STRUCTURAL
GLASS FACADES AND ENCLOSURES

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To my parents and my bride, with the utmost gratitude, esteem, and love.

This book is printed on acid-free paper. ♾

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Preface

This book is about the technology of a building form I refer to as *structural glass facades* (SGFs). It derives from academic experiences over the past few years in the School of Architecture at the University of Southern California. I left academia after completing my undergraduate work to get some real-world experience, with every intention of returning to pursue graduate work. Twenty-five years later, I did. In the interim, I designed and built SGFs with a team of the finest and brightest people ever to walk a building site. So, while the text derives from academic experience, it is rooted in the joy of building: the pursuit of innovation, the manipulation of material and process, the collaborative realization of a mere idea, the utter novelty of every new project, the camaraderie, and, of course, the blood, sweat, and broken bones to be found buried beneath every building; it is the construction industry, after all.

This book is for the next tier of would-be adopters of SGFs, those who have admired the built applications and wished for the budget, or the know-how, or knowledge of what the options were, or what issues were involved in implementing an SGF project. At its core, SGF is a mature technology, tried and tested with many examples, with many of the early development and testing costs characteristic of any emergent technology paid for, and with an infrastructure of capable material suppliers and fabricators ready to go to work on your project. There will always be a cutting edge to this technology; that is the source of inspiration that fuels the evolution. However, as happened with glass fin walls, the technology will ultimately diffuse into the broader marketplace. If this book has the good fortune to facilitate that diffusion, it will be because of the stunning project work it includes.

The Case Studies

The selection of the case studies presented in Chapters 7 to 17 was no simple matter, and the juggling of projects to include continued up to the last possible minute. There were several criteria I developed in making the selections:

- I chose to have fewer but deeper case studies. Some of the selected projects could easily be the subject of an entire book. I wanted at least to consider such issues as project delivery, fabrication, testing, and installation, in addition to the usual design focus.
- I chose to present projects of varying size and complexity rather than to focus only on the grandest or most complex.
- I chose to focus, mainly though not exclusively, on work completed in the United States. The technology was certainly created and developed in Europe, where there is an abundance of exceptionally worthy candidates for SGF case studies, but these projects invariably receive a great deal of coverage in books and magazines; those in the United States are less well publicized. I had no problem identifying a number of relatively recent projects that had received little or no significant coverage. I ended up with two projects outside of the United States that I simply could not bring myself to exclude.

I have long been frustrated by the tendency to document completed projects in a series of photographs taken right after project completion, when everything is buffed and polished and looking its majestic best. A professional photographer with a large-format camera rents a man-lift to access some vantage points that no pedestrian or building occupant will ever experience and produces spectacular high-dynamic-range images that look somehow otherworldly, like a building on Neptune. I personally find a building much more engaging during the process of construction, when it is still partially opened up, the structural frame is revealed, the cladding is crawling its way up, and a tower crane hovers over all like a crown. So, in this book, I have made an effort to include images documenting fabrication, testing, mockups, and installation. It is a challenge; what you discover when you examine such material is that while some of the images are absolutely stunning, most of them are unusable because they were taken with a cell phone or small-format pocket camera, and the images are postage stamp size when printed. It is a tragedy, and the source of many curses from this author (I have started buying decent cameras for people who spend a lot of time on the building site, and I have begun teaching basic digital photography classes). I did, however, manage to find a few images that reflect pieces of the fabrication and installation process. But in the end, the intent to feature process over finished project may well have been in vain; there was no way to avoid using the amazing photographs of pros like Rainer Viertlböck and Paúl Rivera, and great photography combined with the inherent sexiness of SGFs will no doubt overshadow the crusty rawness of the jobsite photos.

