.C. (Elizabeth and Adams 2005). There are many types and variations of earthen structures: adobe, rammed earth, stabilized rammed earth, gunearth, fired ceramic, cob, earthbag, and underground structures. Well-designed and maintained earthen structures have endured the test of time, but there are durability concerns in wet regions and safety issues to be aware of in seismically active areas. The environmental advantages of earthen materials are compelling. Earthen structures create a natural, non-toxic indoor environment. Little energy is typically required to extract, process, and fabricate the material, with the largest energy input usually being human labor. The use of natural materials precludes adverse end-of-life issues. Due to their large mass, earthen buildings are beneficial for passive solar design and have low sound transmission. They also naturally regulate indoor humidity and comfort (Bjørn 2000). Depending upon local soils and the desired mixture of clay, sand, silts and gravel, importing of earthen material may be necessary. But typically, earthen construction materials are locally sourced which means low embodied transportation energy.

Code considerations — The *International Building Code* (IBC) does not directly address most types of earthen construction. Adobe construction is addressed in the IBC (ICC 2006a) in section 2109.8 and is considered similar to unreinforced masonry construction. There is an ASTM standard for earthen construction, ASTM E2392–05, *Standard Guide for Design of Earthen Wall Building Systems*. The ASTM standard is currently under review and revision by Bruce King, an engineer and director of the Ecological Building Network (www.ecobuildnetwork.org). The state of New Mexico has developed its own earthen building code (Title 14), which has been used as a model in parts of Arizona and Colorado. Local ordinances have also been adopted, such as new section R614 in the *International Residential Code* (IRC) (ICC 2006c) amendments in Pima County, Arizona. Various other countries have earthen construction building standards such as Australia, New Zealand, Germany, Spain, Peru, Ecuador, India and Zimbabwe. Even with the available standards it is necessary to have a knowledgeable project team that will work closely with the local building department when considering the use of earthen structural systems.

Structural performance — The majority of earthen structural systems make use of the compressive properties of the material, which depending on the method and mix can vary between essentially nothing and in rare cases can be as high as 8000 psi (King 1997). It is best to use actual test data when determining material compressive strength for structural design. Earthen construction is also empirical, with rules of thumb similar to those used in unreinforced masonry. Good practice follows recommended guidelines for wall height and thickness, opening lengths, opening locations, dimensional ratios for shear piers, and so on. Walls are typically used in bearing and as shear wall elements. Timber or concrete bond beams are used for load distribution and to provide out-of-plane support to the walls under seismic loads. In high seismic regions, reinforced concrete bond beams are recommended above and below windows and at the roof line. Rules of thumb and code references provided in this section will change with time and engineers should consult multiple current references prior to the design of an earthen structure.

Due to many earthquake-induced structural failures of earthen buildings and the resulting loss of life, rebar or bamboo reinforcement and stabilized earth should be used in seismic regions. Stabilized earth includes small amounts of binders such as cement, lime, fly ash, or asphalt emulsion. Unstabilized earth and earth block can be analyzed with methods similar to masonry. For stabilized monolithic earthen construction, the structure can be designed much like working stress for concrete design. A factor of safety of two is usually taken on the compressive strength, similar to the analysis of uninspected masonry (King 1997). Due to the high seismic mass, the designer must carefully detail wall out-of-plane anchorage at the roof and ensure adequate roof diaphragm capacity. In the absence of a roof diaphragm to transfer loads, the wall and footing can be designed as a cantilever system, with a large footing and the wall assumed fixed at the base and free at the top. This approach will typically require thicker walls and greater reinforcement, in addition to a larger, more heavily reinforced foundation. In seismic regions, closer attention must be paid to the earthen mix used. Soil analysis is always recommended to determine soil classification, gradation, and pH so that an appropriate design mix can be determined (King 1997).

Adobe: Adobe has been widely used in many parts of the world including Egypt, China, the Indus Valley, the American Southwest and ancient Greece and Rome. Some of the most sophisticated adobe has been constructed in Yemen with structures four to eight stories high. New Mexico has over 75,000 homes built with adobe or rammed earth.

Walls are formed from adobe bricks, often bonded using a clay-based mortar. The bricks are typically stacked in running bond for load bearing walls. Wall thickness might be 10 to 14 inches, although thicker walls up to 30 inches have frequently been used.

Adobe bricks are made of clay and sand, sometimes with straw added. The mixture is formed in molds by hand or machine, removed, and dried in air. Strength depends on the mix design; which should be responsive to the soil type and its moisture content. It is recommended that the first few courses of an adobe structure be stabilized with an asphalt emulsion added to the brick mixture in an amount equal to about five percent of the weight of the other constituents.

A common minimum compressive strength for adobe used in building codes is 300 psi when tested in accordance with ASTM C67-08, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile.* The IBC (ICC 2006a) limits the allowable compressive stress to 30 psi in Section 2109.8.3. The code provisions restrict adobe construction to one-story, except where designed by a registered design professional, in which case two stories are allowed. Wall height, thickness, and lateral support prescriptive requirements are provided in Section 2109.8.4.2 (ICC 2006a). Unsupported wall height shall not exceed 10 times the thickness of the wall. One-story walls shall be a minimum of 10 inches thick for exterior walls and 8 inches thick for interior load-bearing walls. Lateral support is to be provided for walls at intervals not exceeding 24 feet.

Rammed earth: Rammed earth is made from suitable earthen soil that is compacted one layer at a time. The pneumatically or hand-compacted structure must be constructed in place, using form-work for walls. Evidence of rammed earth construction dates back to the earliest of earthen structures (8000 B.C.). Portions of the Great Wall of China are rammed earth and some structures have been in use for hundreds of years in the Middle East, Europe and North Africa. Information on suitable soils and mix ratios can be found in the references by King (1997) and Maniatidis and Walker (2003). There are various types of rammed earth, both in terms of method of construction and mix design. “Soil cement” or “cement-stabilized earth” is rammed earth with 3 to 16 percent cement added by weight to increase the mix strength (percentage varies by soil type) (King 1997). Rammed earth can be compacted between forms placed on both sides of the wall, or constructed as “gunearth”. Gunearth (similar to gunite) is also called pisé in the United States and is pneumatically shot onto a one-sided form placed on one side of the wall. Rammed earth block can be made by machine or hand compressing earthen soil. When constructed correctly, the blocks are uniform, dense and strong. Interlocking shapes can be formed, along with holes for bamboo or steel reinforcement.

Rammed earth without stabilizing agents will typically achieve compressive strengths between 300 and 900 psi. In seismic regions, stabilized earth is recommended. With the addition of cement, compressive strengths in the range of 1000 to 2500 psi are commonly achieved. Cement-stabilized earth cures more slowly than concrete and usually reaches about 60-70 percent strength at 28 days (King

1997). Monolithic rammed earth walls generally provide better seismic performance than brick or block construction with masonry joints.

Cob: Cob is a mixture of clay, sand, straw and water that is thoroughly mixed and then hand-molded into thick, load-bearing walls. Cob has been used extensively in the U.K., Iran, West Africa and the American Southwest. It was the chief method of building in the U.K. from the 1500s until the industrialization of the mid-1800s. Due to cob's particular aesthetic, low material cost, and environmental advantages, there is a resurgence of cob building taking place in England and in Oregon. Cob is labor intensive but needs no mechanization or formwork of any kind. The walls are often tapered down as the wall goes up (about 6 inches taper per 10 feet of wall height). Exterior load bearing walls should be a minimum of 10 to 12 inches at the top. Thus a 10-foot high wall would be about 18 inches thick at the bottom (Elizabeth and Adams 2005). Cob walls have been successfully incorporated into buildings up to 23 feet tall, but most load-bearing walls are built no higher than 10 feet.

Testing and formal guidelines for cob are not as far along as other forms of earthen construction. It has been shown that cob has improved tensile and shear properties over basic adobe due to the straw fibers integral in the mix. Monolithic construction and free-formed curves walls often give cob better seismic performance than types of earthen construction that have masonry joints. Compressive strength of cob will vary widely, but is generally similar to that of adobe (about 300 psi).

Durability — Some earthen structures have been in use for hundreds of years; such life spans are possible with proper design and maintenance. The most important life-cycle concern, apart from the seismic issues discussed above, is avoiding prolonged soaks in standing water. Earthen structures need adequate drainage, roof overhangs, and an appropriate foundation that may include a raised stem wall (six inches above adjacent grade is usually adequate except as necessary for snow buildup). Water can affect durability through surface deterioration or overall wall damage due to inadequate drainage. Surface deterioration can result from condensation on the surface of the wall or when salts accumulate on the outside and then expand during wet/dry cycling. Overall wall damage occurs due to capillary rise of standing water at the base of the wall. (Garrison and Ruffner 1983). In addition to proper drainage, deterioration can be managed by replastering the exterior on a regular basis. Variations between the properties of the earthen material and protective coatings can also induce thermal cracking or cause moisture buildup behind the coatings. For example, higher cement content in an exterior finish coat means differing coefficients of thermal expansion which can cause cracks that allow water to penetrate the wall. It can also trap interior moisture and cause degradation inside the wall due to the lack of permeability of the exterior finish. It is best to plaster with a mixture that has comparable ratios of earth and binder materials as was used for the structure (Garrison and Ruffner 1983).

Reuse and disposal — Earthen structural elements are not often reused, although occasionally old adobe bricks from a deteriorating site will be used to repair another structure from about the same time period. Wood bond beams may be salvageable depending upon how long they were in place and whether or not the structure was adequately protected from water intrusion. Due to their ability to naturally break down at the end of their useful life, earthen structures do not need to be disposed of in a landfill.

Synergies with other building systems — Earthen construction has been widely used around the world for many centuries in part due to its ability to maintain comfortable indoor temperatures despite outside temperature extremes. Earthen walls are thick and the large thermal mass may be used as an advantage in passive solar energy design. Where mechanical systems and plumbing are installed, the pipes and ducts typically do not run within the earthen walls. Some electrical may be installed in the walls, given that the conduits can withstand compressive loads and wall thermal effects. Wires and small piping can also be installed behind wainscoting or other finish features.

Specifications — Some CSI *Masterformat* (2004) sections for earthen and related materials are as follows:

- 042100 – Clay Unit Masonry
- 042400 – Adobe Unit Masonry
- 044000 - Stone Assemblies

Appropriate specification sections for other types of earthen construction require some creativity. For cement stabilized (rammed) earth or gunite earth, the unassigned section 039000 can be used. Other earthen techniques that do not employ cement stabilizers might be placed in Earthwork Division 310000, but this is typically intended for underground earthwork and soil/site stabilization. Specifications for earthen construction should reference ASTM E2392-05.

Rating systems and earthen construction — A primary goal of green building rating systems such as LEED is to influence the current market, so unconventional (or low-tech) systems are not adequately addressed or rewarded. In LEED, material credits are based upon the cost value of the material or product being considered. The material cost in earthen construction is generally low compared to the associated labor costs. Earthen materials would be expected to contribute to the regional materials credit, but with low material costs it may not affect the credit outcome. Earthen construction can influence energy optimization credits where passive heating and cooling strategies are being employed.

State of the art/Case studies — David Easton and Rammed Earth Works have been building rammed earth structures in the United States since the early 1990s. They are innovators and consultants who emphasize site-sourced materials. Their website is www.rammedearthworks.com.

Ward+Blake Architects (www.wardblakearchitects.com) have a patent on a post-tensioned rammed earth system called "EarthWall". It has been used on a handful of residences in Wyoming.

Straw bale

There are advantages and disadvantages to all building materials. Following are some general advantages and disadvantages for straw bale construction.

Straw bale advantages:

- straw is a waste product; use in construction avoids burning in the fields, disposal in landfills, or tilling back into the soil;
- typically uses locally sourced materials;
- the bales provide high sound and thermal insulation; the plasters provide thermal mass and stiffness;
- aesthetics of adobe style (thick walls) architecture; and
- often selected for owner-built construction.

Straw bale disadvantages:

- best suited for single-story construction; two story construction is possible;
- although recognized by a few building codes, standards for design, details, and construction practice are not fully developed;
- thick walls require larger roof areas and footprints/lot sizes;
- electrical wiring and plumbing must be run in the walls or in the floor adjacent to the walls, with the wiring enclosed in conduit; and
- precautions must be taken to guard against developing mold within the walls.

Overview — Straw bale construction dates back to the late 1800s in the Midwest, where straw bale buildings were built in agricultural communities. Despite their poor reputation in children's stories, straw buildings have proven to be quite durable when detailed properly. Some early straw bale buildings built in the Sand Hills region of Nebraska (circa 1880-1930) have survived very well to this day (Steen et al. 1994).

The advent of modern agriculture has brought about straw baling equipment. After the grain is harvested, the straw stalks that remain in the field are cut and tightly bundled into bales by machine. The most common bale is a three-string bale, so named because the compressed straw is tied off with three strings. Three-string bales weigh around 80-95 pounds each, and are about 22 inches wide, 16 inches high, and 48 inches in length. The straw stalks within the bale are aligned in the 22-inch direction. The string, sometimes referred to as baling wire, is typically made from polypropylene; a common polypropylene twine is marked "350-pound test". In construction, the bales are typically laid flat (with the 22- and 48-inch dimensions defining a horizontal plane); in other cases they are laid on edge (the 16- and 48-inch dimensions defining a horizontal plane).

There are two basic structural systems that use straw bales. In post and beam construction, straw bales are used as non-structural infill between the posts and beams, with timber framing supporting gravity loads. In the other type of structural system, the bales themselves are used as load bearing elements; both gravity and lateral loads are resisted by the straw bale walls. The bales are usually placed in a running bond. Adjacent walls are inter-connected at corners by continuing the running bond from one wall into another. At openings, however, partial length bales are needed, and these have to be made by cutting and restringing the bales. Conventional roof framing systems are often used.

Plaster applied to the bales plays an important role in conferring strength and stiffness to the bale walls, and helps integrate the somewhat irregular surfaces resulting from stacking bales into a more monolithic wall assembly. A variety of materials are used to create different types of plasters, and these are often reinforced with chopped straw fibers or plastic or steel wire meshes. The tensile reinforcement confers some degree of tensile strength and ductility to the plaster, and prevents the development of large, unsightly, cracks in the plaster as it cures.

A wide range of plasters are used in straw bale construction. The plasters function to fill in the irregular surface of the bale wall, integrate the bales into a coherent mass, and provide a smooth finish surface. The plaster also protects the bales from fire, insects, and rodents. The plaster must retard the entry of moisture into the wall during rainstorms, while allowing moisture generated inside the building to pass through the plaster (rather than condensing inside the bale wall); this requires that the plaster act as a vapor-permeable membrane while having low liquid permeability, much like the fabric Goretex®, used in outdoor clothing. In load-bearing construction, the plaster is part of the load path, and also supports and protects any mesh reinforcement that may be provided for tension and shear.

The primary binders used in straw bale plasters include clay, lime, and cement. Other constituents include an inorganic filler such as sand, water, and possibly chopped straw or other fibers. Earthen plasters rely on clay binders, sometimes supplemented by lime, cement, or even manure. Lime plasters use one of the various forms of lime, preferably a hydrated or slaked lime, and sand. Cement-based plasters are made using sand and portland cement, and may also include lime or pozzolonic admixtures such as fly ash.

The plaster mix should be formulated using a strategy of displacing as much volume of binder (such as clay or cement) by sand as practicable, while ensuring enough binder is present to fully coat and integrate the sand, and chopped straw, where present, into the plaster matrix. A well-graded sand, composed of particles having a large range of sizes, should be used. The straw may be chopped in a "chipper-shredder" machine, and should be screened to remove the finest sizes. This strategy will maximize strength and minimize cracking. Trial mixes having different proportions of constituents should be made in advance to assess strength and workability prior to use. Strengths of earthen plasters can be expected to vary with moisture content, while strengths of cement-based plasters can be expected to increase with time if sufficient moisture is available to allow cement hydration to continue.

Plasters are typically 1-1/2 to 2 inches thick, and are typically applied in three coats: the first (scratch) coat is used to fill in low spots in the wall and build up thickness; the second (brown) adds thickness and further flattens the surface; and, the finish coat provides color and texture to the visible surface.

Primary sustainability considerations — Straw is usually obtained as a waste product from the production of cereal grains, with rice and wheat straw being among the most common types of straws used in construction. Use in construction is an alternative to either burning the straw in place in the fields, or where this practice is prohibited, tilling the straw into the soil or disposing of the straw in landfill. Use in buildings, therefore, avoids air pollution and the immediate release of sequestered carbon into the atmosphere, or costly tilling or landfilling. Straw bale walls are thick and therefore provide good thermal insulation, reducing wintertime heating needs and reducing interior daytime temperatures in summertime. Interior plasters can provide significant thermal mass. However, the thick walls require larger roof areas than conventional construction. In urban areas, the thick walls reduce the amount of the lot that is available for use as indoor or outdoor space; where setbacks limit the dimensions of the building, the wall thickness results in less inhabitable space.

Sustainability impacts — Straw bales reduce pollution from field burning and the expense and resources required for tilling the straw into the fields or transporting and disposal in landfills. However, field baling equipment consumes fossil fuels, and the polypropylene baling twine commonly used is made from petrochemicals.

Bales ideally should be locally sourced to minimize transportation impacts. Rice or wheat straw is grown in almost all of the states; bales can be readily obtained after the grain is harvested. Typically surplus bales are stored and can be obtained year-round.

Straw bale construction is built on-site, typically with locally sourced bales. Plaster components are typically locally sourced with the exception of lime and cement binders, where used. Lime and cement production is associated with significant amounts of carbon emissions. A significant fraction of the carbon emissions (about half in the case of cement production) is associated with heating the source materials to the temperatures needed for the desired chemical reactions to occur, and thus is non-recoverable. The remaining emissions are associated with the chemical reactions that produce the cementitious materials. After hydration, some carbonization will occur in both lime and cement plasters. This carbonization will sequester or recapture a portion of the carbon released during the production of the cementitious materials—the portion associated with the chemistry. That portion associated with the burning of fossil fuels to achieve the high temperatures needed for the reactions to occur cannot be recovered by carbonization.

The bales themselves are heavy, and often must be carried and positioned by people working in pairs. As the walls gain height, the bales have to be raised before placement; scaffolding and pulley systems are often useful.

Bale walls have proven to be quite durable if precautions are taken in detailing and construction. Details must ensure water cannot migrate from the soil into a bale wall, ensure rain and wind-driven rain to not saturate the external plaster skins, avoid condensation within the bale wall by not having cold water supply lines running in the walls in contact with the bales and by ensuring the walls are vapor permeable (so that water vapor can travel through the bale wall without condensing). During construction, bales and walls must be kept dry. Any bale that gets wet or which was previously wet (as evidenced by discoloration from mold) must be discarded.

Many people appreciate the ambiance afforded by the natural finishes and thick walls characteristic of straw bale construction; the ambience may well contribute to occupant well-being.

Straw bale buildings can be designed to be very durable, and may continue to function for a hundred or more years. Since the materials have low sustainability impacts, there is less need to consider design for deconstruction. However, the bales can be reused or composted, and any posts and beams can also be reused.

Techniques to improve sustainability — As with many building systems, energy (or sustainability) embodied within the structural materials is relatively small compared with that consumed during the operation of the building over its lifetime. As such, the importance of architectural design considerations (siting, glazing, insulation, passive solar strategies, the choice of mechanical systems, and so on) cannot be understated. This is particularly the case with straw bale construction, given the very low embodied energy and high insulation value present in what is predominantly an agricultural waste product. Even so, there are opportunities to further reduce the impacts of this building system as follows:

- Load-bearing straw bale walls should be used rather than post and beam construction.
- Openings in the walls and the locations of cross walls should be planned considering the dimensions of the bales, to minimize bale cutting and retying on site.
- Earth plasters should be used, except possibly for walls that are designated to resist lateral loads. For these walls, lime or cement-based plasters should be considered.
- Portland cement used in footings should be minimized, possibly by incorporating boulders into the footing design, and possibly by using high volume fly ash or blast furnace slag to reduce the amount of portland cement.
- Structurally efficient and benign framing should be selected for the roof. This might involve site-built roof trusses, FSC certified lumber, or reused lumber.

Synergies with other building systems — Straw bale wall construction is typically founded on reinforced concrete footings and makes use of wood truss roofing systems. Some details can be found in CASBA (2000).

Code considerations — Only in the last two decades have straw bale buildings been built in the United States with building permits. In many cases these are issued in rural locations and on the basis of simple mandates or guidelines, rather than formal building codes that specifically address straw bale construction. In Texas and the western United States, two states, ten counties, and at least six cities have officially adopted a straw bale code. The city of Tucson, in Pima County, Arizona was the first jurisdiction to adopt a straw bale building code, in January, 1996. A helpful summary is provided in King et al. (2006).