The case studies started with a class exercise I gave in a course I had the great pleasure to teach at the School of Architecture, University of Southern California. The course, titled "Skin and Bones," focused on SGF technology and the use of glass in the building skin. The class of 20 consisted mostly of graduate students, with a scattering of undergraduate and PhD students. We quickly discovered that they were all equal in their ignorance of glass as a building material. We had great fun exploring glass and the glass systems and structures that comprise SGF technology. We worked out a comprehensive strategy for the case studies, which we embodied in a format that included everything from site and climate analysis to concept development and sustainability features. The structural system, glass, and the glass system were to be the core content of each case study, but I was amazed to discover the diversity of approach the students pursued. Some became immersed in climate analysis, producing pages of colorful charts and graphs. Others explored the green aspects of the architecture: the in-floor radiant thermal conditioning, the natural ventilation system, the daylighting strategy. Most of them treaded very lightly in the core areas, leaving that work to me with respect to this book and providing me with a clear demonstration of my shortcomings as an instructor. I now know the importance of narrowing the focus! Nonetheless, many of these case studies started with a student, and I want to express my appreciation to all of them for their efforts; we had an extraordinary time with "Skin and Bones."

I became aware a long time ago that it is not necessary to know everything about a subject, or to be able to do everything yourself, to accomplish something. If you intend to conquer a nation, you are likely to need some help. The same is true if you intend to build a building or an SGF. Just the design of a building entails teams of designers, consultants, specialists of various sorts, and lots of workers. The real power is in knowing how to get a thing done, not necessarily knowing how to do it yourself. I have found that this includes new and innovative building technology as well. I have had a nearly lifelong passion for exposed structural systems and highly transparent glass facades. I was going to be a brain surgeon, but then I saw the Centre Pompidou and decided that I had to find a way to get involved with the technology. I succeeded in that pursuit, and it put me in touch with a great many designers who shared this passion and wanted to include some form of advanced facade technology in their project work. A few were successful in adopting the technology; most never tried. The reasons are many but have to do with:

- Discomfort arising from lack of familiarity with the technology
- Concerns about risk and liability
- Cost

Given a career building things that my team and I had never done before, and that in many cases nobody had ever done before, I had to learn to deal with these concerns. I had many conversations about the challenges and risk of delivering innovation within the context of a fixed-price construction contract, a risk profile that has placed the ability to obtain surety bonding foremost among the prerequisites for conducting business in this unique marketplace. Working together, my project team members developed a strategy we called "managing the process of innovation"—an implementation strategy for developing and delivering innovative building technology. It was an experimental endeavor, both the business and the product, and it was good work that brought many opportunities.

It is my hope that this book in some small way may encourage, or even inspire, some on the sidelines to step out and push the building envelope.

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When creating case studies, success is a direct measure of the cooperation received from the people close to the work. Everyone is busy and no one has time, but these people made the time to support this work, and it could not have been done without them. I only hope to have done them and these stunning projects justice. The ultimate credit goes to the many people who made these projects happen. The errors and misinterpretations in the reporting belong to me alone.

Much of this book is ultimately rooted in the work of ASI Advanced Structures and the shared experience of designing and building so many challenging projects with such an incredibly talented group of people. These people and experiences taught me most of what I know, and I want to thank all who shared in that endeavor.

This book is the result of recent academic pursuits at the University of Southern California School of Architecture. The quality of this learning experience was much enhanced by the remarkable faculty in the Chase L. Leavitt Graduate Building Science Program, and the new PhD program focused on the building facade; my deepest gratitude to Professors Doug Noble, Goetz Schierle, and Marc Schiler. As always, my fellows are my teachers: thanks to the MBS and PhD students with whom I have shared such invigorating learning experiences.

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Introduction

Structural glass facades and *structural glass facade technology,* along with the acronym SGF, are terms used in this book to describe a relatively recent form of building technology comprising a component of the building envelope. The use of *facade* here is synonymous with *building skin*. SGFs integrate structure and cladding, and can be used in long-span applications and where heightened transparency and the expression of structure are often predominant design objectives. The structural expression often takes the form of an attempt to dematerialize the structural system. The structures are exposed and generally finely detailed, with an emphasis on craftsmanship as a consequence. The design pursuit of enhanced transparency in these facade systems has resulted in the development of increasingly refined tension-based structural systems, where bending and compression elements are minimized or eliminated altogether. This class of building technology is most effectively categorized by the structural systems that have developed to support these facades.