However, straw bale construction is in a formative stage and knowledge of best practices continues to develop. In some cases, load bearing construction is prohibited, or out-dated details such as "pinning" are required. Efforts are being made to propose improvements to the Guidelines for Straw-Bale Structures (State of California 2002), with particular attention being given to the use of straw bale walls as a seismic force-resisting system. The codes rarely can keep pace with these developments, and thus can hinder good construction as much as they foster it.

Rating systems and straw bale — A primary goal of green building rating systems such as LEED is to influence the current market toward sustainable objectives. Natural building materials do not have a large market share in the United States and therefore the LEED rating system does not reward their use in proportion to their environmental benefits. This does not mean that buildings using straw bale cannot achieve LEED ratings. In LEED, straw bales can contribute to the local sourcing credits if the straw was regionally grown and baled. Straw bale wall assemblies can influence energy optimization credits where passive heating and cooling strategies are being employed. The Santa Clarita Transit Maintenance Facility designed by HOK received a LEED gold rating using straw bale infill walls. Building energy consumption is modeled to be 40 percent below California Title 24 energy standards. Straw and other agri-fibers can also contribute toward the Rapidly Renewable materials credit, but to achieve a credit, a minimum of 2.5 percent of all materials by cost would need to meet the criteria for rapidly renewable (harvested within a 10-year cycle or shorter)—this can be difficult to achieve because, as a waste product, straw is inherently inexpensive.

State of the art — An extensive series of tests and research on the material properties of straw bale structures was recently completed. A wealth of information on topics such as structural behavior, thermal and moisture properties, and fire safety was collected. Results are described at www.ecobuildnetwork.org/strawbale.htm and are summarized by King et al. (2006).

Some emerging applications of straw include the production of compressed straw block (similar to a concrete masonry unit in size, and an enlarged Lego® block in shape) and panels of straw known as strawboard (e.g. Meadowboard®) or structurally insulated panels made from straw (e.g. Agriboard®)

Bamboo

There are advantages and disadvantages to all building materials. Following are some general advantages and disadvantages for bamboo construction.

Bamboo advantages:

- rapidly renewable material;
- bio-based material;
- carbon sequestration;
- ability to deform without failure and regain original shape; and
- high strength and high strength to weight ratio.

Bamboo disadvantages:

- non-prismatic members and difficult connections;
- limited code development and research;
- durability;
- transportation energy; and
- insulating properties.

Bamboo plays a major role in the lives of over one-half of the world's population and has thousands of uses. Bamboo is technically a grass. While thousands of species grow across temperate and tropical climates, a handful of species have been specifically cultivated for their structural properties. Examples include Moso (p. *heterocycla pubescens*) in Asia and Guadua (*guadua angustifolia*) in Latin America. Structural bamboo has been widely used for buildings in many other continents, but widespread use in North America has been limited. The best structural poles do not grow well here, so they are usually imported. Code-related guidelines for the use of bamboo are improving, but are still minimal.

Bamboo is considered a "rapidly renewable material". Rapidly renewable materials are grown and harvested within a ten-year life cycle. Bamboo grows fast and mature poles can be harvested at three to five years. It is also a "bio-based material". Bio-based materials are those originally derived from living organisms and can be categorized based upon their carbon content. Bamboo forests sequester carbon and control erosion due to their extensive root systems. The underground root system quickly sends up new shoots alongside existing poles. These benefits must be enhanced by good forest management which includes ecosystem and soil considerations (Malin and Boehland 2006). Bamboo stands are not directly certified by the Forest Stewardship Council (FSC) but can gain certification as a non-timber forest product, "Where bamboo occurs within the matrix of an FSC-certified natural forest or plantation it may be certified/labeled as a non-timber forest product (NTFP) following FSC's general guidance for NTFPs" (FSC, 2004). . The International Network for Bamboo and Rattan (INBAR) continues to study future development of a sustainable management standard specific to bamboo forests that also considers poverty alleviation and issues specific to small holdings.

Although bamboo has often been considered "the poor man's wood", it has recently been used for higher end structures by innovative architects such as Simón Veléz, Jorg Stamm, Oscar Hidalgo and Shoei Yoh. Modern uses have been for upscale resorts, residences, and the Expo 2000 pavilion in Hanover, Germany. The Hanover pavilion, designed by Colombians Simón Veléz and Marcello Villegas, is a two story, 21,500 square-foot structure with 24-foot overhangs. It was built to scale in Colombia and load tested prior to building department approval in Germany.

Durable and lightweight roof systems are made using bamboo shingles and bamboo framing for thatched roofs. Bamboo is sometimes used as concrete reinforcement in place of steel rebar or in fiber-reinforced concrete. Oscar Hidalgo has developed a concrete reinforcing system using Guadua splits woven into cables (Elizabeth and Adams 2005).

The affordable housing potential for bamboo is tremendous. In parts of Latin America and India, bamboo is used for structural post and beam frame systems with earthen or concrete plaster over bamboo lath being used for the walls. This low-cost and quickly built structural system has increased insulation and fireproofing protection over bamboo-only structures. Evaluation of this system for use in seismic regions requires testing of designs that provide complete load paths. Hybrid construction in the Middle East has consisted of using large structural bamboo poles as bond beams and roof systems on earthen structures.

Solid-section manufactured bamboo — The cross section of hollow bamboo culms varies over the length of the culm. A more uniform material can be created by bonding together either chips or flakes, to make bamboo OSB, or strips, to make solid-section panels. Strips can be assembled to make single-ply or three-ply panels, with the strips in any one ply all oriented in the same direction and alternate plies oriented at right angles to one another. The strips are obtained by cutting whole culms radially, boiling the strips in water containing lime and/or borate to remove starches, and then drying and trimming the strips to shape.

Several efforts to commercialize solid section bamboo beams are underway in the U.S. A prototype bamboo I-joist was developed at Santa Clara University and showcased in their 2007 Solar Decathlon house. Initial tests led to the selection of bamboo OSB for the web, but supply chain interruptions forced the substitution of 3-ply panels. The flanges were formed by laminating material cut from single-ply panels. While unjointed bamboo flanges can achieve tensile strengths of 15,000-19,000 psi, the offset finger joints used in the joist proved to be the weak link, limiting the ultimate strength of the laminated flange (gross area) to about 4000 psi. Webs made from bamboo OSB had average ultimate shear strengths of about 2100 psi; while those made from 3-ply material had average ultimate shear strengths of about 2300 psi. The average modulus of elasticity ranged from approximately 2,000,000 psi to 2,300,000 psi. The shear modulus using bamboo OSB webs was about 250,000 psi, while it was about 140,000 psi for beams made with webs fabricated from 3-ply bamboo web material. Thus, the bamboo OSB was found to be slightly weaker and much stiffer than the 3-ply bamboo web material. Note that stiffeners should be provided where bamboo OSB webs are used, just as for conventional wood I-joist members. (Aschheim 2009)

A preliminary acceptance criteria was developed for the bamboo I-joists used in the Solar Decathlon. The acceptance criteria was based on existing acceptance criteria for wood I-joists (ICBO 2004) and bamboo culms (ICBO 2000) (Aschheim 2009).

Code considerations — Mechanical testing of structural bamboo has recently been conducted at the University of Hawaii and Washington State University. In the year 2000, the International Code Council (ICC) approved AC162 (ICBO 2000), *Acceptance Criteria for Structural Bamboo*. The first evaluation report for structural bamboo poles is ICC ESR-1636 (2005) completed for Bamboo Technologies, a residential builder located in Hawaii. The ICC report indicates the pole species, Tre Gai (*bambusa stenostachya*) from Vietnam, and the pole size, between 2-3/4 and 3-1/4 inches in diameter. Poles are to be borate treated and quality control stamped per the report. The ICC report is to be used for Type V non-rated residential and commercial structures limited to one story and 2000 square feet.

Structural performance — Bamboo is a lightweight building material and strength varies by species. The material properties of structural bamboo are likely unfamiliar to most structural engineers. Table 3.6-1 summarizes test results determined by Washington State University (2002) and design values in the ICBO report ESR-1636 (2005) for the species used by Bamboo Technologies (*bambusa stenostachya*).

Table 3.6-1. Bamboo material properties (Bambusa Stenostachya)

Material property	WSU Test average WMEL 01-047	ICC Report ESR-1636
Tension (psi)	14,003	1,110
Compression (psi)	6,249	590
Shear (psi)	1,132	185
Bending (psi)	14,967	1,500
Modulus of Elasticity (psi)	2,298,000	1,700,000

Bamboo in compression has a tendency for premature buckling due to a lack of straightness. The full compressive strength is difficult to achieve in practice based upon pole section variability. Bamboo tends to creep under stress, producing large bending deformations without failure, regaining its original shape once the loading is removed. Bamboo buildings with lightweight roofs and an intentionally designed lateral load path have fared well during earthquakes. Recently constructed structures up to 60 feet tall in Armenia survived near the epicenter of an earthquake in 1999. In Costa Rica, 20 houses designed by bamboo innovator Jules Janssen survived near the epicenter of an earthquake that measured 7.5 (Elizabeth and Adams 2005).

The most difficult aspect of structural design remains the connections, since bamboo tends to split when nailed. Clear specifications for connection design and construction are yet to be developed. Designers such as Simón Veléz, Marcelo Villegas, Renzo Piano, and Bamboo Technologies have designed and built creative and effective connections. Connection options are many: mortise and tenon, pegged and lashed with fiber ties, steel plate and bolt systems, rebar dowels in concrete filled bamboo ends, etc. Simón Veléz has been using bolted connections with grouted nodes to achieve 26 foot long cantilevers and 60 foot spans in roof structures. Some designers are also using redundant roof systems by installing a second set of rafters in a mini-truss layout. This prevents connections from being placed in tension for wind uplift loads.

Durability — Untreated exposed bamboo typically cannot withstand pests, water, or contact with soil. Durability varies by species, but untreated bamboo typically provides one to three years of life exposed and in contact with soil, four to six years under cover and free from contact with soil, and 10-15 years in interior uses. There are some cases of untreated bamboo lasting 60 years, but it is not the norm.

Treated bamboo regularly lasts 15 years in exposed conditions and 25-50 years protected. (Janssen 1995).

Treatment processes include both traditional and chemical processes with varying levels of toxicity and waste production. The favored traditional method is smoking. Most poles to be used as structural bamboo undergo either a pressure treatment (Modified Boucherie method) or are subjected to a boron based liquid solution. Boron liquid treatments are compostable and benign in comparison to other liquid treatment options. Maintenance of bamboo is similar to wood and varies by level of exposure and climate.

Reuse and disposal — Bolted, tied, or mortise and tenon joint connections can be disassembled and reassembled. Bolted and then grouted connections are more difficult to disassemble and reuse, although the grouted node can be cut off and the remainder of the pole reused. Fiber recycling can be done with a process similar to that of recycled paper, but such recycling is not widely done in industry. Bamboo itself safely and easily biodegrades. Potential environmental concerns associated with structural bamboo disposal would have to do with toxic treatments or adhesives, where these may have been used.

Specifications — Specifications for structural bamboo can be provided in section 069000, which is an unassigned section in CSI *Masterformat* (2004). The Federal green specifications indicate section 069000 to be used for Alternative Agricultural Products such as bamboo, straw, corn and soy-based materials.

Synergies with other building systems — Bamboo has low thermal insulating properties and thermal mass when not coupled with additional finishes or concrete/earthen hybrid construction.

Rating systems and bamboo — Use of bamboo in a building project will contribute toward achievement of a materials and resources credit in the LEED green building rating system. In LEED Version 2.2, credit MR6 requires that 2.5 percent of the total value of all building materials and products, by cost, are rapidly renewable materials such as bamboo.

State of the art/Case studies — Colombians Simón Velèz and Marcelo Villegas have designed and built hundreds of modern bamboo homes, resorts, clubhouses, pavilions and a Cathedral in South America. Their unique aesthetic is contributing to a bamboo revival in some parts of the world.

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Additional resources

American Bamboo Society: www.americanbamboo.org

Bamboo Technologies: www.bambootechnologies.com

California Straw Building Association (CASBA): www.strawbuilding.org

Cob Cottage Company: www.cobcottage.com

Development Center for Appropriate Technology: www.dcat.net

Ecological Building Network website: www.ecobuildnetwork.org

Earth Architecture: www.eartharchitecture.org

Green Home Building: www.greenhomebuilding.com

International Network for Bamboo and Rattan (INBAR): www.inbar.int

Natural Building Network: www.naturalbuildingnetwork.org

Rammed Earth Works: www.rammedearthworks.com

The Last Straw — The International Quarterly Journal of Straw Bale and Natural Building, www.strawhomes.com

Earth Construction - A Comprehensive Guide: Hugo Houben and Hubert Guillaud, Intermediate Technology Publications, London 1994

4.0

INFRASTRUCTURE

Sandeep P. Mathur, P.E.

While the ideas of sustainability are gaining popularity in the building arena, the basic concepts can and should be extended to roads, bridges, and other infrastructure applications. The highway system in the United States includes nearly 4 million miles of public roads, including 46,837 miles of interstate and 115,319 miles of other National Highway System routes (AASHTO SPA 2009), along with the nation's inventory of over 590,000 bridges (AASHTO 2005) and numerous support structures. Large parts of this transportation network are in need of repair, rehabilitation, restoration or replacement, demanding massive amounts of resources. In the transportation design arena, the structural engineer has a much more dominant voice in the selection of the form, type, and location of various elements of the infrastructure network, and thus, can exert greater influence in improving the sustainability of these elements.

This section will discuss the concepts of sustainability as applicable for typical bridges and roadways, as well as provide an overview of areas for structural engineers to consider in improving sustainability of nation's infrastructure. Means of improving sustainability that are typically beyond a structural engineer's ambit of influence, such as national policies on oversize/overweight vehicles; access management; expedited environmental clearances; ensuring worker safety; minimizing public disturbance; and other construction issues are not covered in this section.

Opportunities for structural engineers to improve sustainability

Sustainability of the nation's infrastructure can be advanced by structural engineers not only by use of materials that have less embodied energy, but also by use of details and techniques that ensure durability, maintainability and reusability and thus help mitigate deterioration and save scarce resources. Use of methods that accelerate and facilitate construction/rehabilitation will also aid in this effort.

To balance the social, economic, and environmental impacts of new construction or major renovation, it is important to keep in perspective that while material and resource consumption, along with related emissions, occurs throughout the life span of a facility, the large part of this takes place during its "use" phase. This is the fuel burned by all vehicles passing over the infrastructure, and is exacerbated by construction congestion and traffic queues over the life of the structure. Saving even a small amount of this fuel and these emissions is critical to designing more sustainable transportation infrastructure. Hence, while many of the methodologies mentioned in this section can be used to improve the life span of the transportation network, it is important for structural engineers to analyze their design situation, evaluate the various inter-related issues, and employ a comprehensive design approach to improve the sustainability of our nation's infrastructure.

Some of the areas for structural engineers to explore in improving the life and sustainability of new and existing transportation facilities are discussed below.

Bridges

Each structural component presents engineers with unique opportunities for improved sustainable performance.

Bridge decks — Bridge deck deterioration is one of the leading causes of structural deficiency in bridges. With majority of bridge decks built with concrete, there are many opportunities available to structural engineers in making bridges more sustainable, which include the following:

Specify complementary cementing materials (CCMs) and chemical admixtures in concrete bridge decks. Proper use of these materials can help achieve targeted performance needs, such as decreased permeability, increased workability, and reduced water requirements. Decreased permeability impedes chloride intrusion from deicing salts, which is used in many parts of our country for thawing ground snow. The use of CCMs, to offset cement content in reinforced concrete, reduces carbon dioxide (CO_2) emissions that result from manufacturing of portland cement clinkers, minimizes waste and reduces the amounts of material placed in the landfills. For detailed discussion on use of these materials to improve sustainability, see Section 3.2 – Concrete of this report.

Besides CCMs, consider use of other materials and design methods to *control concrete slab cracking* such as specifying largest size aggregates that can be properly placed, using smaller diameter bars at closer spacing (Nilson and Winter 1986), providing adequate cover (2-in. minimum for top mat steel), and using epoxy-coated or corrosion resistant bars in areas subject to chloride ingress (NCHRP Report 123 1985 and NCHRP Report 333 2004). Structural engineers may also consider use of *bi-directional post-tensioning* in bridge decks to provide a permanent state of compression during service. A combination of transverse and longitudinal post-tensioning, which provides a biaxial state of compressive stress in the deck, resists the formation of cracks that typically could allow chloride penetration.

To reduce the use of virgin materials, the structural engineer should investigate the use of *recycled concrete as aggregate* in concrete decks. Recycled-concrete aggregates have been used successfully in many European countries, reducing the environmental impacts related to processing and extracting original materials and the amount of concrete filling landfills. Also, *lightweight aggregates*, particularly those engineered from natural resources, and lightweight concrete requires less fuel to transport and less energy usage in construction and their use should be explored. The California Department of Transportation (Caltrans) has used expanded shale structural lightweight concrete in bridge decks for several years. The use of lightweight aggregates should be considered especially in seismic areas where reducing the dead load is an important factor. For more discussion on aggregates, see Section 3.2 – Concrete of this report.

The benefits of using *prefabricated components* in accelerating bridge constructions are well known. Besides minimizing traffic disruptions and congestion, prefabrication improves constructability, work zone safety, and minimizes the impact on the local environment (because less work is conducted over sensitive environmental areas). The quality of the components is also improved because the production occurs in a controlled environment, which generally results in more-durable components and lower life-cycle costs. Prefabrication offers exceptional advantages for deck construction, particularly for removing deck construction from the critical path of bridge construction schedules. Partial-depth prefabricated deck panels can act as stay-in-place forms and assist in accelerating deck construction (FHWA TIG 2009), and their use should be explored.

Consideration should be given to selection of proper *bridge deck protective systems* that slow the rate of chloride intrusion. These include *wearing surfaces* such as asphalt overlay, latex-modified concrete, low-slump concrete, or integral (sacrificial) concrete. These overlays have been used by various state Department of Transportations (DOT) with mixed results (Tonias 1994). Integral wearing surfaces that are cast monolithically with the bridge deck have been successfully shown to improve long-term service performance.

Cathodic protection, powered with solar panels (where applicable), is a good method for protection against deicing salt-induced reinforcement corrosion in concrete structures, and especially bridge decks. Cathodic protection is recommended wherever long-term protection is required on corrosion damaged structures with a significant residual life or, increasingly, to new undamaged structures in aggressive chloride environments (CPA 2009).

Where *deck joints* are used, they should be selected to have the maximum useful design life for the intended application. Conventionally over a 75-year bridge design life, joints are expected to be replaced every 10 to 12 years (resulting in significant construction and related traffic congestion activities). Jointless bridges (see further discussion in the following Substructure section) and new joint systems with a longer service life can reduce the road closures needed for joint replacement – which reduces emissions due to traffic congestion.

Structural engineers should ensure that *bridge deck drainage issues* are properly addressed. Details requiring consideration for proper bridge drainage have been well documented (FHWA TA 2009). To the extent possible, bridge joints should be eliminated (see more discussion under the following Superstructure section). Where scuppers or bridge drains are required, they should be appropriately sized and spaced to prevent any deck ponding or hydroplaning effects. For closed drainage systems, access for cleaning and flushing the system must be provided (NCHRP Report 123 1985). Consideration should be given to capturing and treating surface runoff using underground leaching basins, mechanical treatment systems, storm water retention basins and other treatment means before releasing it in nearby streams and water bodies. Some agencies have created ponds with beautiful landscaping next to large inter-changes turning eyesores into eyefuls.

Main load-carrying members — To lessen material consumption, minimize waste and reduce transportation costs, structural engineers are encouraged to use *high-performance materials* and to fully optimize member designs. Long-term performance benefits can be achieved in highway structures when high-strength materials (HSM), primarily steel or concrete, are properly used in the superstructure support system. The main benefits for utilizing HSM in bridge elements is to extend span lengths of bridges with commonly fabricated girder types, reduce the depth of superstructures, and eliminate girder lines to offer cost-efficiency. The vast majority of concrete bridges in the United States are constructed with compressive strengths less than 10 kip per square inch (ksi) (FHWA HPC 2009). Current AASHTO design specifications allow, at the discretion of the engineer, the use of higher strengths if tests are conducted to establish various mechanical properties of concrete. Where it will result in a design with less material overall, structural engineers are encouraged to use higher concrete strengths (8 to 12 ksi) in concrete girders, higher grade steel reinforcement (75 ksi) or high steel strengths (50 to 75 ksi) in rolled and plate girders, and conserve virgin material.

Transportation officials consider *life-cycle cost analysis (LCCA)* an important technique for assisting with investment decisions (NCHRP Report 483 2003). LCCA is an engineering economic analysis tool that allows transportation officials to quantify the differential costs of alternative investment options for a given project. LCCA can be used to study new construction projects and to examine preservation strategies for existing transportation assets (FHWA Asset Management 2009). LCCA considers all agency expenditures and user costs throughout the life of an alternative, not only initial investments. If not already factored, an LCCA should also consider all costs associated with extraction of natural resources, environmental impacts of manufacturing and final development, transportation costs, and decommissioning or reuse of the structure. It is recommended that during the initial design phase various span arrangements, girder types, material types, and spacing be studied, along with life-cycle costs for various alternates, to find the most optimum solution. While the lowest life-cycle cost option is usually preferable, the structural engineer should evaluate the social, economic, and environmental aspects of the alternatives before final selection. It is important that structural engineers involved in bridge design be knowledgeable of this holistic design approach and how to implement it to justify the final structure type and location selection. If used objectively, LCCA can play a key role in improving the sustainability of the infrastructure system.

Structural engineers are encouraged to actively participate in *context-sensitive design efforts* and to develop applications of criteria and standards so that roads and bridges can better fit in their context. A context-sensitive solution (CSS) is a collaborative, interdisciplinary approach that involves key stakeholders in the development of a transportation facility that fits its physical setting and preserves scenic, aesthetic, cultural, historic, and environmental resources, while maintaining safety and mobility. CSS is an approach that considers the total context within which a transportation improvement project will exist.

CSS principles include the employment of early, continuous and meaningful involvement of the public and all stakeholders throughout the project development process. Structural engineers should use the CSS methodology in creating new approaches to the flexible application of design controls and standards, with more attention to pedestrians, bicyclists, and transit. These efforts may include the following:

- Select alignments and bridge skews to minimize footprint and environmental disturbance. It is important that final span arrangement and alignment selection consider not only economic factors, but also development impacts on the surrounding environment and natural habitat;
- Specify use of locally available materials;
- When applicable and justifiable utilize design exceptions, such as reduced geometric criteria or reduced live load to suit the facility with its usage and expected service life;
- During design phase consider the function of the road and vehicle speed relative to their context in terms of access and mobility for all users;
- Consider ways to improve compatibility of roads and bridges with the environment by using vegetation, finishes, and other features that accentuate and improve esthetic appeal for users both on and off the roadway. Use xeriscaping, or dry-landscaping, by using low maintenance, drought-resistant adapted or native plants;
- Coordinate with utility companies prior to bridge replacement or rehabilitation to minimize construction surprises and delays; and
- Active involvement of structural engineer in public meetings to address public concerns.

Engineers should keep an eye for the future while designing members, and also for possible widening and, in longer term, deconstruction. Design parameters should be based on future predicted climate conditions. In terms of bridge design, this means designing based on weather model predictions instead of historical weather data. When only limited funds are available and only a part of the facility is being built initially it is more pragmatic to strengthen the exterior members to accommodate future anticipated widening. *Adaptability and deconstruction* should be considered in design of transportation facilities by structural engineers by using the following:

- prefabricated panels for quicker construction or deconstruction;
- phased construction possibilities;
- cantilevering off the existing fascia members by strengthening them;
- existing structure to support new members;
- semi-integral abutments that allow jacking-up of the superstructure when future widening is anticipated;
- movable barriers to adjust traffic volumes;
- simple connections with clear load paths;
- standard details and components;
- few large members rather than many small members;
- mechanical fasteners, avoiding adhesives and welding;
- use of sections from a demolished bridge or an overpass for purposes of shore erosion control or stabilization, ecosystem restoration, and/or marine habitat creation; and
- reuse of functionally obsolete and structurally deficient bridges for temporary detour routes and for foot/bike paths where possible.

As mentioned previously, structural engineers play a vital and more dominant role in the field of bridge engineering. This provides them with an opportunity to design structures using forms and styles that *optimizes material properties*. Whether it is by using arches, trusses, cables, pre- or post-tensioning, hybrid members, haunched girders or strengthening plates in critical stress regions, structural engineers should utilize innovative designs to minimize the mass of material, evenly distribute forces between elements, and maximize material strengths. By making best use of high strength materials, superstructure spans can be optimized to reduce intermediate piers, reduce maintenance, and enhance the visual appeal of bridges.

Structural engineers should keep abreast on the use of newer and more advanced *non-destructive testing (NDT) techniques* to identify existing member properties. At a time when existing infrastructure is aging and in great need for rehabilitation, use of non-destructive testing techniques including impact echo, ground penetrating radars, dye penetrant, strain gages, ultrasonic methods, and other NDT methods should be preferred, over material removal. For new construction, inclusion of strain gauges at key locations can help in security monitoring and long-term evaluation of these bridges.

Structural engineers should incorporate features and details that facilitate maintenance work. A prime design consideration must be access for maintenance and inspection. *Accessibility* to component parts that require maintenance such as bearings, hinges, drainage and lighting systems and internal access to closed structures, with due consideration for ventilation and illumination, should be provided.

The natural aging of steel bridge structures coupled with harsh environments and exposure to roadway deicing chemicals has created a growing corrosion control maintenance burden on the nation's bridges. Until the mid to late 1970s, virtually all steel bridges were protected from corrosion by three to five thin coats of lead and chromate containing alkyd paints applied directly over mill scale adherent to the formed steel (Turner 2009). The presence of potentially hazardous materials in existing bridge paint has complicated maintenance processes and created dramatic cost increases for major and routine level bridge paint maintenance. Use of uncoated weathering grade steel for bridge superstructure offers several advantages. It provides both short-term environmental advantage by eliminating the need for initial painting of the structure, and long-term advantage by eliminating the removal of the coating and disposal of contaminated blast cleaning debris over the life span of the structure. While weathering steel has been used in bridges and other large structural applications for some time now, it is not suitable in all applications (FHWA TA 2009). Some understanding of various *corrosion mitigation techniques,* and applicability of weathering steel, is important for the structural engineer. When deciding on use of paints or coatings, volatile organic compound (VOC) emissions, applicability, durability, and life-cycle costs are some important factors that must be considered.

Where possible *solar collectors*, with back-up systems, should be used to power digital signage and lighting on the bridges. If necessary, and available, procure grid-source green electricity.

Substructure — Depending on the loading and soil parameters, appropriate substructure units should be selected. While hammerhead pier configuration has the least footprint, multi-column piers are more effective for wider bridges. Web walls may be utilized on stream crossings where there is a possibility of debris collection between columns. Shape, location, scour (for stream crossings), clearances, maintenance issues, and material strengths are important parameters that should be considered in *bridge pier selection, with an effort to reduce their numbers and footprint.* Spans should be made as long as feasible and intermediate piers should be avoided. Use of prefabricated pier columns and caps should be explored.

Bridges that minimize joints and bearings such as *jointless bridges* are encouraged. Joints leak over time, allowing salt-laden water and other contaminants to enter the structure through the joint, accelerating corrosion damage to girder ends, damaging bearings, and supporting substructures. To prevent these damages, the concept of bridges with integral or semi-integral end bents has been gaining momentum throughout the country, especially for typical roadway bridges with spans up to 200 feet. Bridges with integral end bents utilizing a single row of piles offers numerous advantages including the following (Wasserman and Walker 2004):

- increased redundancy, which reduces damage in catastrophic events;
- superior protection for girder ends;
- faster construction;
- minimized tolerance problems in construction;
- reduced maintenance costs and increasing service life;
- shorter end spans that are more resistant to uplifts; and
- improved ride quality with fewer joints and diminished vehicular impacts.

In congested areas, to reduce bridge end spans and eliminate abutment slope protection, use of vertical *mechanically stabilized earth (MSE)* walls in front of stub abutments should be explored. Based on past experiences, use of MSE walls accelerates construction, with more efficient use of resources, as opposed to constructing traditional retaining walls.

Structural engineers should keep abreast on new products and design methodologies to utilize the best solution available. *Use of new materials*, such as fiber-reinforced polymers (FRP), expanded polystyrene (EPS) geofoam, zinc-epoxy dual coated bars, etc. are gaining momentum. There are different varieties of FRP and methods for attaching them to a structure. FRP have been used successfully for repair, strengthening, or retrofit of piers and girders. EPS geofoam is lightweight, rigid foam plastic that is approximately 100 times lighter than most soil and at least 20 to 30 times lighter than other lightweight fill alternatives. EPS geofoam can be used as an embankment fill to reduce loads on underlying soils, repair slope failures, reduce lateral load behind retaining structures, accelerate construction on fill for approach embankments, and minimize differential settlement at bridge abutments. It has been successfully used by various state Department of Transportations (FHWA Corporate Research and Technology 2009). Engineers must continually identify innovative materials and construction techniques that accelerate project schedules and prolong structure design life.

Foundations — Consideration should be given for in-place soil modification, including liquefaction mitigation, instead of large scale soil replacement, if the environmental and engineering teams determine that contaminated soils can be safely left in place. In-situ *solidification/stabilization (S/S)* involves mixing a binding reagent into the contaminated media or waste using soil augers and has been used to treat both organic and inorganic hazardous waste constituents. Cement-based mixture designs are most commonly used for S/S treatment of hazardous waste, however, a variety of additives such as fly ash, hydrated lime, or bentonite can also be used to meet specific project requirements. Ex-situ remediation techniques include chemical treatment, land farming, and bio-remediation. Though the S/S approaches are mostly under the aegis of a geotechnical engineer, the structural engineer must work closely to facilitate the use of these techniques on a specific project.

For stream crossings, it is important to protect pier and abutment footings against scour failure. Proper understanding of the scour and its impact on pier column geometry, footing depth, and pile unbraced length should be addressed by the structural engineer. Use of locally available material and recycled crushed concrete for *scour mitigation* should also be explored. Where practical, piers should be located out of the main current in the stream, for example outside the thalweg at high flow, and sufficient freeboard should be provided from underneath the bridge superstructure.

Consider *self-consolidating concrete (SCC)* for drilled shafts and foundations in order to expedite construction and reduce problems associated with poor consolidation around congested reinforcement. SCC offers numerous advantages including excellent pumpability and flowability, high resistance to aggregate segregation, reduced permeability, and ease of placement requiring fewer workers for a particular pour.

Protect foundations from aggressive environments by use of proper cement type, coating on timber piles, painting or cathodic protection of steel piles, adequate concrete covers and other techniques that prolong their useful life.

Pavements

By improving ride quality, extending pavement life, and ensuring safety, pavement preservation programs allow people and goods to continue to move safely and efficiently throughout the nation. Structural engineers who are involved in road design should consider the following strategies to improve sustainability of roads.

Minimize roadway width — Roadways should provide the minimum pavement width to support travel lanes and emergency, maintenance, and service vehicle access. This width should be based on traffic volume and minimum road speeds. Designers should take advantage of reduced requirements for low-volume roads as stipulated in AASHTO guidelines. For example, 20 feet is the suggested minimum width for a two-lane road with a design speed of 30 miles per hour and an average daily traffic of 50 to 250 vehicles.

Reduce the total length of roads — When considering new corridors usually the alignments with least footprint are those that have the shortest route. Shorter roads reduce the amount of pavement, curb, gutter, and storm-sewer construction, saving money on construction, design, and materials. Additional long-term savings come from reduced maintenance costs.

Minimize right-of-way widths — A right-of-way that is wider than necessary results in needless loss of trees. It consumes land better used for other purposes. Encroachments into watershed areas, landmarks, parks, prime farmlands, and those affecting habitat should be minimized and properly mitigated.

Reduce pavement roughness — Increases in pavement roughness lead to higher fuel consumption (due to increased friction between the tires and the pavement) and more tire wear. They also lead to slower driving speeds since drivers tend to be more cautious — and thereby lead to lower lane capacity.

Treat storm water at edges of roadways — Where topography, soil, and slope permit, use vegetated open channels in the road right-of-way to convey and treat storm-water runoff. Curbs and gutters provide no storm-water treatment benefit. The best way to mitigate storm water impacts from new developments is to treat, store, and infiltrate runoff onsite before it can affect water bodies downstream. Innovative site designs that reduce imperviousness and smaller-scale low impact development practices dispersed throughout a site are excellent ways to achieve the goals of reducing flows and improving water quality. Consider the use of open channels, grass channels and dry swales to convey storm water. Open channels cost as little as one-third of curb-and-gutter or drainpipe systems.

Use LCCA for pavement selection decision — Engineers are encouraged to use LCCA during the pavement selection decision process. Various state DOTs base their design selections upon life-cycle costs that include the effects of user delay and increased vehicle operating costs due to the presence of a work zone.

Develop context-sensitive design — Several of these techniques have been discussed earlier (see discussion earlier), and should include encouraging tree plantation in right-of-way while maintaining clear sight distances.

Use existing local resources and reuse old materials — Use of existing local materials, reuse or recycling of old highway materials and other secondary and waste materials where practical should be encouraged. Processes involving in-place reuse of existing pavement materials during reconstruction should be considered. This not only reduces the requirement for new materials, but also does away with the need for the associated transportation impacts. Several state DOTs currently use recycled crushed concrete as aggregate, with many case studies available for reuse of recycled materials (RMRC 2009). ASTM C33 (2008) for aggregate can be applied to crushed concrete. ASTM D448 (2008) applies to backfill or sub-grade, and can be used to grade crushed concrete aggregate. SAFETEA-LU directs the use of debris from bridge demolitions in shore erosion control or stabilization, ecosystem restoration, and marine habitat creation.

Use of fly ash in pavement design — The many benefits of incorporating fly ash into a portland cement concrete have been demonstrated through extensive research and countless highway and bridge construction projects (FHWA Pavements 2009). For in-depth discussion on use of fly ash refer to Section 3.2 – Concrete of this report. In pavement design, fly ash can be used in the following situations:

- in stabilized base course when combined with aggregates;
- in production of flowable fills that can be used as a backfill material for various applications;
- as an effective agent for chemical and/or mechanical stabilization of soils, such as soil stabilization, soil drying, and control of shrink-swell;
- can be used as mineral filler in hot-mix asphalt (HMA) paving applications;
- in grouts used to fill voids under a pavement system without raising the slabs (sub-sealing), or to raise and support concrete pavements at specified grade tolerances by drilling and injecting the grout under specified areas of the pavement.

Use of precast prestressed pavement — Consider the use of precast prestressed pavement to accelerate construction, improve quality, and save energy. This is an emerging technology that is being tested by several state DOTs.

Future challenges, opportunities, and directions

Not only do lives depend on safe roads and bridges, but the U.S. economy relies on transporting goods to market and getting workers to their jobs. Congestion in the cities in the United States costs several billion dollars each year and wastes billions of gallons of fuel (TTI 2009). The demands on our highway network are greater than ever, and they will continue to grow into the next millennium. While awareness among structural engineers to make the nation's infrastructure more sustainable is increasing, more needs to be done. Detailed guidelines for structural engineers and their role in helping achieve long term sustainability of the infrastructure are needed.

On the international front, several efforts have been undertaken to arrive at set of goals and corresponding indicators to measure sustainable practices in civil engineering projects. United Kingdom's Institution of Civil Engineers has developed a proprietary assessment and award scheme for publicly awarding high environmental quality in civil engineering projects by weighing practices in various categories, which include environmental management, land use, water issues, energy, waste, transport, and use of materials (CEEQUAL 2009). The International Federation of Consulting Engineers (FIDIC) has developed project sustainability management guidelines that describe a process for ensuring that a project's goals for sustainable development are aligned and traceable to goals and priorities that are recognized and accepted by society as a whole (FIDIC 2009). The UK Highway Agency (UK

Highway 2009) identifies that any future plans should consider the following three key issues:

- Reuse versus new build. Any decision for new build options should not be automatically promoted without consideration of other approaches, for instance, to maintain and reuse the existing road.
- Design for minimum waste. For highway construction or maintenance this relates to the fate of any residual material, as well as, the sources of potentially recyclable material that can be used at the site or elsewhere and the use of life-cycle approach for optimum resource selection.
- Aim for lean construction. This cuts across many issues, for instance, minimizing waste, energy, and water usage. It also encompasses broader concepts such as value for money, good management (up and down the supply chain), and innovation.

The choice of a poorly designed infrastructure element can lead to environmental impacts decades into the future, causing our children and grandchildren to bear not only the economic cost of future maintenance, but the societal cost of continuing carbon emissions and global climate change that the structural design community has the opportunity to mitigate in the original design. This guide is an attempt at increasing every structural engineer's important role in improving sustainability of infrastructure in the United States. As mentioned earlier, that while many different ways of improving the life span of the transportation network have been presented here, it is important for structural engineers to analyze their design situation, evaluate the various inter-related issues, and employ a comprehensive and holistic design approach to improve the sustainability of our nation's infrastructure.

While only bridges and highways have been covered here, some of these basic issues are also applicable to wider range of transportation network, including mass transit, railroads, and airports.

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5.0

CASE STUDIES

Many projects have been designed and constructed employing many of the sustainable practices discussed in this Guideline. This section presents the following case studies and demonstrates specific examples of sustainable design:

Section 5.1 — Candela Structures

Section 5.2 — San Francisco Federal Building

Section 5.3 — Dalby Forest Visitors Center

Section 5.4 — The Nomadic Museum

Section 5.5 — One Bryant Park

Section 5.6 — Ithaca College Business School

Section 5.7 — The David Brower Center

Section 5.8 — BedZED

Section 5.9 — Crafting Green Specifications

Section 5.10 — The Savill Building

The Sustainability Committee acknowledges the invaluable contributions of time and energy by the following committee members who identified the case study possibilities, contacted and worked with the outside authors to develop content and obtain permission forms, and helped edit and format the case study chapters: Jennifer Anna Pazdon, Mark Webster, Helena Meryman, Terry McDonnell, and Sarah Vaughan.

5.1

THIN SHELL STRUCTURES OF FELIX CANDELA

Jennifer Anna Pazdon

Figure 5.1-1. Bacardi y Cia Warehouse, exterior view of groined vaults. (Photo by Bruce M. White)

Project:	**Thin Shell Structures of Felix Candela**
Building Type:	Industrial/Commercial
Location/Year:	Mexico/1950s – 1960s
Structural Engineer:	Felix Candela
Designer:	Felix Candela
Area:	Various

Introduction

Felix Candela's thin shell concrete structures offer an instructive and enduring example of the structural engineer's role in sustainable design. Candela was a designer/builder who valued methods of construction as integral to the ultimate design of his structures. With these considerations in mind Candela realized works that are durable, employ minimum and locally sourced, structural materials, and achieve various synergies. Although Candela's work precedes the lexicon of sustainability employed today, his writings and lectures point to conservation of resources, as exemplified by his structures, as a fundamental goal of the engineer: "this fact makes me very proud, because any development that saves money and effort in construction contributes more to the general well being of mankind than all the messianic claims so common in the profession (Candela 1991)". Today Candela's beautiful, economical structures provide a road map towards sustainable design and construction for contemporary engineers.

The hypar form

To guarantee the economic competitiveness of his works compared with conventional construction, Candela used the hyperbolic paraboloid (hypar) form: a saddle shape described by straight lines that is inherently stiffened by its curvature (Fig. 5.1-1). By using this ruled surface, or one that can be described by a series of straight lines, Candela greatly expedited the construction of formwork. The hypar shape exploits concrete's strength in compression, minimizing material usage by operating in a primarily in-plane stress state. Modern analyses confirm that demand stresses within Candela's shells are well below capacity of the concrete with a characteristic thickness of 4cm and a span of 15m. Although the curved form may seem exotic, building experience and a concern for economy motivated Candela's use of the hypar. Unlike today's contemporary trend toward visually complex designs lacking structural logic, Candela utilized his thorough understanding of the hypar form to simplify analysis and construction (Fig.5.1-2).