The various structural systems can support any of the glass system types discussed briefly in Chapter 2. While the technology may be classified by the structure types, it was the advent of point-fixed (frameless) glazing systems that propelled the early development and application of SGFs, and while associated with a cost premium, point-fixed glazing systems remain the most commonly used. These systems are mechanically bolted or clamped to supporting structure rather than continuously supported along two or four edges, as are conventional glazing systems.

However, while literal transparency, dematerialization of structure, and point-fixed glazing systems have come to characterize SGFs, the technology is not limited to their use. Other glazing systems have been developed and frequently used in response to objectives beyond mere transparency. Similarly, some designs have been developed as an expression of structure rather than as an attempt to make them disappear. In fact, the current state of the technology can support design drivers ranging widely from controlled transparency to cost.

SGF technology remains emergent, still evolving, yet it is not new. Rather, it is mature and robust, ready for broader infiltration into the building marketplace. There is, however, no consistent nomenclature in general use describing this technology. *Sweets Catalog*, the largest product catalog in the construction marketplace, includes Section 08970, "Structural Glass Curtain Walls," which includes brochures by glazing subcontractors featuring project examples of SGFs. The use of the term *curtain wall* in describing these works is generally confusing, if not inappropriate.

Curtain Wall Systems versus SGFs

While curtain walls dominate the building envelope, especially in high-rise construction projects, and often incorporate glass as a cladding element, they are differentiated from SGFs in several important respects discussed following. Curtain walls are a glass system type; SGFs combine a glass system type and an exposed structural system. Curtain walls are integrated glass system types, typically with a high level of prefabrication, that are configured to accommodate the short- to mid-range spans typical between floor slabs of multistory buildings. SGFs integrate a glass system type with an expressed structural system and are capable of a much greater spanning range. The spanning requirement of the glass system is often a relatively small increment, while the primary spanning capacity is transferred to the facade's structural system. Framed systems dominate curtain wall applications, although frameless curtain walls of some interest have been completed and do present some potential advantages over the framed systems. Conversely, frameless systems find most frequent use with SGFs, although interesting examples of the use of framed systems can be found. SGF technology is inclusive and embraces many forms, from simple mullion systems to all-glass structures, from floor-to-floor spanning systems to those that span hundreds of feet.

The difference between curtain walls and SGFs is partially one of application. Curtain walls are exterior cladding systems intended for multistory buildings, mid- and high-rise structures in particular, where the wall system is required to span conventional single-story heights. The systems typically span between floor slabs. Early systems used steel framing members, but virtually all contemporary systems are of aluminum. Vertical mullions of extruded aluminum are most commonly used as the spanning members, and the vertical and horizontal mullions provide full perimeter support to the glass.

No one seems certain about the precise source of the term *curtain wall*, at least with respect to its contemporary usage in describing the exterior wall systems used to clad mid- and high-rise structures. The term dates from medieval times, when it was used to describe the heavy stone castle walls "draped" between strategically spaced towers. This bears little relation to the current usage that emerged in the early to mid-twentieth century. Its application in this context likely refers to the non-bearing attribute of a new cladding technology that emerged in the same time frame, and developed through the mid-twentieth century and beyond, to facilitate the enclosure of the recently developed high-rise steel (and, later, reinforced concrete) framing systems. Replacing the load-bearing masonry wall construction practice of the time, curtain wall systems are non-load-bearing cladding systems simply "hung" from the building structure like a curtain.

Typical curtain wall spans follow conventional floor slab spacing at approximately 10 to 15 ft (3 to 4.6 m), although units spanning over 40 ft (12 m) have been used in areas with larger spans, as sometimes occurs at pedestrian, penthouse, or other areas of the building where larger ceiling heights are desired. Long-span curtain wall units often require deep aluminum mullions and steel reinforcing.