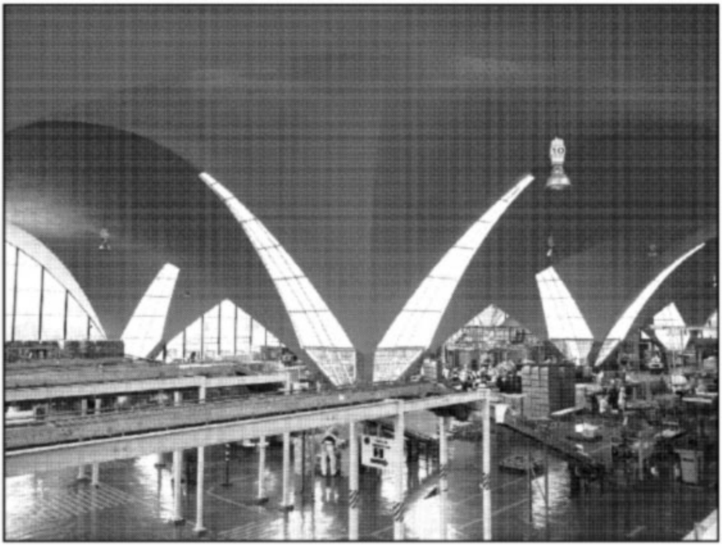

Figure 5.1-2. Interior view of column free groined vault at Bacardi y Cia Warehouse. (Photograph by Bruce M. White)

Candela's most abundant structure was the umbrella, formed from four intersecting hypars with straight edges supported by a central column. The free edges of each of the umbrella quadrants define the set of straight line generators that describe the surface. Candela used a simple cantilever analogy to design his shells, concentrating reinforcement at the edges and valleys where the principal stresses are highest. The umbrella units were repeated in rows to cover large spaces such as markets, warehouses, and subway stations. By varying the proportions of the umbrella units, Candela created skylights to allow day lighting for interiors.

Material minimization and synergies

Faced with the necessity of building economically, Candela reused his timber umbrella formwork (Fig. 5.1-3). After casting an umbrella, he de-centered the forms and translated them to the site of the next umbrella to be cast (Fig. 5.1-4). This clever reuse of formwork expedited construction and reduced materials costs. An additional benefit of the simplicity of straight-line formwork construction was that Candela's design/build company, Cubiertas Ala, could employ local laborers and use locally sourced materials. As a further environmental endorsement, Candela's hypars incorporated drainage pipes through the central column to siphon grey water for use elsewhere on the site.

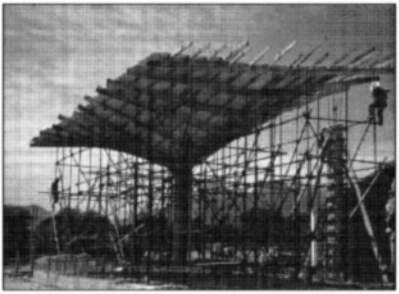

Figure 5.1-3. Construction photos of straight board timber formwork.
(Photo courtesy of Princeton University Candela Archive)

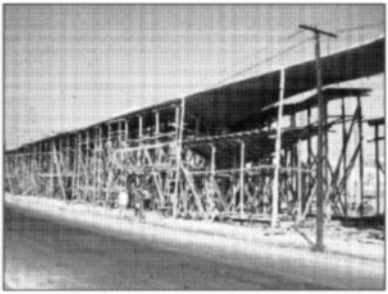

Figure 5.1-4. Forms were lowered and translated to the adjacent umbrella for reuses.
(Photo courtesy of Princeton University Candela Archive)

Thin shell structures enclose maximum space with minimum materials by carrying loads most efficiently within the plane of the shell. Such efficiency makes long spans easier to achieve, and the resulting, column free interiors may be attractive for industrial buildings, museums and exposition centers, among other building types. These structures can provide attractive and clean finished surfaces inside and out that preclude the need for additional architectural finishes. For the structural engineer, the thin shelled structure represents a refreshing expression of the structure of the building which is so often cloaked and obfuscated by architectural cladding in contemporary stick-built construction.

Durability

Candela's structures, most built in the 1950s and 60s in Mexico City, are in excellent condition today. Umbrella type structures such as the Rios Warehouse have withstood more than 50 years of weather and earthquakes with little maintenance other than the occasional coat of paint (Fig. 5.1-5).

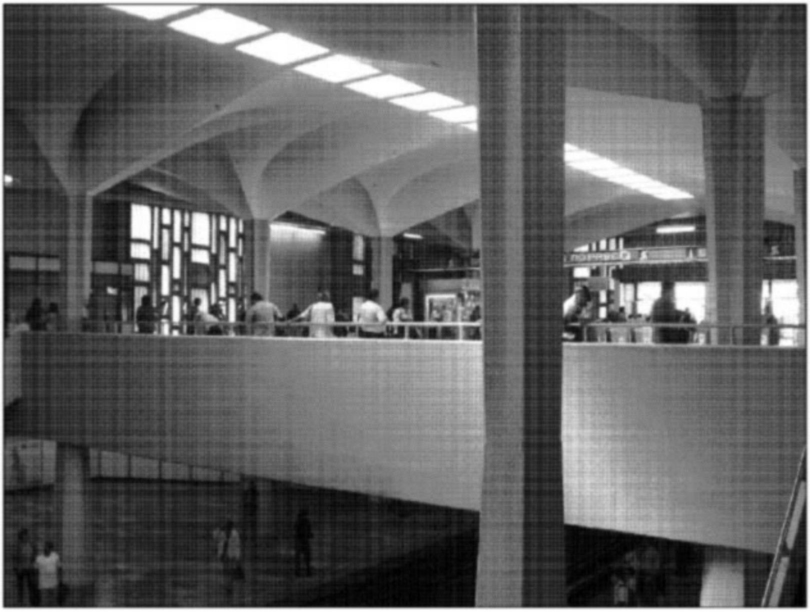

Figure 5.1-5. Interior of Candelaria Subway Station
(Photo by Sarah Halsey)

Candela's structures endure furthermore in the sense that they are cherished, protected, and preserved within their communities. Thus their longevity is due to their physical durability as well as their importance to the people of Mexico City. Candela was a structural designer who seized an opportunity to create a structure that not only satisfies the functional requirements of safety and serviceability but is also a work of beauty to be enjoyed for generations to follow. In this way his works represent a synthesis of structural function with sustainable design. Candela's buildings and his simplified design and construction methods are an inspiration to those structural designers committed to conserving and protecting limited resources through their innovative structural solutions.

Contemporary construction

In Candela's words, "you have to be, besides your own structural designer and calculator and perhaps your own architect, also your own contractor, a very difficult proposition." (Candela 1973). The success of Candela's structures in meeting goals of sustainable design–durability, material efficiency, synergies, local sourcing–suggest that his emphasis on the involvement of the structural engineer in the realization of a project, from conception through completion, is vital to the practice of sustainable design and construction in the future. With proper understanding of shell behavior, analysis can be simplified by approximations as it was in Candela's time. While in our day these approximations may still be adequate, modern analysis with finite element programs make the design of shells even more practicable for today's practicing engineers. Economy in labor costs can be realized with contemporary fabrication techniques for reusable formwork. Furthermore, improvements in the environmental sustainability of concrete and other materials for thin shell construction make thin shells a feasible and sensible option for sustainable building.

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5.2

SAN FRANCISCO FEDERAL BUILDING

Frances Yang, ARUP
Steve Ratchye, Thornton Tomasetti

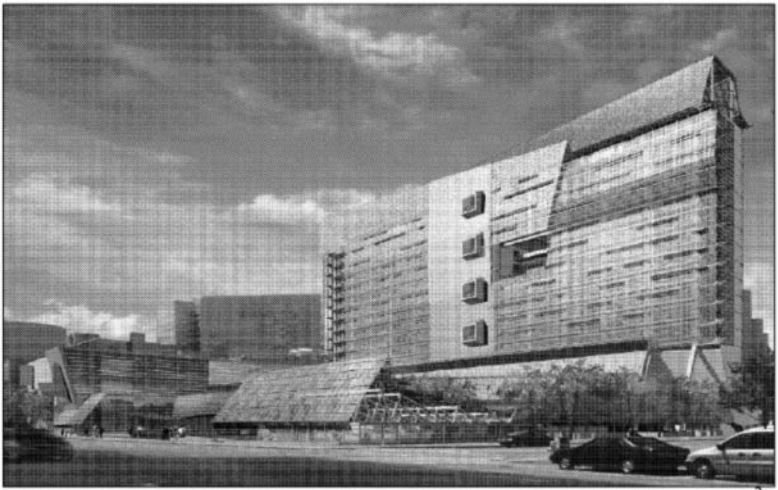

Figure 5.2-1. The new San Francisco Federal Building will provide 56,000 m^2 (600,000 ft^2) of floor space for a number of agencies. (Rendering courtesy of Morphosis)

Project:	**San Francisco Federal Building**
Building Type:	Federal building
Location:	San Francisco
Completion:	2007
Owner:	General Services Administration (GSA)
Structural, Mechanical, Electrical, and Plumbing Engineer:	Arup Los Angeles
Design Architect:	Morphosis
Executive Architect:	SmithGroup of San Francisco
Builder:	Dick/Morganti J.V.
Concrete Contractor:	Webcor Concrete
Construction Manager:	Hunt Construction Group
Geotechnical Engineer:	Geomatrix
Concrete Supplier:	Bode Gravel

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Introduction

Since 1999, the General Services Administration (GSA) has been explicitly committed to incorporating the principles of energy efficiency and sustainability into all of its building projects (Clinton 1999). To help create a new vision of sustainable building, the GSA commissioned the architectural firm Morphosis and multidisciplinary engineering firm Arup to design the new San Francisco Federal Building (Fig.5.2-1).

This gave the structural engineers the opportunity to showcase how in collaboration with Morphosis and the other engineers employed at Arup — including mechanical, electrical, and plumbing — structural engineers can contribute substantially to the sustainability goals of a building project.

Several considerations led to the choice of a concrete structure. Building longevity of civic structures is vital for truly sustainable development, and concrete provides inherent durability compared to other materials. Additionally, a preliminary climate analysis verified that exposed concrete ceilings and walls would provide adequate thermal mass to support natural ventilation, which would significantly reduce operational energy use. Energy used in the operation of a conventional high-rise building in the United States can amount to 80 to 90 percent of the energy used over its life, based on a lifespan of about 60 years (Webster 2004, Cole and Kernan 1996). According to California's Title 24 Energy Code, the mechanical systems to heat, ventilate and condition the air accounts for about 28 percent of this (CEC 2005). Thus, eliminating the need for HVAC in large portions of space within the upper two third floors of the San Francisco Federal Building tower does more to reduce lifetime energy use than most other measures that only target decreasing embodied energy.

Further research verified that ground-granulated blast-furnace slag could be used to partially replace cement and thereby reduce the embodied energy of the structure. Finally, Morphosis desired an aesthetic of exposed concrete surfaces in the finished building. Hence, in choosing concrete as the material of the structural system, the image Morphosis sought after dovetailed with the goals of energy and material efficiency.

Natural ventilation shapes the form

Natural ventilation played a key role in the development of the design (Fig. 5.2-2). A narrow 68 foot-wide(20.8 m) floor plate and an orientation facing prevailing air currents on site allowed wind-driven natural ventilation.

Structural designers initially laid out conventional down turned concrete beams during the early stages of design, but the beam webs would have blocked the airflow required to make the concrete perform as thermal mass. The engineers thus moved to upturn the beams to create an unobstructed soffit across which air flows unimpeded, promoting heat transfer (Fig. 5.2-3). A raised floor covered the upturned beams and created space for services such as wiring and sprinklers. To improve penetration of daylight to the interior, the designers set the column lines back from the facade and raised the bottom of slabs at the north and south edges of the floor plate. This created wing slabs that project from the tops of the upturned beams, allowing sunlight to penetrate more deeply into the offices.

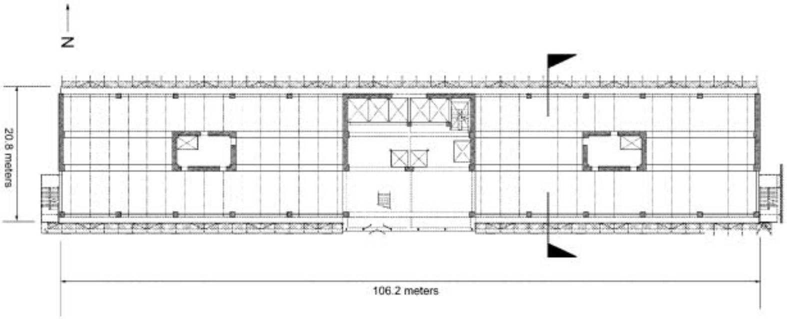

Figure 5.2-2. Typical floor plan in the tower: The shear walls and exterior columns were located to maximize the bay sizes. (Graphic courtesy of Steve Ratchye)

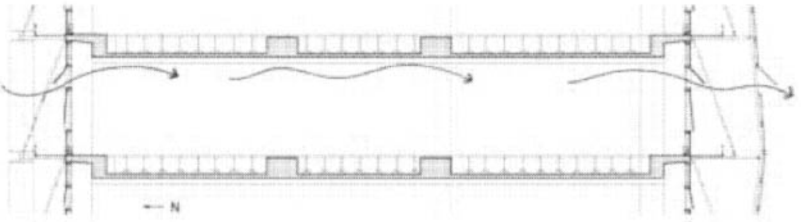

Figure 5.2-3. Cross section of the tower: During the day, heat generated by the occupants, lighting, and equipment is absorbed in the slabs. At night, this heat is removed from the slabs by natural ventilation through the computer-controlled windows. (Graphic courtesy of Steve Ratchye)

The thermal mass of the concrete serves a crucial function in eliminating the need for air conditioning in the perimeter areas of the upper stories. During the day, the exposed slab soffit absorbs heat from computers, people, and lighting. At night, computer-controlled windows open to allow the evening air to flow across the bottom of the floor slabs and cool the concrete. Computational fluid dynamics studies (Fig. 5.2-4 shows an example of the graphic output) verified that the design would significantly reduce the number of hours over a year when the indoor temperature exceeds the comfort levels for naturally ventilated office spaces indicated in the new American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Comfort Standard 55 (ASHRAE 2004). Current research suggests that only the outer 2 to 4 inches (50 to 100 mm) of exposed concrete serves as active thermal mass for a day cycle (Rennie 1998).

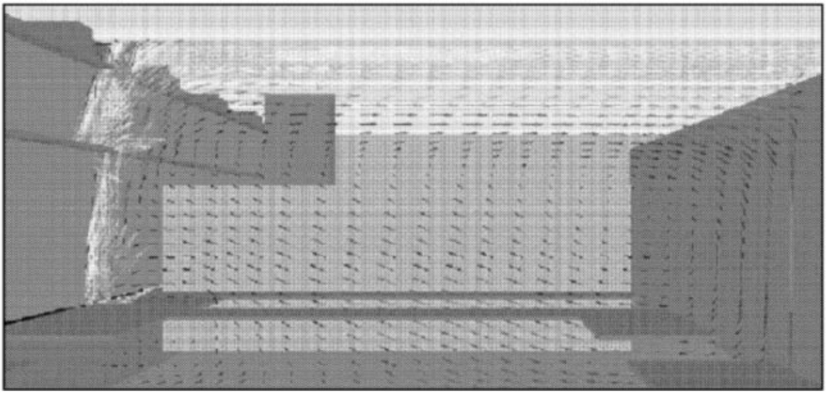

Figure 5.2-4. Computational fluid dynamics models were used to study the natural ventilation and thermal mass of the structure. (Image courtesy of NaturalWorks, Inc.)

Despite the possible structural benefits of using lightweight concrete in this highly seismic region, the higher air content of the material makes it a better insulator and interferes with heat transfer. Normal-weight concrete was therefore chosen due to its greater effectiveness as dense thermal mass.

Figure 1.2-5. A construction photo taken in an office space shows the raised soffit of the wing slab, which highlights the form of the wave slab and allows additional daylight to enter the space. (Photo courtesy of Chuan Do)

The ribbed slabs that span between the upturned beams have a wave profile to reduce mass, increase air contact surface area, improve lighting by eliminating shadows, and enhance the spaces aesthetically (Fig. 5.2-5). The thickness of the wave slabs varies from 12-5/8 to 4-3/4 inches (320 to 120 mm), with the minimum thickness controlled by fire rating.

Two arcs describe the curve of the wave slab (Fig. 5.2-6). The convex radius was kept smaller than the concave radius to reduce concrete mass and still achieve the same structural depth. At the intersection point, the tangents of the two curves match to create a smooth transition.

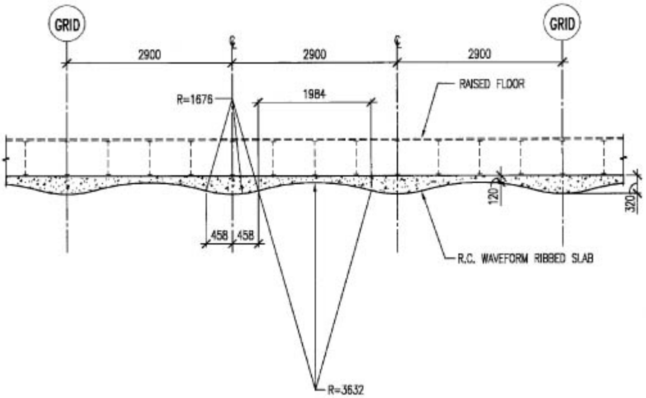

Figure 5.2-6. Cross section of the wave slab geometry (mm). (Graphic courtesy of Steve Ratchye)

Figure 5.2-7. Interior upturned beam elevation. (Graphic courtesy of Steve Ratchye)

The structural engineers limited the size of reinforcement that follows the waveform profile to ease bending. In the upturned beams, the main reinforcement is straight and kept above the oscillations of the wave (Fig. 5.2-7). Although its contribution was included in strength calculations, the curved reinforcement was intended primarily for crack control. Holes for electrical conduits and sprinkler pipes are located in the deepest areas of the interior upturned beams. A perforated stainless steel sunscreen wraps the south façade while catwalks for window cleaning are located between the sunscreen and the window wall. Therefore, as well as accommodating reinforcing steel, conduit, and piping, the perimeter wing slabs also incorporate sunscreen and window wall anchors (Fig. 5.2-8).

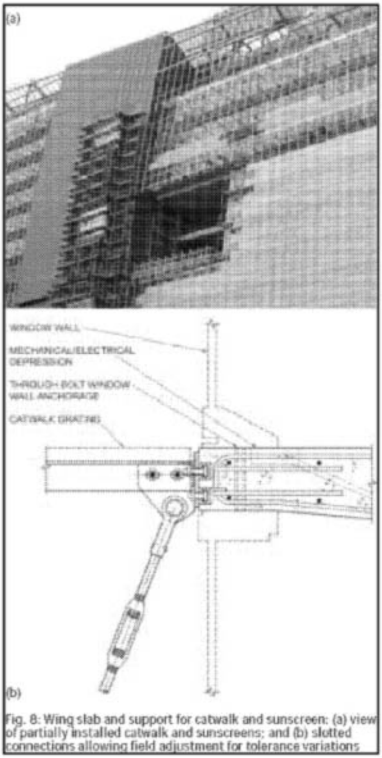

Figure 5.2-8. Sunscreen and window wall anchors
(Graphic courtesy of Steve Ratchye)

Seismic safety

The structural engineers recognized the limitations of code-based prescriptive design procedures and proposed an analytical check per the requirements of Federal Emergency Management Agency (FEMA) document FEMA 356 (FEMA 2000) to confirm the tower met the life safety level of seismic performance. At the time, this document was the standard for performance-based design that considered complex post-yield material behavior and also captures the effects of increased local accelerations. (Note that since then ASCE 41 has replaced it.) The analysis was performed using the nonlinear version of SAP2000. Although this analysis showed that only minor increases were required in the shear strengths for link beams and in reinforcing bars in the boundary elements of the shear walls, it served to reassure the owner and design team that the chosen solution offered better long-term value. The improved confidence in performance over the structure's design life reinforces the philosophy of structural endurance as a key aspect of resource efficient design.

Use of blast-furnace slag

In keeping with the sustainability focus for the building, the large amount of CO_2 emissions related to portland cement production was reduced through use of ground granulated blast furnace slag, a byproduct from steel mills, to replace portions of cement. Aesthetically, the architect appreciated the whitish shade of the slag concrete and, because the specified up-lighting would be reflected off the exposed slab ceilings, the lighting consultant stated it would reduce electricity demands.

Typical mixtures for walls, columns, slabs, and beams replaced 50 percent of the portland cement with slag. The quantity of cementitious material varied from 560 to 840 lb/yd^3 (330 to 500 kg/m^3), and water-cementitious material ratios (*w/cm*) varied between 0.47 and 0.35, depending on the strength required. The mixtures with low *w/cm* incorporated high-range water-reducing admixtures to maintain workability. The relatively recent arrival of slag in the Bay Area required the use of the trial mixture method to gain approval for the concrete mixture proportions. As a result, the required average strength of the slag-cement concrete was significantly higher than the strength specified to meet the requirements in ACI 318 (ACI 2005) when data are not available to establish a standard deviation for compressive strength.

Because the design loads for the walls were controlled by seismic effects, strengths were specified at 56 days, thereby allowing cement savings without affecting the project schedule. A concrete strength of 8000 psi (55 MPa) at 56 days was specified for the basement up through Level 6, where six large, sloped columns frame into the building (Fig. 5.2-9). From Level 6 up to the roof, the walls were specified to have a concrete strength of 6000 psi (41 MPa) at 56 days.