Another source of potential confusion is the term *structural glass*. This term is sometimes used in reference to point-fixed glazing systems, and also in referencing glass used in actual structural applications, such as a beam or column element. The term could as easily refer to heat-treated glass. In contrast, the use of the word *structure* in SGFs refers to the structural system that acts as the spanning element supporting the facade, glass being but one of the possible materials involved. *Structural glazing*, on the other hand, refers to glass that is bonded to supporting structure with a structural adhesive material in the absence of any mechanical capture of the glass pane. Compagno[1] comments that a more appropriate term for this reference would be *bonded glazing*, as the supporting frame is typically the same as that of a conventionally captured curtain wall system. Similarly, there is no consistent or generally accepted categorization or term for other glass and structure system types that comprise SGF technology.

It is conceivable that opaque panel materials other than glass could be used as the exclusive cladding element on a long-span facade structure. It is also conceivable that transparent or translucent plastic materials could be used. The former condition would effectively remove the resulting facade from the class described herein. The latter condition represents a special case so infrequently encountered as to be of no particular consequence to this naming strategy.

SGF Technology

The structural systems used in support of SGFs are explored in the following chapters. Many of the applications of this technology inhabit the top of the pyramid when it comes to complexity and cost. The intent here is to describe the fundamental elements of this technology in a clear and simple form, and in a manner that may provide for better understanding and wider application by the building community, resulting in simpler, more efficient, and economical solutions that begin to fill out the base of the pyramid. To facilitate this simplification, the technology is viewed in terms of the limited application of essentially vertical, mostly planar facade structures as a partial element of the building skin, and in fact, this does represent the majority of existing applications. However, SGF technology is capable of a remarkable diversity of form, as is evident from the case studies in Chapters 7 to 17. All of the basic structural systems can be used in sloped and overhead applications. More significantly, many of the systems can be used to form complete building enclosures. The structural systems can be combined to open up new possibilities of form and performance, creating hybrid structural systems. An example of this is the Berlin Central Station train shed designed by von Gerkan Marg and Partners (GMP) architects with Schlaich Bergermann and Partner engineers, completed in 2005. The vaulted enclosure spans six tracks and curves slightly in plan following the curvature of the tracks; the section is gradually reduced toward either end as the vaults move away from the central station. Flat, multicentered arched cable trusses are set on 43 ft (13 m) centers, and cable-stiffened gridshells span between the trusses.[2]

That the technology can embrace such enormous complexity in geometry and form has been of the utmost interest to the small group of highly innovative practitioners that have developed it and pioneered its use. There will always be a tip of the pyramid to this technology, the cutting edge in long-span glass facades represented by highly custom, innovative designs that push the envelope of the technology beyond the current state of the art. There is also the potential for harvesting the spinoff from these predecessor structures, repackaging it in a simplified, efficient, more accessible form with broader potential market applications, and transferring the resulting technology to a new group of users.

This is an exciting time in the evolution of the glass facade. Both the aesthetic and performance demands on the building skin have escalated dramatically in recent years. Thermal performance is critical to reducing energy consumption and carbon emissions in buildings, and the importance of acoustical performance grows as an increasing percentage of the global population takes up residence in the densest urban centers. At the same time, designers have more tools and techniques at their disposal than ever before. These take the form of new glass materials and coatings, analytical software, and design strategies that deviate substantially and purposefully from the "glass box" approach of the modernist. While many of the early SGF applications were completed with no regard to the performance aspects of the facade, this has changed dramatically in recent years. Nearly every one of the case studies included is part of a project that involves sophisticated strategies for enhanced building performance embracing sustainability and green building practice.

A unique building technology for the realization of SGFs is evidenced by the diverse and growing body of completed works that feature prominently in the built environment. The aim of this book is to identify and explore the various elements that comprise this technology, including the *architectural glass* used both as cladding and occasionally as structure, the exposed *structural systems* used in support of the facades, and the *glass systems* that serve to fix the glass to the supporting structure, and then to explore their application in a group of case study projects.

The Vision

The vision combines disparate elements of natural form: a spider's web of structure with a soap bubble film, minimalist filigree structures hovering in a sea of light, seamless transparent membranes spanning vast spaces, disappearing with a shimmer, reappearing in a brilliant reflection of their surroundings. Such has been the stuff of dreams for building designers since the early nineteenth century with the concepts of the garden city movement for sun-drenched interior spaces, followed at midcentury by the construction of the great iron and glass conservatories in Europe and England that first demonstrated the exciting potential of glass in architecture. Today these dreams are being realized through the development of a robust technology built on advances in structural design technique and material science, and through a growing body of completed and increasingly innovative structures.