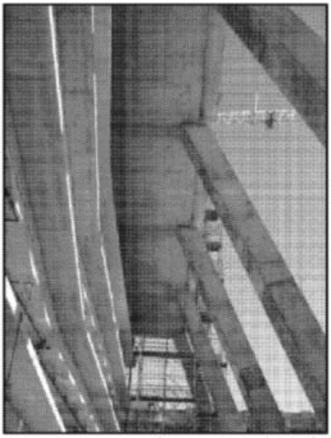

Figure 5.2-9. Sloping columns: Connecting at Level 6 of the building, the columns frame a dramatic atrium for the office tower. (Photo courtesy of Steve Ratchye)

Sustainability goals coincided with the desire to reduce heat of hydration on the massive pile caps. In the mixture for the pile caps, some 8.5 feet (2.6 m) thick, slag cement replaced 70 percent of the portland cement. This mixture contained only 140 lb/yd3 (85 kg/m3) of portland cement, but still reached 6000 psi (41 MPa) at 28 days in the trial batch test results.

Construction

During the construction detailing process, the wave slab presented an opportunity to re-examine traditional construction techniques. For ease of placement, the contractor requested substitution of prestressing strand for the specified small, curved reinforcing bars. Section 7.3 in the 2004 Eurocode 2 (EN 1992) stipulates that strand is only 60 percent as effective at controlling cracks as conventional deformed reinforcing bars. Therefore, the structural team stipulated an increase in the number of strands for crack control as a condition for allowing the substitution (Fig. 5.2-10).

Forming the wave slab presented its own construction challenge. The contractor used a top layer of 5/16 inch-thick (8 mm) high-density overlay plywood over a second layer of 1/2 inch-thick (13 mm) plywood to create the wave profile. The plywood layers were screwed to metal studs that were, in turn, supported on vertically oriented plywood fins cut to the wave profile. Steel beams spanning between columns, shear walls, and shoring supported the vertical plywood.

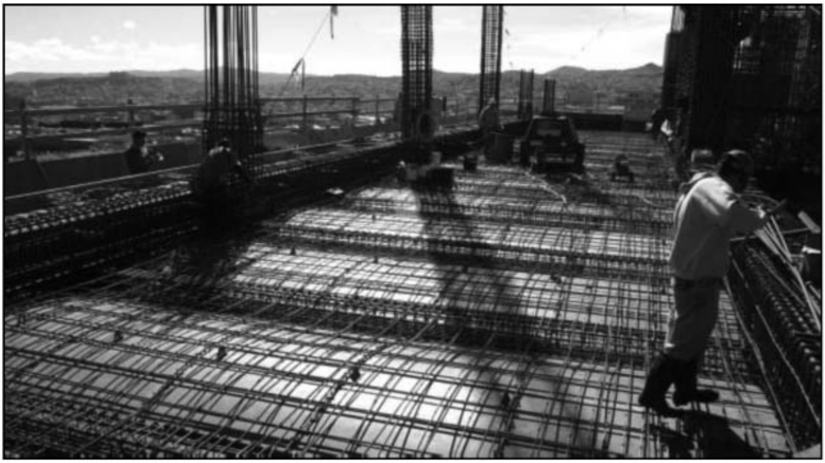

Figure 5.2-10. Wave slab reinforcement: Because it could more readily follow the soffit profile, prestressing strand was used as bottom reinforcement. At the deepest portion of the slab, the main reinforcement was detailed as a beam with stirrups. (Photo courtesy of Steve Ratchye)

The concrete floors were split into two placements — one for the wave slab and another for the upturned beams and wing slabs. A combination of shear keys and surface roughening made the two placements work together structurally. Although the structural drawings allowed 4000 psi (28 MPa) concrete for slabs and beams, the contractor opted to use the higher strength concrete required for the shear walls to allow rapid removal of shoring and keep the project on schedule.

Conclusion

Although the energy efficiency goals of the building team were not driven by any intent to gain recognition from rating systems, federal entities directed GSA to pursue Leadership in Energy and Environmental Design (LEED) certification for the project well after the building team had completed design. The structural design would help earn the following credits for the project, which is under review for a LEED Silver rating:

- Energy & Atmosphere credit 1: Optimize Energy Performance (3 points)
- The structure contributed by designing the concrete to serve as thermal mass, by upturning the beams to allow uninterrupted airflow across the soffit, and by utilizing slag to create a whiter and more reflective exposed interior surface, which improved the efficiency of the lighting.
- Materials & Resources credit 4: Recycled content (2 points)
- Recycled content came from the slag, rebar, and hot rolled steel.
- Indoor Environmental Quality credit 8: Daylight and Views (2 points)
- Thinning of the concrete to a "wing slab" at the perimeter contributed to bringing daylight deeper into the building.
- Innovation & Design credit: (1 point)
- The San Francisco Federal Building received this for additional efforts to demonstrate itself as a green building project. All the above aspects of the structure contributed to this credit.

Thus, 8 points of the 33 required for LEED Silver came from decisions about structure, with 5 of the points related to energy reductions during the building's operation that the structural design enabled.

When structural engineers think outside the traditional "green scope" they are limited to, namely materials specification and procurement, they can affect a much larger environmental strategy. The San Francisco Federal Building exemplifies how structural engineers played this greater part in green building design by approaching the task with an understanding of whole building life performance, executed through a thoughtful, steadfast, and coordinated team effort.

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5.3

DALBY FOREST VISITORS CENTER

Neil Currie, Halcrow Yolles
Terry McDonnell, Halcrow Yolles

Figure 5.3-1. Entrance to Dalby Forest Visitor's Place (Photo courtesy Halcrow Yolles)

Project:	**Dalby Forest Visitors Center**
Building Type:	Tourism
Location:	United Kingdom
Completion:	2006
Structural Engineer:	Halcrow Yolles
Architect:	White Design Architects
Area:	8,500 square feet

Project description and sustainability goals

Halcrow Yolles were appointed to design The Dalby Forest Visitors Center as a flagship for sustainable construction and to serve as an educational tool for the public and visiting students allowing them to learn about the environment, sustainability, and the forest (Fig. 5.3-1). The central design themes for this project were to design and construct a building with locally sourced material where possible, integrated with an extremely low impact on the surrounding land and environment, and that that building could be removed and recycled in its entirety in order to quickly revert the land back to its original condition. The project is widely recognized in the engineering community for accomplishing all three goals.

Set in the valley of Lower Dalby on the fringe of the North Riding Forest Park, the Dalby Forest Visitors Center design team accomplished the projects goals by using the latest sustainable technologies in architecture, structural, and civil engineering, and building services using locally sourced materials where possible. The final design included contemporary environmental design such as rain water recycling, natural ventilation, solar power, micro-turbine wind power, non-intrusive foundations, and the prominent structural feature that the entire building can be deconstructed and relocated or removed for recycling, if a decision is made to return the land to its original state or to relocate the visitor's center (Fig. 5.3-2).

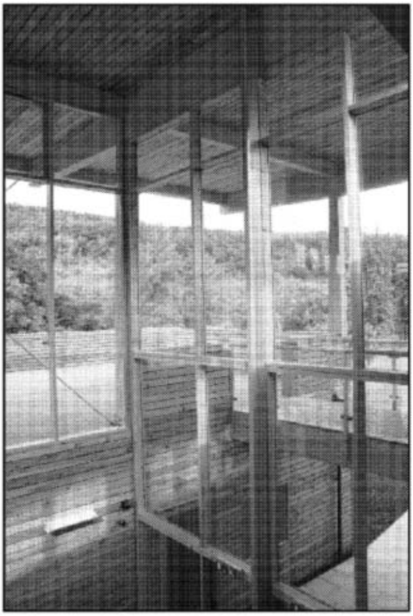

Figure 5.3-2. Interior of Dalby Forest Visitor's Center
(Photo courtesy Halcrow Yolles)

The center was built within a remote forest valley site that is designated in the UK as a Site of Special Scientific Interest (SSSI). An SSSI designation is assigned by the English government to preserve land that represents the best of examples of wildlife and geological features within the country. This designation establishes legal protection in order to preserve nature within the SSSI boundaries. Buildings within this designation require designs that minimize intrusion on wildlife and geological features.

It was the intention that this building would have minimal intervention within the valley given its remote location and also have the capability to be removed with zero long term impact on the valley's ecology. These goals were a particular challenge when considering the valley site selection. A more detailed than normal cut and fill analysis of the valley floor were performed by the structural engineers in order to minimize artificial movement of earth as much as possible. The cut and fill exercise was performed for a variety of different foundation solutions including, lime based concrete, timber strip footings, timber pad footings, timber driven piles, and self auguring steel piles.

During each phase of the design, thought was given to the type of construction vehicles and equipment that would be necessary on site for the design options chosen. Ultimately the designers wanted to limit the amount of damage construction vehicles could do to the valley site during construction. Design options put forth by the team represented ones that required only very light construction vehicles. The lighter the vehicles, the less would be the disturbance to the valley ecology immediately surrounding the building and on the entry path to and from the building. In fact, pains were taken to keep as much of the building pre-fabricated off-site until it was absolutely necessary to bring a component to the site for erection.

The heaviest vehicle was a single light excavator that could be converted to a multitude of uses (Figure 5.3-3). This single excavator was used to construct the access path, grade the site for the building and install the foundations. Starting with the foundations, the designers of the structure worked to create structural components that would work within the intended limits placed on construction equipment. The following sections discuss these structural systems.

Figure 5.3-3. Piles being installed at the Dalby Forest Visitors' Center (Photo courtesy Miller Construction)

Foundations

This ability to reuse and recycle applies to the entire structure including the foundation bearing elements. A traditional concrete footing system would have been far more intrusive to the natural geological features. Given the buildings location within the valley and the depth to suitable bearing strata, a traditional footing system would have required elements of slope stabilization and an increase in the excavation volume of the valley. Therefore, self auguring steel helical piles (a unique type of spiral steel augured pile) were selected for the foundation system for of the following benefits and environmental reasons:

- they are small in area when compared to a traditional concrete footing,
- installation time is very quick,
- installation requires less machinery moving on and off site than a concrete footing,
- each pile is installed to a set torque that confirms the load carrying capacity,
- they have an inherent tensile capacity that is important on lightweight timber buildings, and
- the pile may be extracted at the end of its life for reuse or recycling.

In summary, helical piles leave next to zero long lasting imprint on the natural habitat, and can be reused or recycled at the end of the life of a building. These piles are effective in both sand and clay soil types, and are generally used in all soil conditions except bedrock.

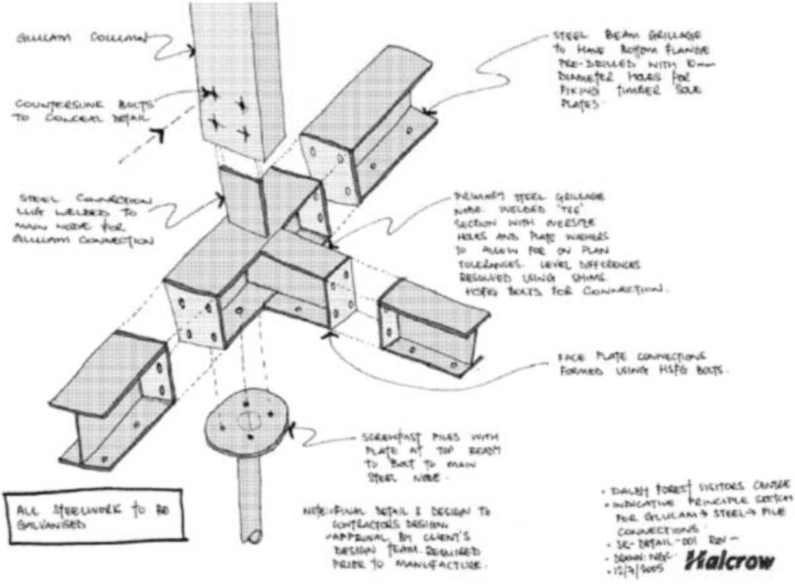

Figure 5.3-4. Schematic diagram of the steel grillage connection to the top of the helical piles. (Rendering courtesy Halcrow Yolles)

Traditionally the helical pile system was developed for rail signal foundations within the UK. This is because their rate of installation is three to four times faster than traditional pile driven or augured driven foundations and they can be installed within a given day by the same crew. In addition, the equipment to drive the helical piles is much less intrusive than augured, driven piles or shallow footings and can be mounted on rails for ease of access. At Dalby Forest the helical piles system seemed to be a perfect solution for the constraining criteria. Helical piles are sized according to the building loads and shipped to the site in their pre-determined design lengths along with the installation tool that is attached to the excavator. A galvanized "fixing plate" (which also serves as a connection plate for the superstructure) is attached to the top of the pile. The galvanizing plate (in conjunction with the top five feet of the pile which is also galvanized) helps protect the entire pile against corrosion. The tool on the excavator then applies torque to the pile in order to screw it into the ground down to its proper depth. Once the pile nears the end of the installation, the speed of the torque arm is reduced to ensure that the pile is installed to the correct design torque. These small diameter piles can match the load capacity of a gravity foundation without the need for excavation that could damage the tree root system. Additionally, at the end of its life, the excavator can return to the site and un-screw the pile out of the ground, similar to installing and un-installing a wood screw.

In order to maximize the deconstructability, recyclability, and reusability goals of the building, a repetitive and easy to build structural system that could merge the helical piles to the superstructure was designed (Fig. 5.3-4). The result was a light weight steel grillage that could efficiently bolt into the galvanized plate at the top of the piles. This system was compatible with the building's ability to be dismantled and relocated if required and the steelwork could be recycled should the building ever be decommissioned. The protection system for the steelwork was specified as a galvanized system in lieu of a painted system. Modern galvanizing techniques allow for 100 percent reclamation of the coatings at the end of the steelwork's life, as opposed to painted treatments that cannot be reclaimed and require greater maintenance. The steel grillage was connected directly to the heads of the piles using the existing bolt holes that were used to connect the installation tool. The insertion of the steel grillage between the timber superstructure creates an effective diaphragm for the transmission of lateral loads preventing any possible skewing of the substructure.

Superstructure

The superstructure is constructed using mainly two-story-high portal and braced timber frames to resist both lateral and gravity loads simultaneously. The frames were formed using Forest Stewardship Council (FSC) certified timber to ensure that the timber species was available from a local wood source. The FSC certification is proven by a chain of custody that is submitted to the design team at the supply chain point of delivery. Within the UK, FSC certified timber is not as strong as Scandinavian sourced timber due to the milder climate of the UK. This increases the member size for glue laminated timber frames slightly. However, the importance of the FSC certification was greater than a minor efficiency improvement in order to meet the sustainability requirements of the structure.

The flooring system is panelized using an off-site construction method formed using a cassette based timber system that interlocks with the substructure steel grillage on the first floor, and interlocks with the moment frames on the second floor and roof. The interlocking floor system is panelized in order to create a strong diaphragm, while at the same time having discreet mechanical fasteners that will facilitate future removal and re-use. Both the frame and flooring system were also designed specifying FSC certified, locally sourced timber.

By using a timber frame and plank flooring system, the superstructure could be put together in discreet locations with galvanized steel connectors (also 100 percent reclaimable), that could also be easily removed in the event the structure is decommissioned in the future (Fig. 5.3-5). A timber shear wall structure, steel frame system (which requires welding), or a composite steel and concrete system would all require much more destructive demolition and waste when compared to this very flexible system.

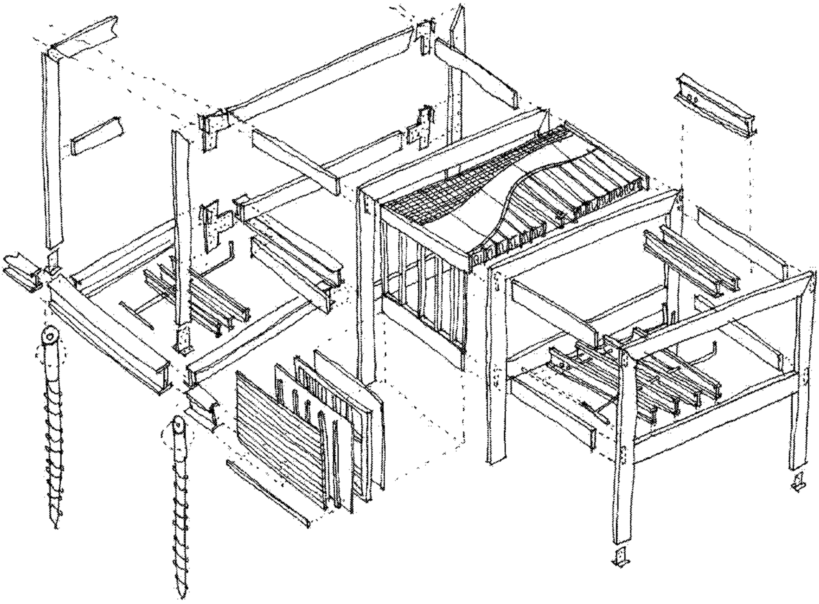

Figure 5.3-5. Rendering of the Dalby Forest structural system that illustrates the deconstructability of the various components.
(Rendering courtesy White Design Architects)

The dedication by all of the design professionals and the client to employ easily re-used and recycled materials on the Dalby Forest Visitors Center did not stop with just the structural systems. The following items list a sample of the additional structural, architectural, and mechanical life cycle items implemented by the design team during this project:

- Roofing membrane was made from recycled tires.

- The cladding was made from off cuts of local cedar, which would ordinarily be scrapped.
- The glues and treatments are boron based. These treatments prevent rot in wood from fungi and insect attack. Most importantly boron based glues and treatments are non-toxic and considered an acceptable sustainable wood treatment or coating.
- The counter in the café is made from recycled mobile phones.
- The building uses a woodchip boiler using waste products from the two local saw mills to heat the building.
- Micro wind generation and photovoltaics aid to reduce the dependency of the building for external electrical supplies.
- Rainwater harvesting and bio-treatment of wastewater minimize the impact on the local hydrological regime.

The design team created an innovative structure that strikes a balance of sustainability and function. By employing the latest sustainable technologies the design team fulfilled the intention that the building should have minimal intervention with the valley and also have the capability to be removed with no long term impact on the valley. The total result creates a flagship building for sustainable construction and provides an inspiring structure to serve as an educational tool for the public to learn about the environment, sustainability, and the forest.

All of the above have contributed to the building being awarded the prestigious Prime Ministers Better Public Building Award in 2007 amongst other notable awards.

5.4

THE NOMADIC MUSEUM

Andrew Coats, Buro Happold

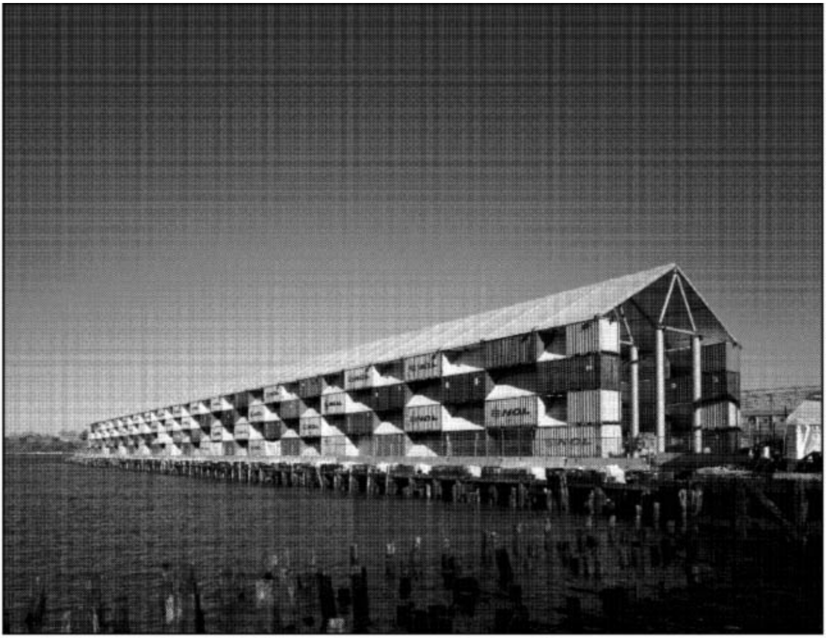

Figure 5.4-1. The temporary structure was designed with highly recyclable materials. (Photo copyright Buro Happold)

Project:	**The Nomadic Museum**
Building Type:	Museum Space
Location:	Pier 54 at West 13th Street, New York
Completion:	2005
Owner:	Bianimale Foundation
Structural Engineers:	Buro Happold Consulting Engineers
Principal Architect:	Shigeru Ban
Associate Architect:	Dean Maltz
Area:	45,000 square feet

Building concept

The Nomadic Museum was designed as a temporary and transportable exhibit space for the *Ashes and Snow* photography exhibition by photographer

Gregory Colbert. The building was designed to stand in New York City for a six-month period, then to be completely dismantled and shipped to Santa Monica, California, for a six-month run. Following the Santa Monica installation, the building was shipped to Tokyo and Mexico City, and planning is underway for a trip to Brazil. The building's first location was on an existing pier on Manhattan's west side extending into the Hudson River. It was the largest temporary exhibition space ever created in New York City. The following discussion refers primarily to the New York installation; the building was modified at other locations, and some of the construction details may have been altered.