The building skin is a vitally important architectural consideration. No other building system impacts both the appearance and performance of a building as does the skin. The use of glass as a component of the building envelope has been increasing since its initial introduction as a building material in the days of the Roman Empire, accelerating in the twentieth century owing to the development of high-rise steel framing systems, an enabling glass manufacturing process, and curtain wall cladding techniques.

The driving force of a new genre of structure has been the design intent of maximizing transparency, and its most common form the long-span glass wall, although advanced facade designs are increasingly assuming larger areas of the building envelope and in some cases acting as the entire enclosure. The push for transparency has resulted in the emergence of new glass facade types in spot applications over the past three decades. The new designs play off the primary attribute of glass, its transparency, and increasingly off the structural properties of glass and the integration of glass components into the structural system. As a body, these completed works represent a discrete building technology.

Characteristics of this technology include highly crafted and exposed structural systems, integration of structure and form, simultaneous dematerialization and expression of structure, complex geometries, extensive use of tensile elements, specialized materials and processes, an integration of structure and cladding system, and a complex array of design variables ranging from facade transparency to thermal performance and bomb blast considerations. While the facade structure types are derived from the broad arena of structural form, they have become differentiated in their application as part of a facade design.

The facade structures have developed in parallel with the development and application of frameless or point-fixed glazing systems. While any type of glazing system can be supported by the facade structural systems, the point-fixed systems are favored because of their optimal transparency and provision of an uninterrupted glazing plane. Structural systems with minimized component profiles were desired to further enhance the transparency of the point-fixed glass systems. This led to structure designs making extensive use of tensile structural elements in the form of rod or cable materials. A structural element designed only to accommodate tension loads can be reduced significantly in diameter compared to a similar element that must accommodate both tension and compression loads. This thus becomes a primary strategy in dematerializing the structure, as discussed in Chapter 3.

SGF Technology Is Poised for Wider Application

This facade technology has been evolving for over 30 years, with considerably varied application in the commercial building marketplace. Public sector works include airports, courthouses, convention centers, civic centers, and museums. Private sector works include corporate headquarter buildings, hotels, retail and mixed-use centers, churches, institutes, and other privately funded public buildings.

While applications have been limited to a small niche market in the overall construction industry, many innovative designs have been introduced over the years, with many more creative imitations and variations springing from them. As a result, this technology has matured over the years and is no longer largely comprised of experimental structures. It has been tried and tested in a considerable diversity of built form; structural systems have been adapted to facade applications; specifications and methods have been developed, tested, and disseminated; practitioners have built hundreds of highly innovative facade structures in a variety of applications; and development costs have been absorbed. An infrastructure of material suppliers, fabricators, and erectors has developed in response to increasing project opportunities. These factors have combined to make the technology more competitive. Thus, this body of facade types represents a mature building technology positioned for broader application in the marketplace.

Growing Interest in the Use of SGF

At the same time, owing to the high profile and success of projects featuring advanced facade designs, increasing numbers of architects are interested in incorporating SGF technology into their building designs. The new facade designs are becoming increasingly valued by the design community for both their varied aesthetic and their ability to provide controlled transparency ranging from very high to modulated in response to environmental considerations. This combination of growing interest and a maturing technology holds promise for significant growth in the current small niche market of SGF technology.

There is also interesting potential for SGF technology to act as a catalyst for change and development of the more conventional glass facade systems. With its novel designs and innovative use of new materials and processes, SGF applications may point the way to future advances in building skin development. Several of the case studies included here involve the application of SGFs in high-performance facade applications, including double-skin walls.

Few designers fail to find the prospect of sweeping glass surfaces engaging; there is something very close to universal appeal when it comes to light-filled interior spaces blurring the demarcation between interior and exterior, spaces providing view and sunlight and an expansive feeling of openness and scale. Long, sweeping spans of glass are not appropriate for every project, of course, but architects are increasingly looking for such an opportunity, and more developers are wondering about the possibility of incorporating this technology into their special building projects. The use of high-transparency facades has matured to the point that perceived deterrents of cost, complexity, and risk are waning in the wake of a growing body of successful applications. The technology is now more accessible and economical than ever before.