In an effort to limit the overall impact of the temporary space on its surroundings, the building was designed using local materials and built to be fully removable with little impact to the existing pier. The existing pier, which had once belonged to the famous Cunard Line passenger ship company, was constructed using timber piles with a concrete deck. The building had to be designed to be easily transported to its next destination while also limiting any impact to the existing pier to the concrete deck only (Fig. 5.4-2).

Figure 5.4-2. The Nomadic Museum under construction (Photo copyright Buro Happold)

Use of recycled and reusable materials

All materials used both in the construction of the building as well as the fit out of the exhibition were selected for low environmental impact, high recycled content, and ease of deconstruction, transport, and reuse. The choice of shipping containers as vertical support and as lateral shear walls takes advantage of the large number of used containers being stored in U.S. ports. Of the 148 containers used for the construction, 37 were purchased for use in further transport of the building and the remaining 111 containers were rented locally and returned after the exhibition. The containers themselves, with heavy gage corrugated walls, act as shear walls providing inherent rigidity as part of the lateral system for the building. Shipping containers provide an ideal support structure, with internal structure allowing them to be stacked under fully loaded, ocean transport conditions. The use of storage containers as primary structure has been used in numerous buildings, including the Container City developments in London, also engineered by Buro Happold. Working on the Container City developments provided the engineers with the necessary experience to understand the inherent strengths and weaknesses of the storage containers and potential detailing requirements.

Cardboard can provide a long-term structural solution for structures, with a smaller overall impact on the environment relative to most alternative materials. The material itself can be produced with a high percentage of recycled content and the tubes used can often be produced on the same rolling machines as tubes used for other industrial applications such as newspaper and fabric production. This use of similar systems allows for the cross-use of industrial equipment and the possibility of further efficiency in production. The potential for recycling and reuse of material waste after the deconstruction of the building can further reduce the overall impact from materials production, approaching a cradle-to-cradle strategy.

The use of cardboard for intermediate supports and as members within the trusses provides for an easily deconstructed assembly and fits nicely into the architectural aesthetic of the building. Cardboard is also, ultimately, biodegradable. Both the interior and exterior walls of the tubes were treated with a water-proofing membrane to allow for longer-term use through all of the museums stops. The use of recycled material from a renewable resource provides the lowest impact of any potential materials for this temporary use, while meeting the necessary strength and deflection requirements. The lighter weight of the cardboard in the columns and trusses reduces the overall weight of the building and, in the New York installation, allowed for the use of the existing pier deck without additional reinforcement.

Using locally sourced materials for the initial construction of the building, and designing to allow the use of local containers in future destinations, reduced the overall impact of the building.

Superstructure

The exterior vertical structure for the building was made up of 148 shipping containers from the nearby Port of Elizabeth, N.J. The interior vertical structure utilized a series of 2’-6” diameter cardboard tubes at third points running the length of the building. Framing onto the shipping containers and the cardboard columns were long-span composite trusses made up of 1’-0” diameter cardboard members and aluminum struts. The containers were stacked 34’-0” high with an additional 20’-0” of height to the top of the trusses.

The roof structure was made up of a plastic fabric membrane and cable bracing, providing a lateral diaphragm for the building, while also creating an ideal screen for images projected onto the roof along the full length of the building. Off-the-shelf Twist-Lok-type fasteners, commonly used to fasten down storage containers during ocean transport, were used for all container-to-container connections, and had the capacity to transfer the required shear loads. These fasteners provided the necessary connection strength while also allowing for ease of disassembly. At the base of the building, the bottom row of containers was welded to steel beam sleepers which were in turn fastened to the existing concrete deck with epoxy anchors. The bases of the cardboard columns were fastened to wood disks fitted to the inner diameter of the cardboard tubes, which were in turn fastened to steel plates that were epoxy-bolted into the concrete deck. These base details allowed for full removal of the entire building at the end of the exhibition. The container connections and the use of segmented trusses and cardboard columns allowed for quick disassembly and ease of transport (Fig. 5.4-3).

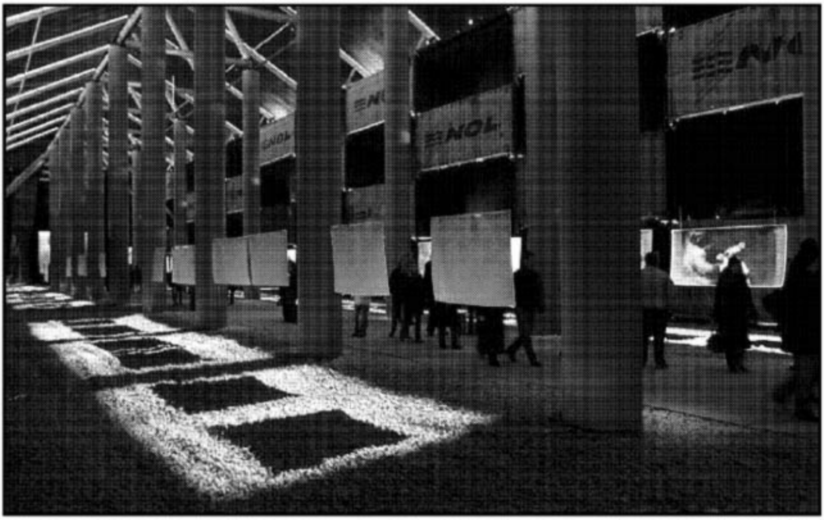

Figure 5.4-e. The interior of the completed building (Photo copyright Buro Happold)

Precedents for reuse structural elements

Buro Happold's experience on the following projects provided a level of confidence in the structural strategies and material choices made in the design of the Nomadic Museum:

- Japan Pavilion, Hannover Expo — 240 ft x 110 ft (72 m x 35 m); 2 layers of 4-3/4 in. (120mm) diameter cardboard tubes at 3.2 ft (1.0 m) on center; braced with glulam ladders. Architect: Shigeru Ban.
- MOMA Arch, Museum of Modern Art, New York — Temporary cardboard arch in the MOMA Courtyard. Architect: Shigeru Ban.

- Westborough Primary Cardboard School — Recycled cardboard tubes used as primary structural for school building with an expected 20-year lifespan. Architect: Cottrell & Vermeulen www.cottrellandvermeulen.co.uk.
- Container City, London — Use of recycled shipping containers for residential spaces. Architect: Nicholas Lacey and Partners www.containercity.com.

Additional resources

Addis, W and Schouten, J. (2004). *Principles of Design for Deconstruction to facilitate reuse and recycling.* CIRIA, London, UK.

Addis, Bill (2006). *Building with Reclaimed Components and Materials: a Design Handbook for Reuse and Recycling.* Earthscan, London, UK

Pogrebin, Robin (2005). A Dockworkers' Strike?, No, It's Art. *The New York Times,* February 24, Arts section, New York edition.

5.5

BANK OF AMERICA TOWER AT ONE BRYANT PARK

Andrew Mueller-Lust, Severud Associates

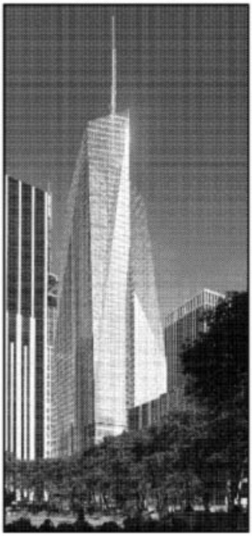

Figure 5.5-1. The tower was designed to be the first LEED platinum-rated high-rise office building in the United States. (Photo copyright dbox for Cook+Fox Architects)

Project:	**Bank of America Tower at One Bryant Park**
Building Type:	High-rise office tower
Location:	New York, N.Y.
Date of Completion:	Fall, 2009 (projected)
Owner:	One Bryant Park, LLP
Structural Engineer:	Severud Associates Consulting Engineers, P.C.
Design Architect:	Cook+Fox Architects LLP
Architect of Record:	Adamson Associates Architects
Developer:	The Durst Organization
Construction Manager:	Tishman Construction Corp.
Foundation Contractor:	Civetta Cousins JV
Concrete Contractor:	Century Maxim Construction Corp.
Concrete Supplier:	Empire Transit Mix Inc.
Structural Steel Contractor:	Owen Steel Company, Inc.
Structural Steel Erector:	Cornell and Company, Inc.
Building Statistics:	945 feet tall (1,200 feet to top of spire) 55 stories 2.2 million square feet of office and trading space

Sustainability concepts

The Bank of America Tower at One Bryant Park employs many sustainability strategies and is designed to be the first LEED Platinum rated high-rise office building in the country, the highest rating in the US Green Building Council program (Fig. 5.5-1). Among the sustainable features are the following:

- high recycled material content,
- locally sourced materials,
- high performance curtain wall,
- daylighting,
- under-floor, locally controlled air system,
- high degree of air filtration,
- waterless urinals and low-flow fixtures,
- gray water system,
- gas-fired co-generation plant, and
- thermal storage system.

Many of these systems had an impact on the structural design, but were not necessarily influenced by it. One feature that is in the structural engineer's control is the recycled material content. The structural steel industry is already inherently efficient in this regard: the recycled content of structural steel can approach 100 percent. The concrete industry is becoming more focused on recycled content, however, especially with the use of blast furnace slag and other supplementary cementitious materials as a replacement for cement. Their use reduces the amount of cement produced along with a similar amount of carbon dioxide, diverts material from the waste stream and produces concrete with similar or enhanced properties when compared to concrete made only with cement.

Supplementary cementitious materials

Supplementary cementitious materials have been used in concrete production for many years but usually only in relatively small percentages. For instance, a standard concrete mix design might employ 10 percent of fly ash. Recent studies, however, have shown that some of these materials can be used at a higher rate with no deleterious effect on the concrete. In fact, in many cases the properties of the concrete are improved.

Such is the case with granulated blast furnace slag (GBFS). GBFS is a waste product of the steel smelting process and is formed from the chemical interaction of lime and non-metallic minerals in iron ore. The resulting material is very similar to portland cement. Substitution of GBFS for cement produces concrete that is denser and more durable when compared to mixes using cement only. Furthermore, studies commissioned by The Durst Organization have shown that substitution of GBFS for cement at a rate of up to 45 percent also increases the strength of the concrete by about 25 percent. The additional strength comes at a later age — 56 days as opposed to 28 days for ordinary concrete — and the initial set can be delayed as well.

At the Bank of America Tower, GBFS was substituted at a rate of 45 percent for all concrete. With a total concrete volume of 86,000 cubic yards, over 17,000 tons of cement was saved, an equal amount of waste was consumed and almost 16,000 fewer tons of carbon dioxide was released into the atmosphere. The environmental benefit is obvious and the building will benefit from concrete that is stronger (helpful for its shear walls) and denser (useful in its foundation which is mostly below the ground water table, Fig. 5.5-2).

There was very little resistance to the use of GBFS in the concrete mainly because the concrete supplier for both the foundation and superstructure, Empire Transit Mix, had previous positive experience with essentially the same mix designs at The Helena. At the outset of that project, all of the contractors were skeptical that such a high percentage (also 45 percent) could be used effectively. This was especially true of the superstructure concrete contractor since they had to maintain a two-day cycle. This meant being able to get concrete placed and finished in one day and the forms stripped the next day. They wanted to have more traditional mix designs approved as a fall-back but ownership and the design team resisted. In the end, however, finishing was not a problem and the concrete contractor never needed any alternate mixes.

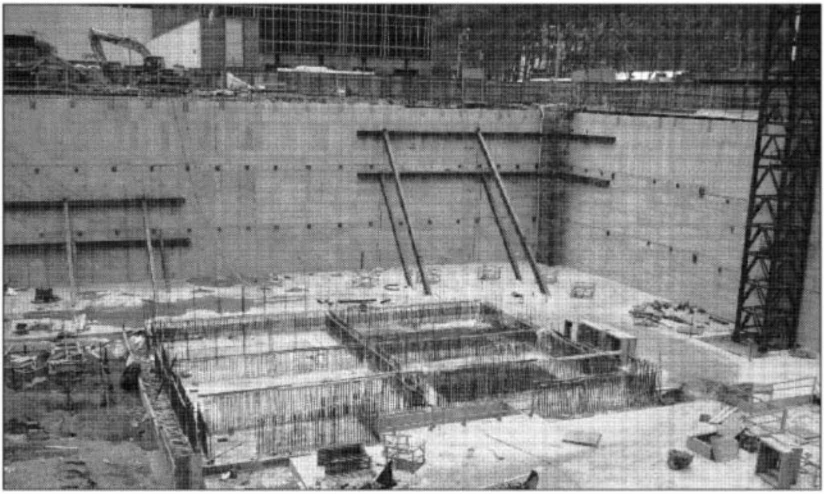

Figure 5.5-2. Foundation walls, slab on ground, and core footings used GBFS in the concrete mix design. (Photo copyright Severud Associates)

At the Bank of America Tower, there were minor problems with two of the higher strength mix designs. The concrete contractor found that their 9,000 psi and 7,000 psi mixes did not pump as easily as they would have liked; it is not clear whether the GBFS influenced this. They used their 10,000 psi and 8,000 psi mixes instead. Similarly, they found that their 5,950 psi mix pumped and finished extremely well so they used it in place of their 5,000 psi and 4000 psi mixes in many locations.

As a result, there is very little concrete at One Bryant Park with strengths below 5,950 psi.

Form removal was not critical at One Bryant Park so early strength (or lack thereof) did not affect the concrete work. Strengths at 28 days were specified and there were only a few times when the concrete did not come up to strength. On another recent project, strengths at 56 days were specified for mix design but there were more problems with low strength. Therefore, it may be advisable to specify 28-day nominal strengths, depending on project conditions.

Aside from the pumping issues described above, there were no complaints from the contractors about mixing, transporting, placing, finishing or curing.

Future uses

Higher percentages of GBFS — up to 90 percent — have been used but mostly in mass concrete such as roadways and dams. At the higher rate of substitution, initial set of such concrete can be significantly delayed so its use where finishing is a concern, such as in residential floor construction, could be problematic. In these cases, placing and finishing a test panel (which can be done on grade) can be helpful and should be included in the specification.

For areas where finishing is not critical, however, use of higher percentages of GBFS may be worth considering. These would include spread footings and mat foundations, foundation walls and possibly even columns.

It should be noted that with GBFS or other supplementary cementitious material replacement, concrete strengths of over 12,000 psi are attainable.

It should also be noted that some building departments are considering code amendments that would limit the maximum amount of cement in concrete, a significant policy shift from most codes, which currently require a minimum quantity.

5.6

ITHACA COLLEGE BUSINESS SCHOOL

Mel Garber, Robert Silman Associates
John Anderson, Robert Silman Associates

Figure 5.6-1. Ithaca College Business School obtained a LEED-platinum rating. (Photo copyright Graham Steward, used with permission.)

Project:	**Ithaca College Business School**
Building Type:	University building
Location:	Ithaca, N.Y.
Completion:	2008
Owner:	Ithaca College
Structural Engineer:	Robert Silman Associates
Architect:	Robert AM Stern Architects
Area:	38,800 square feet

Introduction

Ithaca College has taken green building into the business world, namely with the construction of the new School of Business. The Dorothy D. and Roy H. Park Center for Business and Sustainable Enterprise is a 38,800 square, foot 4-story steel-framed building on the Ithaca campus designed to house lecture auditoriums, classrooms, and offices complete with an enclosed bridge walkway between the new Business School and the existing Job and Friends Hall. The building is the first university business school to obtain a LEED-platinum rating (Fig. 5.6-1).

The School of Business opened in January 2008 and features a wide range of innovative green building features. Designed by Robert A.M. Stern Architects and Robert Silman Associates the non-structural related green building features include: a vast vegetated roof, extensive daylighting, a high-albedo roof, storm water reclamation for use within the building's plumbing, high-performance glazing, premium efficiency motors and boilers, waterless urinals, low-velocity displacement ventilation, locally-quarried rubble stone base, native vegetation for landscaping, 50 percent of electricity from renewable sources, extra insulation, southern building orientation integrated with passive solar design, and Forest Stewardship Council-certified wood (Fig. 5.6-2). The $18 million project incorporated a majority of materials from within 500 miles, diverted over 90 percent of the construction waste from the landfill, and emphasis was placed on specifying structural materials with low-toxicity.

Figure 5.6-2. The building is situated on the site in order to optimize passive solar design. (Photo copyright Graham Steward, used with permission.)

Figure 5.6-2. Recycled concrete aggregate was specified for structural sub-base material used as backfill on the Business School building.
(Photo copyright Graham Steward, used with permission.)

Structural considerations

In 2001, Robert Silman Associates began a year-long process of revising the firm's structural specifications to address sustainability goals (See Case Study 5.9 — Crafting Green Specifications in this section). Through the inclusion of green issues relating to materials, construction procedures, and best available practices, the office created an in-depth green template that was individually modified for each particular project. In turn, the sustainability specifications provided the design and construction team with the guidance and environmental expertise needed to enhance the sustainability of a project. Thus the structural engineer was able to identify areas where their actions would have a potential environmental impact and provide practical environmental improvements.

For the Ithaca College School of Business there were several specific structural requirements that allowed for modification and refinement of sustainability goals. Below grade rock made the initial scheme of basement parking infeasible due to high cost of excavation. The foundations are isolated pad footings bearing on undisturbed soil. The soil profile required a retaining wall along the north elevation and structural fill to raise the ground floor at the southern elevation. Recycled concrete aggregate (RCA) was specified in accordance to ASTM D1241-00 for structural sub-base material used as backfill (Fig. 5.6-3).

The superstructure is a steel frame with both braced frame bays and moment frames for lateral support. In accordance with Design for Disassembly, the floor system utilized precast concrete planks spanning to steel beams, with the addition of topping slabs at several floors. A partial mezzanine mechanical floor was built between the 1st and 2nd floors. The program requirements included large auditoriums and atria, as well as the use of setbacks to allow for natural shading at various floors, therefore several transfer and cantilevered beams were used to achieve these design requirements (Fig. 5.6-4).

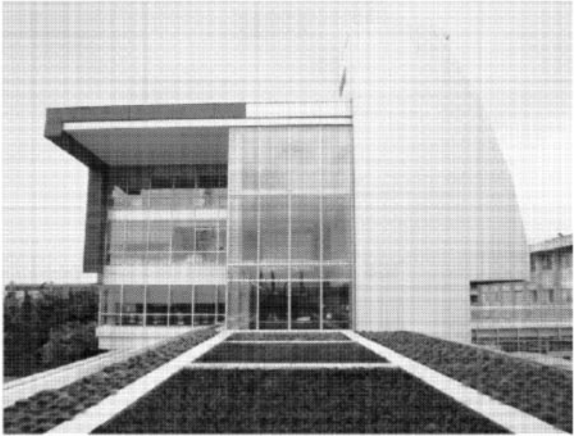

Figure 5.6-4. The use of setbacks provides natural shading (Photo copyright Robert Silman Associates, used with permission.)

Green building structural features

A primary design of the owner was to minimize the impact of the building's structure on the environment, in the present as well as the future. A featured aspect of this project is a structural system that will truly lend itself to disassembly and re-use rather than demolition and to incorporate materials with recycled content in the newly fabricated products. The design team's approach to material specification strove to maximize the amount of post-consumer recycled material, while improving performance through greater durability and strength. We specified material additives, coatings, and processes to minimize harmful emissions including CO_2, HAPs (hazardous air pollutants), ODCs (ozone depleting chemicals), and VOCs (volatile organic compounds). Form coatings used biodegradable form release agents made from soy or rapeseed oil.

The steel frame superstructure employed as much as possible bolted connections, especially at the braced-frame bays and moment frames. In particular, shear connections employed all-bolted double-angle connections as per AISC Table 10-1. This allowed the building to be designed for eventual deconstruction rather than demolition. The steel elements used were high-strength rolled shapes and tubes to maximize efficiency and minimize material required. In addition, preference was given to material sourced from plants with ISO 141000 certification to ensure a standard of good environmental practice in accordance with the ISO standard. Where welding was necessary, we specified the least environmentally harmful process available (vaporized metal emitting). Submerged Arc Welding (SMAW) was used for plate girders, fillet and butt joints in pipes, cylinders, columns and beams, and other welds where 'downhand' or horizontal positions were possible. Gas Metal Arc Welding was used when SMAW was not appropriate (such as for angled, irregular, or short connections).

Careful detailing to address thermal bridging followed a collaborative process with the rest of the design team to minimize the perforation of the inner envelope with steel structural elements required to support the exterior façades.

The use of a precast concrete plank floor system also lends itself to disassembly. The use of supplementary cementitious materials (SCMs) for all concrete materials was specified. The total percentage of portland cement did not exceed 75 percent of the cementitious mix for the project. Compared to conventional 100 percent portland cement based concretes, SCMs such as fly ash and slag impart beneficial properties to concrete such as greater long-term strength, reduced cracking, and improved durability. While Portland cement production is responsible for 5 to 8 percent of global CO_2 emissions, SCMs are materials diverted from the waste stream. RSA has previous experience specifying up to 25 percent replacement of portland cement with fly ash in precast plank.

Concrete foundation work included a higher percentage of SCM as a portland cement replacement. Rigid insulated forms were also incorporated in the construction of below grade walls. Recycled concrete aggregate was specified for use in the foundation design both as a sub-base material and as up to 30 percent replacement of coarse aggregate in accordance with ASTM C33. All compounds (form-release, curing and sealing compounds, and concrete admixtures) were specified to be vegetable-based or low VOC.

The enclosed bridge walkway between the new Business School and the existing Job and Friends Hall was constructed using precast, pre-stressed double-Tee sections, supported on cast-in-place columns. The use of the double-Tee sections was selected to minimize the number of support members along the walkway and to be easily deconstructed if required eventually. While this type of construction is generally found in parking garages, its use as the structure for the walkway bridge proved to be a simple and elegant solution, while also offering future disassembly possibilities.

In conclusion, the Ithaca College School of Business provides both a figurative and literal center for excellence in sustainability. Through an integrated design process and creative solutions by the design and construction teams, Ithaca College provides an example of excellence in sustainable design for tomorrow's leaders of a sustainable society.

5.7

THE DAVID BROWER CENTER

Mark Stevenson, Tipping Mar

Figure 5.7-1. Designed to achieve a LEED rating, the project's ultimate goal was to remain functional after an earthquake. (Photo copyright WRT/Solomon E.T.C.)

Project:	**The David Brower Center**
Building Type:	Mixed-use
Location:	Oxford and Kittredge Streets, Berkeley, Calif.
Completion:	2009
Owner:	The David Brower Center
Structural Engineer:	Tipping Mar
Architect:	Wallace Roberts & Todd, LLC
Area:	225,000 square feet

Project description

Situated in the heart of downtown Berkeley within 1km of the Hayward Fault, the complex will be a model of integrated sustainable design. This mixed-use, 225,000-square-foot urban project was designed for the use of non-profit and environmental advocacy. The project can be divided into three main facets:

- The 4-story, 50,000-square-foot David Brower office complex, with its distinctive elongated bullet shape, forms the northern boundary of the complex and features office space and a conference center.
- Directly to the south lies Oxford Plaza, a multi-unit residential building incorporating subsidized housing. It is supported on a second-story post-tensioned (PT) podium slab over ground floor retail and restaurant space.
- Single level, below-grade parking covers the entire site.

Sustainability goals and achievements

Designed to achieve a LEED Platinum rating from the U.S. Green Building Council, the complex is named for David Brower, one of the preeminent environmentalists of the 20th century. Its sustainable design features include natural ventilation, the incorporation of sophisticated natural day-lighting strategies, photovoltaic panels, and rainwater collection. In addition, specialized concrete mixes, with high-volume replacement of cement with blast-furnace slag, were integrated into the design to reduce the quantity of portland cement. Typical cement replacement ratios ranged from 50 percent for slabs, columns and walls to 70 percent for the mat foundation, furthering the design goals of high material efficiency along with reduced embodied energy and life-cycle costs.

Seismologists predict a 7.0+ magnitude earthquake will likely occur well within the expected lifespan of this structure. A typical code-compliant building would be considered well-performing if it remained standing and allowed safe evacuation of the inhabitants after a major seismic event, even if substantial structural damage occurred. Generally the primary structural system retains sufficient residual strength to remain in service, but residual drift and widespread damage to non-structural components renders it unfit for continued use. Permanent offsets can interfere with the functioning of doors, windows, elevator shafts and other components to such an extent that the structure must be demolished and rebuilt. Clearly a major aspect of sustainable construction is continued functionality. Protection of the investment in energy and materials is a major “green” construction goal (Fig. 5.7-1).

High-slag concrete

There was initial resistance to the use of slag concrete from the prime contractor, sub-contractors and concrete suppliers. Slag is not regularly stocked by most concrete plants in the West (it is much more common on the East coast), and not all concrete firms were able to locate a supply. Tipping Mar persisted against this opposition to slag concrete in the project. Key to final acceptance was the structural engineer’s successful use of slag previously on the Chartwell School project and their willingness to have a series of preliminary meetings and discussions with the concrete supplier and the general contractor. They spent an appreciable number of hours researching slag information, documenting past use and discussing its characteristics with other design team members. Ultimately Hanson – Berkeley, the ready mix company, was able to find a slag supplier and installed a temporary silo at their Berkeley plant to service this job. Since they did not have a history of slag mix design and testing, Tipping Mar collaborated with them to develop a series of test batches for strength sampling.

High-slag concretes are slower in early strength gain than conventional mixes and surface finishing may be more difficult. These were typically the main points of opposition raised by sub-contractors. However, Tipping Mar’s experience has shown that these properties do not necessarily present major obstacles.

Rate of strength gain is particularly important in multi-story construction where floor cycle time may be critical to the project schedule. Experience showed that for construction during the coldest part of the winter, typically 7 days were required for PT slabs to reach the minimum compressive strength to allow tensioning of the tendons. Compared to 5 days or so for conventional mixes, this potentially added 2 days to the schedule for each floor. However, given the 2 to 2.5 week floor cycle time, this slower set did not have an appreciable impact on the project schedule. Additionally, the difference in set time between conventional and slag mixes decreases when the concrete is placed during warmer conditions.

One part of the strategy to reduce cement use was to define concrete strengths at 56 days, rather than at the typical 28-day limit. Since construction dead and live loads are typically a fraction of design loads, this means that concrete members do not have to achieve full strength to allow construction to proceed. The biggest problem in achieving design strength was in the 8,000 psi core mix (which was the highest compressive strength used on the job). Some sections of core placed in February took 120 days to reach full strength. However, the core compressive strength was only an issue towards the end of structural work when the post-tensioning loads were applied to the cores. To ensure that the upper level of the core would have adequate strength to allow stressing as scheduled, an extra sack of cement was added to the mix of the top-most level, so that there was no delay in completion of the concrete structure.

High-slag concretes do cause some unusual finish conditions. The slower set caused concrete finishing to take longer than is typical. Also, some mixes had water/cement ratios (0.55 – 0.60) that were higher than normal. The relatively high water/cement ratio, combined with a tendency to release more bleed water than standard mixes, caused in some cases the formation of a dusty top coat on the dried slabs. This was most pronounced on the mat slab surface, which serves as a finished floor at the parking garage, where a 70 percent slag mix was used. However, the final broom-finish was completely acceptable. At upper floors using 50 percent slag mixes, the smooth trowel finishes were perhaps not quite as smooth as typical non-slag mixes yield, but were again acceptable.

The majority of the mix designs used 50 percent slag with several variations used. Because finishing was less critical at the garage, and to take advantage of the decrease in mass heat gain during cure, a very-high slag mix of 70 percent was used in the mat slab, which ranged from 24 to 36 inches in depth. As noted above, to promote more rapid strength gain, a lower slag ratio was used in the uppermost portion of the core. Shotcrete mixes used in the basement walls typically required more cement than poured-in-place, with slag ratios of 20 percent to 50 percent.

Recommendations

After successfully employing slag concretes on a number of projects, the structural engineers are convinced that this is an effective and useful method of producing "greener" concrete with a reduced carbon footprint. Additionally, it replaces a primary energy-intensive material (cement) with an industrial waste product (slag). Slag cements have produced very satisfactory results in a variety of applications. An added attraction is that the high-slag concretes are lighter and less grey in color than traditional mixes.

One must keep in mind, however, the limitations of this material — high-slag mixes are not appropriate for every application. Besides the longer set times and trickier finishing, the greater amount of bleed water can reduce the crispness and sharpness of fine details and edges. At seams and holes in forms, the bleed water tended to wash out the lines and occasionally leave rounded, crumbly corners. At some exterior walls with horizontal chamfered reveals, the appearance of the corners was not acceptable and required subsequent patching and floating. It seems where finely detailed surfaces or sharp, exposed corners occur that less slag should be used in mix formulation.

5.8

BEDDINGTON ZERO ENERGY DEVELOPMENT

Lachlan McDonald, Ellis & Moore Consulting Engineers

Project name: **Beddington Zero Energy Development**
Project Type: Residential
Location: London Rd., Wallington, London, Borough of Sutton, UK
Completion: 2002
Owner The Peabody Trust
Structural Engineer: Ellis & Moore Consulting Engineers
Architect: Bill Dunster Architects (Now Zed Factory)
Services Engineer: Arup
Sustainability Consultants: Bio Regionable Development Group

Description of project

This was a green residential development of 120 units where one-third of the units were for sale, one-third of the units were for shared ownership, and one-third of the units were for rent. The contract sum was £17M ($24.7M).

Introduction

The Beddington Zero Energy Development known as BedZED is a green residential development where a number of reclaimed and recycled materials were used as an alternative to new materials to reduce embodied energy in the development.

A total of 3,404 tonnes of alternative materials including 1,862 tonnes of reclaimed on-site sub-grade fill were sourced and utilized, accounting for approximately 15 percent by weight of the total materials used on the project. All the successful measures implemented at BedZED to source and utilize reclaimed or recycled materials resulted in cost saving for the client or the contractor. The use of reclaimed timber for external stud work and reclaimed paving slabs proved to be too difficult to achieve within the constraints of time and budget. Because of the use of reclaimed materials, the procurement and construction program had to be flexible because, for example, some of the materials were difficult to source on short notice.

Reclaimed structural steel

The project used 98 tonnes of reclaimed structural steel, approximately 95 percent of the total. A range of structural sections were specified to ensure that appropriate sections could be sourced, identified, and assessed for condition. On this project no material testing was performed on the material as the sections were clearly identifiable and the properties ascertained from the standard tables for joists. The steel came from one source, which was not anticipated prior to commencing the search for suitable sections.

The selected steel was taken to the fabrication works, sand blasted, fabricated, and painted. The reclaimed steel required an extra pass through the sand blaster to ensure that it was clean and ready for painting.

Reclaimed steel could not be used for the curved sections because the specialized fabricator refused to pass the steel through the bending machine. Also, reclaimed steel was not used for steelwork such as balconies and balustrades because there was too much work involved in procuring the material and fabricating it to fit its new purpose.

The contractor purchased the reclaimed steel on behalf of the owner and the structural engineer saw that the steel was designed and fabricated in accordance with the current codes of practice. The cost of the reclaimed steel was 4 percent lower than the cost of the equivalent new steel.

Reclaimed timber

Reclaimed timber was used in non-exposed conditions as load bearing studwork. The strength of the timber was assessed visually and the species type identified in the laboratory under a microscope. The timber was found to be satisfactory once treated, however whilst the timber was purchased at a lower rate than new timber, the additional costs including stress grading and treatment made the reclaimed timber the more expensive option.

Recycled aggregate

Recycled crushed aggregate was used for the construction of the road sub-base, such that 980 tonnes of crushed concrete replaced the same quantity of normal limestone to achieve a significant cost savings.

Recycled crushed green glass sand

In the UK crushed green glass is easily obtainable due to the non re-usability of green wine bottles. On this scheme 279 tonnes of recycled green glass were used to replace bedding under paving slabs. This gave a cost saving of approximately 15 percent as compared to traditional sand.

Lessons learned

This project proved that reclaimed materials can be successfully used on new build projects. The assumption that new buildings should all be *new* was challenged and successfully overcome. In engineering terms, the expected life of structural components, such as timber and steel, was shown to extend far beyond the life of an original building.

As far as structural steelwork is concerned, there are no technical barriers to reuse. A satisfactory inspection procedure is required to deal with the practical aspects. On BedZED relatively new steel was used, but it is anticipated that if more use is made of reclaimed steel then older and more problematic sections will be used. This will require testing and identification from historic tables to assess load carrying capacity and continued durability. It is necessary for the contractor to be flexible on the procurement programs to ensure that the appropriate sections can be obtained. Ideally, the procurement should occur in advance of the construction program so that all the necessary sections can be sourced.

The reuse of structural timber depends on identifying species and stress grading. On BedZED this proved to be more difficult than the structural steelwork as there are only a few lumber yards in the UK where reclaimed timber can be graded and identified. For the reuse of timber to become widespread, it is necessary to have yards dedicated to storage of reclaimed timber where species and stress grades are determined.

On this occasion recycled aggregates were used under the roads. The objective in the future is to reuse the aggregate in concrete and not downgrade it to backfill. This was not possible on this project due to the impurities in the aggregate.

The replacement of sand with crushed glass proved satisfactory once precautions for health and safety concerns were taken. The crushed glass complied with building codes requirements for the grading standards for sand, but the project team had not used it previously and were concerned about the possible dangers of children falling and injuring themselves. The team decided that all crushed glass must be unexposed; in this case it was covered with paving slabs.

In conclusion, there are a few technical considerations with the use of reclaimed materials. Additional time may be required to procure the material and confirm its technical properties. Many contractors are reluctant to consider the use of reclaimed materials as it involves them in additional process of procuring materials that require assessment rather than ordering new materials, which are clearly identified and relate directly to the design codes. That said, this project proves that reclaimed materials can be used successfully in new construction.

5.9

CRAFTING GREEN SPECIFICATIONS

Helena Meryman

Project:	**Crafting Green Specifications for Concrete, Steel and Wood Construction**
Completion:	2001
Structural Engineers:	Robert Silman Associates (RSA)

Project description

In the spring of 2001, Robert Silman Associates (RSA) — a structural engineering consulting firm — began an office-wide sustainability education program. The major work product that resulted was a set of totally original "green" specifications for cast-in-place concrete, precast plank, structural steel, light gauge steel, metal deck, and rough carpentry. The educational program consisted of a speaker series that presented the environmental problems caused by the built environment, and workgroups in which RSA staff researched and reported on how the issues of sustainability were connected to structural materials and construction methods.

Process

A significant factor in the success of this program was the avid involvement of senior staff. In workgroups, Principals worked alongside junior engineers questioning the sustainability of every aspect of material manufacture and method of construction. An engineering summer intern with considerable experience in green building acted as the facilitator for the research groups. The facilitator suggested resources and new angles of inquiry, picked up any slack, coordinated efforts and kept the ball rolling. The writing of the green specifications initially came from the workgroups investigating the various structural materials.

The fruits of each group's research were applied to a specification. For example, the group working on the environmental issues related to steel would review the conventional steel specification and flag areas where changes should be made for a green version of the specification. In addition, they drafted a front piece of "problems" and "solutions" for the material. This was a starting point and a big leg up on the task of rewriting the specifications; however, in many instances the groups' research uncovered more questions than it answered and revealed inadequacies in the existing knowledgebase.

This challenged the process — should we put writing on hold until our research can provide more definitive answers, or do we proceed as best we can while writing and researching in parallel? The group chose to start writing for the following two reasons:

- The field of existing information on the topics of interest was still fairly nascent — questions and answers were actively evolving as attention to the subject was growing.
- Morale was waning — design engineers are probably not researchers by temperament, the staff wanted to see a useful work product take shape sooner than later.

The workgroups began rewriting the specification sections while continuing their research. Specification writing teams met every week or two to assess progress, trouble-shoot information holes and assign new writing and research tasks. Eventually, (a year into the project) staff was pulled away on other projects; the intern and facilitator was now a staff engineer and became the primary researcher and writer on the green specification project, and Principal staff remained involved.

Philosophy and format

How do you get engineers excited about writing green specifications? Focus on the power that green specifications have to incrementally — yet steadfastly — change the industry. The challenge is to find the best way to communicate new information to facilitate the adoption of green practices and materials.

For the firm's green projects to be successful, the green specifications had to truly engage the stakeholders. It is crucial to ensure that the entire team of contractors understands what is behind a project's green goals, and our firm hoped it could also make them care. To accomplish this, the RSA green specifications were written with educational sections in the first section. These paragraphs are designated for information purposes only. They give an overview of the environmental concerns related to a material, and strategies to mitigate the environmental impacts. Many of the provisions relating to sustainability may be new to the bidders and the successful contractor. It is believed that explaining the big environmental issues to contractors and construction managers will give them a greater professional and personal investment in achieving the specified "green" practices.

It is a good idea to keep the green additions and changes to a conventional specification in a different font color or better yet a MS Word defined style. This facilitates the updating of information, editing for a specific project, and general revisions. In addition, this format is useful in creating a set of parallel cost neutral specifications than could replace the conventional specification.

Resources

There are many more resources available now than there was when RSA took on this project. RSA relied heavily on the AIA's Environmental Resource Guide (ERG), which is still available on CD. The archives of the Environmental Building News and their companion publication "The Green Spec Directory" continue to be valuable resources. Much of the research benefitted from getting the right technical person at a product manufacturer on the phone; talking to sales representatives was always a waste of time.

Lessons learned

The commitment required to write original "green" specifications was more significant, and the complexity of issues to be navigated was more daunting, than anticipated. The timeline to complete the project was extended many times. This could have been avoided by defining several goals at the outset, such as the following:

- What does it mean for a specification to be complete?
- What is the process to recognize completion?

Since specifications are living documents that are ideally continually updated with current products and standards, knowing when a new specification is "done" is not necessarily obvious. Establishing a peer review and finalizing process up front is critical.

Finally, every project needs a champion and every project champion needs resources. Essential to the success of the green specification project were the unfettered amount of non-billable hours. Specification research and writing was part of the workweek, not strictly an after-hours activity; RSA set up a special job number to track how much resource the project was using, but no one was ever told to stop spending time on it. For long-term specification maintenance, it is also a good idea to define some new permanent positions; these roles should be filled with those with the keenest interest in sustainability. One person is needed to physically manage the specifications (versions, revisions) and ideally, two people would be assigned to periodically update the specifications and facilitate their use on specific projects.

5.10

THE SAVILL BUILDING

Richard Harris, Buro Happold

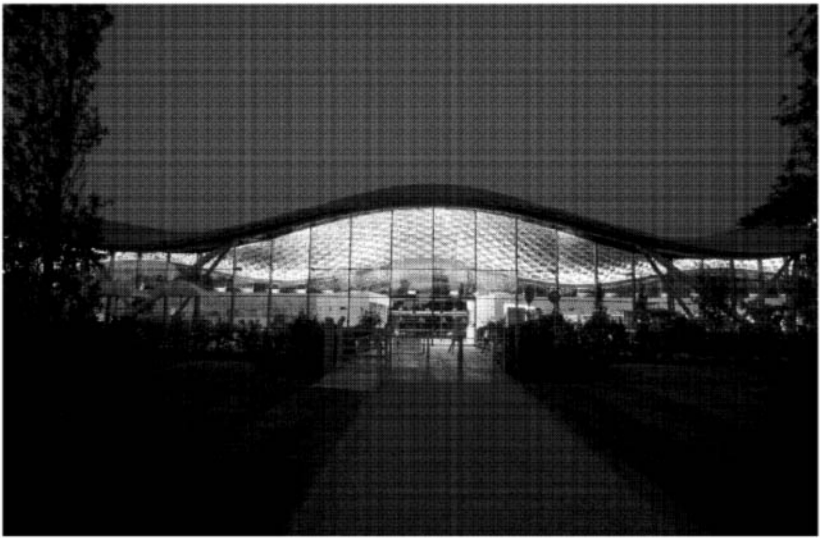

Figure 5.10-1. This site-sensitive project reflects the surroundings. (Photo copyright Warwick Sweeney)

Project:	**The Savill Building**
Building Type:	Shop and Visitor Centre
Location:	Windsor Great Park, London
Completion:	2007
Owner:	Crown Estates
Structural Engineers:	Engineers HRW with Buro Happold
Architect:	Glenn Howells Architects
Carpenter:	The Green Oak Carpentry Company
Area:	18,000 square feet

Sustainability concept

The building location is sensitive — within Windsor Great Park overlooking Savill Garden (Fig. 5-10.1). The form — three gently undulating oak clad domes — reflects the landscape shape.