This book is about the technology of long-span glass facades and building enclosures: the design issues, structural systems, materials, and methods that comprise this technology. It surveys current work through a group of case studies, and in doing so will be of interest to anyone engaged in the building arts: architects, engineers, designers, developers, contractors, students, and others inspired by the use of glass in architecture, but especially those interested in actually utilizing this technology. This book is about sharing a passion and perhaps, in the process, creating broader interest in the use of SGF technology, whether by the architect interested in a highly glazed concept for a new airport facility, the developer of a new office tower contemplating a dramatic lobby space that merges interior and exterior public spaces, a glazing contractor contemplating a first-time bid on a project that includes a tension-based SGF, or a student wishing to explore a structural glass enclosure on a studio project. The strategy is to:

- Inform readers about the possibilities and variations of form and structure, what has been done, what is possible, and perhaps some avenues of possible future exploration

- Compare the various options with respect to primary considerations of relative aesthetics, transparency, materials, spanning capacity, deflection behavior, reaction loading, constructability, maintenance, and cost
- Identify the key issues that the design and build teams must address to ensure successful integration of this technology into a building program, arming the designer, the builder, and the implementer with the right questions and an indication of where to find the answers

There may be some benefit in reading through the material in sequence, but this is not necessary to access and benefit from the technical and descriptive content within. The reader is encouraged to explore the material as interest dictates.

Context: Glass and Structure

Interwoven Strands

Structural glass facade (SGF) technology evolved from a variety of innovative experimental structures over the past three decades or more. With its roots in Northern Europe, the technology can be traced back to a few seminal projects and a handful of pioneering architects and engineers. From a broader perspective, the technology can be seen within the fabric of the built environment as a complex of interwoven strands from the same loom, the primary ones including:

- Humankind's early development of glass as a material, especially, the later development and application of glass as a transparent material in the building envelope
- The creation of inventive structural systems and their application in architecture
- The development of building forms based on extensive use of glass (i.e., the skylight, atrium, winter garden, and conservatory)
- The evolution of a performance-based architecture using the unique solar transmission properties of glass

Glass has inspired the long-term pursuit of transparency in the building envelope that has ironically masked other influences on SGF development, eclipsing them in the dominant aesthetic of literal transparency. An influence equal in importance to glass is structure; a strong bond between structure and glass characterizes SGF technology, and a fascinating history of geometrically complex, lightweight structural systems has developed during the same period. Other influences relate to building form and application; there is an important history of the use of glass in performance applications such as solar architecture and in the enclosure of light-filled spaces such as the long-span atrium. The intertwined strands of glass, structure, and application have crossed repeatedly and to spectacular effect from a common beginning in the industrial age of the early nineteenth century.

Glass as Material

"Glass is arguably the most remarkable material ever discovered by man," states Michael Wigginton in his comprehensive book on architectural glass.[1] An estimated 4000 years ago, probably at the site of an ancient pottery kiln in the eastern Mediterranean, some curious soul stopped to wonder at the unusual properties of an inadvertent mix of sand and ash that had been exposed to the kiln's heat and ignited a love affair between humans and material, glass in this instance, that has been going strong ever since. Two millennia later, the technique of glassblowing was discovered in the first century BC on the Palestinian coast, laying the foundation for the diffusion of glass technology throughout the Roman world. The composition of glass by the time of the Roman Empire had been refined to a mix similar to the slightly green-tinted soda lime glass used today in the manufacture of flat glass: 69% silica, 17% soda, 11% lime and magnesia, and 3% alumina, iron oxide, and manganese oxide.