The roof structure spans 90 feet × 300 feet (27 m × 90 m) and comprises a timber gridshell, constructed of 4 layers of 3.2 inch × 2.0 inch (80 mm × 50 mm) sections supported on a steel structure to create wide openings onto the Savill Garden

(Fig. 5.10-2). The structural integration of the timber shell with the steel perimeter tube and the legs is a very efficient solution.

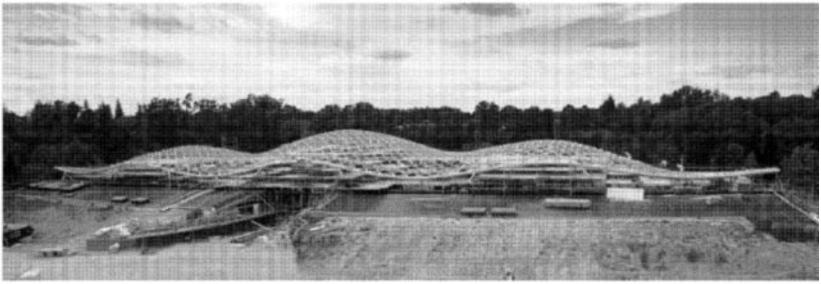

Figure 5.10-2. The gridshell under construction
(Photo copyright Warwick Sweeney)

The roof overhang shades the building façade and reduces solar heat gain. The height of the space allows heat to rise to the top of the roof. The shape of the roof allows fans at the high points of the domes to extract hot air.

Use of timber

The structural timber is European larch, grown in the Windsor Forest, the sustainably managed woodland surrounding the building. The forest is Forest Stewardship Council (FSC) certified and a Site of Special Scientific Interest (SSSI). An SSSI is an area of land designated by English Nature, a government agency, as a unique and varied habitat requiring preservation. In the case of Windsor Great Park, the SSSI designation is due to the fact that it forms part of the largest continuous tract of woodland and parkland in the county of Berkshire. The site provides habitat for a range of rare species of invertebrate including some that are internationally important. The plantations are being replanted with larch, Douglas fir and sweet chestnut species. The Park receives over 2 million recreational visitors a year.

The larch for the main gridshell timbers was tested extensively to determine visual grading rules to match predictable strength. The latest jointing technology was utilized to cut out the defects and use finger joints to join the lengths together, forming laths of the required length and of a consistently high quality, produced from normal-grade timber. The removal of defects by finger jointing produces “improved” timber. The advantage of using “improved” timber laths was that the quality of the material was maximized very quickly and cheaply with minimum wastage. By creating reduced-defect timber, the mean and minimum strengths are increased, leading to a higher grade. A further benefit is that larch with all sapwood removed is naturally durable, avoiding the use of preservatives. The technical term for the process is “optimization.” The laths were finger jointed into 20-foot lengths and then scarf-jointed into 260 continuous single pieces each up to 100 feet long. Four hundred larch trees in total were used, and converted into 12 miles of small section laths.

A structural skin of birch plywood fixed over the grid creates the shell, which covers 16,000 square feet. Over this is fixed a layer of insulation and a lightweight metal skin, which waterproofs the building.

Oak, also from Windsor forest, was used for both the flooring inside the building and the rain screen that creates the final layer over the roof. One hundred trees were selectively felled in 2004 and 2005, in line with the forestry management plan, for these purposes.

Preservative treatment is required for neither the oak nor the larch, due to the natural durability of the selected timber.

The remaining timber in the structure consists of laminated veneer lumber (Kerto LVL manufactured from Norway Spruce) for the fingers that join the shell to the steel perimeter tube and Finnish birch plywood, as noted above, to cover the roof. Both these were supplied from sustainable sources in Finland.

Why use timber?

In this application timber was the best material to minimize damage to the environment. It grows through photosynthesis in the leaves of trees, storing carbon dioxide from the air to make the carbon compounds in its structure. Intelligent use of timber equates a healthy combination of sustainability and development. Every pound of carbon in wood fixes 1.44 pounds of CO_2 equivalent, and 50 percent of wood consists of carbon removed from the atmosphere.

Timber not only acts as a carbon sink while it is growing, it acts as a carbon store during its entire life in a building. Although timber production involves the use of fuel, in the form of forestry, transport, sawmilling, and planning, on balance it removes very much more carbon dioxide from the air than it emits. In addition, the energy used in production is only 15 percent of the energy potential in the wood product and its residues. Further, at the end of its life, timber can be used for biomass energy, replacing the need to burn fossil fuels or other hydrocarbons.

Comparison with other types of structure

A shell is a three-dimensional structure that, due to its shape, resists applied loads primarily through in-plane stress, and is therefore thinner and lighter than structures that resist gravity loads primarily through bending. If regular holes are made in the shell, with the removed material concentrated into the remaining strips, the resulting structure is a "gridshell." The three-dimensional structural stability is maintained by shear stiffness in the plane of the shell, achieved by preventing rotation at the nodes, which are points of intersection of the grid members, or by introducing bracing.

Steel and concrete gridshells are constructed to their final form. Thus, it is necessary to fabricate the nodes and interconnecting members to the precise final geometry. An example of a steel gridshell is the roof over the Queen Elizabeth II Great Court in the British Museum in London. In this gridshell, each node was different and each one had to be prefabricated to a prescribed geometry. Such requirements have obvious impacts on the cost and the rate of construction. Timber gridshells overcome such difficulties as the lattice can be laid out as a flat mat initially and then pushed into shape.

The development of a doubly curved gridshell from a flat, square, or rectangular grid is made possible by the low torsional stiffness of timber. During forming, the timber lattice allows rotation at the nodes, and bending and twisting of its constituent laths (Fig. 5.10-3). Once formed, shell action is accomplished by adding triangulating bracing or plywood sheathing, thereby providing in-plane shear strength.

Figure 5.10-3. Manipulation of a timber gridshell (Image copyright Buro Happold)

Working as a shell, the timber can be used to its best structural effect and very much higher strengths and stiffnesses may be used in the design than would normally be expected from UK-grown timber. Figure 5.10-4 shows the stress distribution, indicating how loads flow towards the stiff quadraped structures.

To virtually eliminate waste, the design incorporated first grade timber in the main lath elements and lower grade timber in blocking pieces and shear blocks. This provides excellent utilization and minimizes waste. The weight of timber in the shell structure and its covering is 30 tons, equivalent to a weight of less than 4 pounds per sq foot, which is very much less than an equivalent concrete structure, saving materials in the sub-structure and foundations.

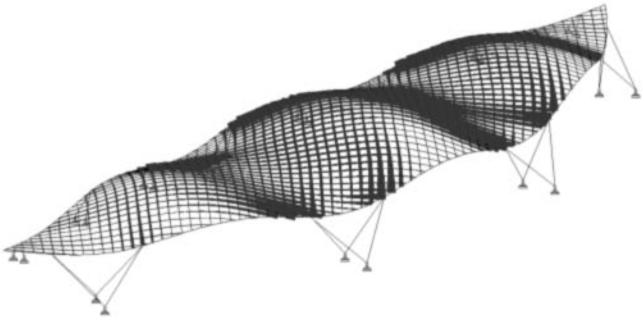

Figure 5.10-4. Indication of stress distribution in shell where heavier lines indicate higher axial stress (Image copyright Buro Happold)

Precedents for timber gridshell construction

Buro Happold's experience on the following projects provided a level of confidence in the structural strategies and material choices made in the design of the Savill Building:

- Mannheim: 200 ft × 200 ft (60 m × 60 m); 4 layers 2.0 in. × 2.0 in (50 mm × 50 mm) at 20 in. (0.5 m) spacing; hemlock; braced with twin 1/4 in. (6 mm) cables every node.
- Japan Pavilion, Hannover: 240 ft × 110 ft (72 m × 35 m); 2 layers 4.7 in (120 mm) diameter cardboard tubes at 3.2 ft (1.0 m) spacing.; braced with glulam ladders.
- Earth Centre, Doncaster: 20 ft × 20 ft (6 m × 6 m); 2 layers 1.3 in. × 0.6 in. (32 mm x 15 mm) oak at 16 in (400 mm) spacing; braced with twin 1/4 in. (6 mm) cables at alternate nodes.
- Downland Gridshell, Chichester, West Sussex: 160 ft × 50 ft (48 m × 15 m); 4 layers 2.0 in. × 1.4 in. (50 mm × 35 mm) at 3.2 ft (1.0 m) spacing; braced with oak timber cladding rails at alternate nodes.
- Chiddingstone Castle Gridshell, Kent: 40 ft × 16 ft (12 m × 5 m); 4 layers 1.6 in. × 1.4 in. (40 mm × 35 mm) sweet chestnut at 36 in. (925 mm) spacing; braced with twin 5/32 in. (4 mm) cables at alternate nodes.
- Savill Garden Gridshell: 300 ft × 80 ft (90 m × 25 m); 4 layers 3.1 in. × 2.0 in. (80 mm × 50 mm) larch at 3.2 ft (1.0 m) spacing; braced with plywood roof membrane.

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Index

AAC 191
adaptability. see design for adaptability and deconstruction
adobe 227–228
Advanced Energy Design Guides 25
aggregate 151–152, 151f, 152f, 174–176
American National Standards Institute 25
ANSI. see American National Standards Institute
ash: fly 160–164, 160f; rice husk 167–170, 168f, 169f
ASTM International 25
ATHENA EcoCalculator for Assemblies 128
ATHENA Impact Estimator for Buildings 127

bamboo 235–239, 238t
Bank of America Tower 285–288, 285f, 287f
Beddington Zero Energy Development 299–301
BEES. see Building for Environmental and Economic Sustainability
brick masonry 190–191; reuse of 103–105, 105f
bridges 244–250; decks 244–245; foundations 250; load-carrying members 245–248; substructure 249
building components: reuse of 99; wood 218–219, 219f
building enclosure 12–13
building envelope 81–82; and steel 204–207, 205f
Building for Environmental and Economic Sustainability 27; life-cycle assessment software 128
building materials, natural 225–239; adobe 227–228; bamboo 235–239, 238t; cob 229; earthen construction 226–230; overview 225–226; rammed earth 228–229; straw bale 231–235
building orientation 11–12, 14
buildings, historic 94
buildings, residential 299–301

Candela structures 258–262, 258f, 260f, 261f
case studies 257–309; Bank of America Tower 285–288, 285f, 287f; Beddington Zero Energy Development 299–301; Candela structures 258–262, 258f, 260f, 261f; crafting green specifications 302–304; Dalby Forest visitors center 273–279, 273f, 274f, 275f, 276f, 278f; David Brower Center 295–298, 295f; Ithaca College Business School 289–294, 289f, 290f, 291f, 292f; Nomadic Museum 280–284, 280f, 281f, 283f; San Francisco federal building 263–271, 263f, 265f, 266f, 267f, 268f, 269f, 270f; Savill Building 302–309, 305f, 306f, 308f
CCM. see complementary cementing materials
cement: blended 172; complementary cementing materials 158–160, 173t, 174t; slag 164–165. see also concrete
Chemical Scorecard 138
CHPS. see Collaborative for High Performance Schools
CMU 190
cob 229
Collaborative for High Performance Schools 22; and design for adaptability and deconstruction 91
complementary cementing materials 158–160; in blended cements 173t;

specifications and classes of 174t
concrete 148–184; aggregate 151–152, 151f, 152f, 174–176; binder specification 172–174, 173t, 174t; blended cements 172; and carbon dioxide 152–153, 152t; complementary cementing materials 158–160; construction 177–179; deconstruction 179–181; and design for adaptability and deconstruction 179–180; durability 157–158, 184; engineering solutions 155; environmental impacts 150–155; extraction impacts 150–152, 151f, 152f; fly ash 160–164, 160f; maintenance 184; mineral ultrafines 170–172; mix design 155–156; reuse of 109; rice husk ash 167–170, 168f, 169f; silica fume 166–167; slag cement 164–165; solid waste 154–155; specifications 53–58; strength 156–157; and sustainability 148–149; sustainable construction 181–182; and toxicity 141; water recycling 176–177; workability 158. see also cement
concrete, pervious 183–184
concrete, Portland 150–151, 181
concrete, precast 182; reuse of 109; specifications 58
conservation 94
construction, earthen 226–230
contamination: of brick masonry 105; of structural steel 107; of wood 102. see also toxicity
convection currents 15
Cradle to Cradle Certification 26

Dalby Forest visitors center 273–279, 273f, 274f, 275f, 276f, 278f
David Brower Center 295–298, 295f
daylighting 13–14
deconstruction. see design for adaptability and deconstruction
design for adaptability and deconstruction 85–91; benefits of 86; Collaborative for High Performance Schools 91; and concrete 179–180; drawbacks of 86; general considerations 89–90; Green Globes Program 91; guidelines 91; life-cycle considerations 90; strategies for 87–88, 89f; terminology 85–86
design integration 10–16; building enclosure 12–13; building orientation 11–12, 14; convection currents 15; daylighting 13–14; double skin facade 12–13; interior lighting 13–14; radiant energy 15; screening 14, 15–16; site placement 14; solar design 11–14; sun path 11–14; thermal mass 12; thermal shields 12; ventilation 14–15; wind 14–16
DfAD. see design for adaptability and deconstruction
dioxins 133–134
double skin facade 12–13
downcycling 73–74, 85
durability 80–83; of concrete 157–158; and design for adaptability and deconstruction 87; elements of 81–82; standards and guidelines 82–83; of steel 208; of wood 220–221

earthen construction 226–230
Ecologo 26
Energy Star program 22–23
Environmentally Preferable Products/Purchasing 27
EPA. see U.S. Environmental Protection Agency
EPP 27
European REACH legislation 137

federal buildings 263–271, 263f, 265f, 266f, 267f, 268f, 269f, 270f
finishes 68
Floorscore 27
fly ash 160–164, 160f; toxicity of

163–164
foundations, reuse of 109–111
furans 133–134

GBI. see Green Building initiative
GGHC. see Green Guide for Healthcare
Green Building initiative 23; recycled content 75–76
Green Globes program 23, 40–46; achievement levels 40–41, 41t; assessment and certification processes 41; and design for adaptability and deconstruction 91; provisions 42–44; sections 44–46; for structural engineers 41
Green Guide for Healthcare 23
Green Homebuilding Guidelines 24
Green Label 26
Green Label Plus 26
Green Product Guide 26
Green Seal 27
Greenguard 27
GreenSpec Directory 26

heavy metals 134
historic preservation 94
historic restoration 94

infrastructure 243–253; bridges 244–250; pavements 250–252; and sustainability 243–244
interior lighting, artificial 13–14
International Organization for Standardization 25
ISO. see International Organization for Standardization
Ithaca College Business School 289–294, 289f, 290f, 291f, 292f

LCA. see life-cycle assessment
Leadership in Energy and Environmental Design. see LEED
LEED 23–24, 29–39; achieving credits 35–38, 35t, 36t, 38t; building reuse 31; certified wood 33; construction waste management 31; credits 31–34; development of 29–30; improving 38–39; innovation 33–34; materials reuse 32; objectives of 29–30; rapidly renewable materials 33; recycled content 32, 75; regional materials 32; structure of 30–31, 31t; summary of 30t
life-cycle assessment 26, 117–128; components of 121–124, 122f, 123f, 124f; contribution to 125; and design for adaptability and deconstruction 90; examples of 125–126; life-cycle stages 119–121, 119f; overview 117–118; purpose of 118–119; resources and tools 126–128; software 127–128; sources of data 127; standards 126–127; and toxicity 140
Living Building Challenge 24
local manufacturing. see local materials
local materials 77–79; advantages of 77–78; and concrete 177; defined 77; strategies 78–79; trade-offs 78
local sourcing. see local materials

maintenance, reduced 80–83
masonry 190–196; AAC 191; benefits of 194–195; brick 190–191; CMU 190; construction and design 193–194, 194f; deconstruction 195; demolition 195; engineering solutions 193; environmental impacts 191; implementation techniques 195–196; overview 190–191; refining and manufacture 192–193; specifications 58–59; sustainability 191–192
metrics 17–28; energy 20; environmental standards 25; high-performance design 17–18; indoor environmental quality 21; inspiration 21; life-cycle assessment 26;

materials 20; measurement context 18–19; measurement scope 19–21; measurement usage 21–22; mitigation 17; neighborhoods 21; net-zero goals 18; product-based ratings 26–27; rating systems 22–24; reasons for measuring 17–18; regenerative design 18; related to steel 209; restorative design 18; site design 20; water 21
mixed-used buildings 295–298, 295f
museums 280–284, 280f, 281f, 283f

NAHB. see National Association of Home Builders
National Association of Home Builders 24
natural building materials 225–239; adobe 227–228; bamboo 235–239, 238t; cob 229; earthen construction 226–230; overview 225–226; rammed earth 228–229; straw bale 231–235
Nomadic Museum 280–284, 280f, 281f, 283f

office towers 285–288, 285f, 287f

pavements 250–252
PBTs 133
Pharos Project 27
post-consumer waste 73
post-industrial waste 73
project delivery 47–48

radiant energy 15
rammed earth 228–229
recyclability 73
recycled content 72–76, 85; case study 299–301; definitions 72–74; quantification of 75–76; rating systems 75–76; reasons for specifying materials 74–75; recycled product database 76; and steel 202
Recycled Content Product Database 26
recycling. see recycled content
renovation 94
retaining walls, reuse of 109–111
reuse 85, 93–113; adaptive reuse of existing buildings 94–99; of aerospace and aeronautics sector components 111–112; of brick masonry 103–105, 105f; of existing building components and materials 99; of foundations 109–111; options for 98; of precast concrete 109; of prestressed concrete 109; of retaining walls 109–111; seismic concerns 97–98; of shipping containers 112–113, 113f; of steel 203–204; of steel bolts 109; of structural steel 105–109, 107t, 108f; of temporary structures 111; terminology 93–94; of wood 99–103, 100f
rice husk ash 167–170, 168f, 169f

salvaging 94
San Francisco federal building 263–271, 263f, 265f, 266f, 267f, 268f, 269f, 270f
Savill Building 302–309, 305f, 306f, 308f
Scientific Certification Systems 27
screening 14, 15–16
seismic issues 97–98
SFI. see Sustainable Forestry Initiative
shipping containers, reuse of 112–113, 113f
shopping centers 302–309, 305f, 306f, 308f
silica fume 166–167
site placement 14
site/foundation 53
software 127–128
solar design 11–14
specification writing 48–68; concrete division 53–58; coordination 50–51; crafting green specifications 302–

304; finishes division 68; masonry division 58–59; overview 48–50; precast concrete division 58; site/foundation 53; specification example 52–68; steel division 59–63; topics to consider 51–52; wood division 63–68
State of California Proposition 65 137
State of California Special Environmental Requirements Specification 25
steel 198–209; code considerations 209; corrosion protection 208; design for deconstruction 203–204; durability of 208; environmental impacts 200–203; foreign 202–203; greenhouse gases and wastes 200–201; material efficiency 204; metrics 209; overview 198–199; production supply chain 199–200; recycling 202; resource utilization 201–202; specifications 59–63; strategies for reuse 203–204; structural finishes 208; sustainability 209; thermal properties 204–207, 205f; and toxicity 141; waste management 203
steel, structural 105–109, 107t, 108f
straw bale construction 231–235
structural materials 132–142
structural steel 105–109, 107t, 108f
structural systems 81
sun path 11–14
sustainability 1–6; defined 1–2; economic factors 5; environmental factors 2–5; social factors 6; Triple Bottom Line 2
sustainable forestry 213–216, 214f, 215f, 216f; Sustainable Forestry Initiative 216
Sustainable Forestry Initiative 216
thermal mass 12
thermal shields 12
toxicity 132–142; environmental 133–134; of fly ash 163–164; human 133–134; life-cycle assessment 140; managing 135; obstacles and difficulties 140–141; product information 138–140; significance to structural engineering 132–133; sources of information 135–138, 135t; types of 134. see also contamination
Triple Bottom Line 2

university buildings 289–294, 289f, 290f, 291f, 292f
U.S. Environmental Protection Agency 136–137

ventilation, mechanical 15
ventilation, natural 14–15; case study 263–271, 263f, 265f, 266f, 267f, 268f, 269f, 270f

waste: post-consumer 73; post-industrial 73
water 176–177
wind 14–16
wood 212–223, 212f; advanced framing 220; building components 218–219, 219f; deconstruction 222; durability 220–221; forest certification 215–216, 216f; overview 212–213; preservative treatment 221–222, 221f; product selection 217–218, 217f; recycling 222, 222f; reuse of 99–103, 100f; specifications 63–68; sustainable forestry 213–216, 214f, 215f, 216f; Sustainable Forestry Initiative 216; and toxicity 141