Glass as Architecture

The use of glass in architecture has grown steadily since its first application as window glass, dating back to approximately the first century AD. Its characteristics of color, translucency, and transparency are so uncommon that mystical properties were often associated with it by the various cultures using it. Early glassmaking processes were secrets closely guarded by governments. Glass was traded as a prized material among kings and emperors. The wealthy classes developed an appetite for glass that pushed producers to make larger and better-quality products over the centuries, a trend that continues today. Over the years, the taste for glass spread throughout the population as glass in window applications became a commodity item in Northern Europe in the late eighteenth and into the nineteenth centuries. Today, most working people value floor-to-ceiling glass in the corner office if they can get it, or at least a window if they cannot, and it is rare to encounter a residential room without at least one good-sized window. The modern manifestation of glass technology in the built environment is the glass office tower (Figure 1.1) and, increasingly, the high-rise condominium.

Glass as Window

The emergence of glass in window applications is attributed to the Roman imperial period. Window glass was first used in isolated applications, such as in the public baths to reduce air drafts. Early window glass was rather crude and unevenly translucent, as the techniques for producing transparent glass products were yet to be developed. Glass at this point was not about providing transparency or a view; it was most likely used for security and insulation from the exterior environment and for natural lighting. Then, around AD 100 in Alexandria, Egypt, an early empirical materials experimenter added manganese oxide to the melt and transparent glass was discovered. Important buildings in Rome were soon adorned with cast glass windows, as were the villas of the wealthy in Herculaneum and Pompeii.[2]

In spite of the poor optical quality of this early glass, the basic future architectural glass production methods were developed during this period. Rudimentary glassblowing and casting processes were available by the first century AD, and both could be used to produce glass that was relatively flat and translucent, although its size was very limited and its thickness in both processes was difficult to control. It was not until approximately the eleventh century that Germanic and Venetian craftsmen refined two processes for producing sheet glass, both involving glassblowing techniques. One involved blowing a glass cylinder and swinging it vertically to form a pod up to approximately 10 ft (3 m) long and 18 in (45 cm) in diameter. Then, while the pod was still hot, its ends were cut off, and the cylinder was cut lengthwise and laid flat. The second process involved opening a blown glass ball opposite the blowpipe and spinning it. This process was to become common in Western Europe, and *crown glass,* as it was called, was prized for its optical properties, although its size remained very limited.

The push for transparency and increasing sheet size in glass appears to date from the beginning of its use as an architectural material. References to the various glass processes and comparisons between them often include the relative size limitations and optical imperfections.

Wigginton identifies the first true glass architecture as Northern European Gothic. Utilizing structural elements of arches, vaults, and flying buttresses, the builders of the great cathedrals of the period were able to construct stone frames, highly expressive structures, with large openings to the outside to admit light. Local climatic conditions never would have allowed for this if the openings had exposed the interior spaces to the raw elements. A robust glass technology was available to fill this need in dramatic fashion. Glass was available only in small pieces, but craftsmen had learned the recipes for producing many color variations. The window makers developed a structural system comprised of leaded bars that were used to tie a mosaic of pieces into a single membrane of glass veined with lead and capable of spanning large openings. These expansive stained-glass windows represent an early precursor to SGFs. Similarly, the morphology of the structural masonry frames with glass

FIGURE 1.1 Comcast Center, Philadelphia, 2008, Robert A.M. Stern architect.

membrane infill built around Paris from the twelfth through the fourteenth centuries heralds the new architecture that would emerge in Chicago in the late nineteenth century in the work of Louis Sullivan and others, where large glass sheets were used as infill to the new multistory steel framing systems.

Glass production and the secular use of glass increased steadily throughout the Italian Renaissance. By the eighteenth century, window glass had become a commodity item in Northern Europe. Double-hung windows were also developed in England during this period. The use of glass in architecture branched to the development of fenestration as a design element in the building elevation and to the creation of the conservatory. This later development was to have a huge influence on the future use of glass in architecture.

Glass as Building Skin

SGF technology has its roots in the great iron and glass conservatories of the nineteenth century. That century witnessed the unfolding of the industrial age and the introduction of metal to architecture with such dramatic examples as the Palm House at Bicton Gardens by D. and E. Bailey (based on designs by John Loudon), the Palm House at Kew Gardens by Richard Turner and Decimus Burton, and Joseph Paxton's Crystal Palace.

The conservatory structures in Europe and England are a dramatic departure from masonry architecture, where heavy masonry walls act as both weather barrier and load-bearing structure, instead adopting structural iron framing systems that allow for far greater design freedom. The weather barrier is provided simply by draping a nonstructural cladding material (glass) over the structural framing system: a building skin. Glass as building skin was made possible by the age of steel that emerged from the Industrial Revolution. Cast and wrought iron replaced the lead bars of the Gothic cathedral windows, allowing for the construction of complete enclosure framing systems comprised of slender metal components. Glass was easily attached to these frames. Quite suddenly, building enclosures could be transparent, clad entirely in glass. This development set the stage for the Modernists of the twentieth century and the advent of high-rise towers sheathed in glass.

In the first half of the nineteenth century, conservatory structures flowered under the influence of such designer-gardener-builders as J.C. Loudon and Joseph Paxton. The conservatories were impressive as performance-based architecture responding to the demanding requirements of the exotic botanical species they housed, entirely free of the prevailing conventional masonry architectural style of the period. With little in the way of prior art, the pioneers in this new building form proceeded intuitively with the development of the structural systems. They created slender wrought iron bars and methods to connect them. The structures were so minimal that in certain instances the literature of the time describes them as deflecting in light winds until the glass was affixed to the frame. The glass was actually being used as a stressed skin to stabilize the structure. These innovators were far ahead of their time in using glass as a structural element, even before the advent of glass-strengthening techniques.

While the building form represented by the conservatory structures quickly transcended its early botanical applications to become an important public structure type, perhaps as best represented by the Crystal Palace, there was little integration of this building form with the conventional architecture of the time.[3] The great conservatories were largely freestanding autonomous buildings. Certainly they inspired, just as they continue to inspire new generations of designers today. Equally certainly, they continually increased the desire for and use of glass in architecture.

Meanwhile, in the great cities of Europe and America, density and land values were creating pressure to build upward, pushing the limits of the predominantly masonry building practices of the time. By the end of the nineteenth century, a Chicago engineer named William Jenney had devised a method of steel framing and thus gave birth to the technology of high-rise buildings. Exterior walls became functionally different in a significant way; like the earlier iron framing systems used in the conservatory structures, they were no longer load-bearing, carrying only their own weight over a single-story span. They no longer needed to be masonry (although masonry remained the predominant wall material for years to come); in fact, masonry was an inappropriate material for most of these new applications because it was unnecessarily heavy.

The Advent of the Curtain Wall

The use of glass as a predominant element of the building facade exploded in the twentieth century, fueled by Modernism, especially post–World War I Modernism, and the development of steel frame structures, improving sources of glass supply, and the development of curtain wall cladding systems. Visionary designers and tradesmen produced a relatively small number of landmark buildings in the first half of the century utilizing these new materials and processes, paving the way for the paradigm shift that was to come in the 1950s, when the modern curtain wall industry was born. Stunning and influential architectural innovations like the Bauhaus Building in Dessau by Gropius in 1926, the Seagram Building in New York City by Mies van der Rohe in 1954, and the Lever House by SOM in 1952 were among these early buildings.

Flat glass for architectural applications is produced today through the float process. Invented by Alastair Pilkington[4] in the 1950s, the process was commercially viable by the early 1960s. The float process provides the convenience of making glass horizontally, similar to the older casting processes. In the older processes, the bottom side of the cast glass sheet suffered from poor surface quality that could only be remedied by expensive grinding and polishing. The float process solved this problem by floating the liquid glass on a bed of molten tin. The resulting product is flat, smooth, and transparent, the recipe for high optical quality. The float process provided the fabrication technology required for the next boom in the use of glass in architecture, replacing the drawn glass process of the time.

Glass was thus becoming increasingly available and economical. The new steel-framing technology opened the door to a dramatic use of glass as a predominant element in the building skin. Designers were struggling with solutions to replace the masonry practices dominant at the time. In the early twentieth century, aluminum was becoming available in larger quantities at lower cost. By the 1920s, this material was beginning to see significant use in architecture.

The required infrastructure was thus in place, and the post–World War II boom in America and Western Europe resulted in an explosion of high-rise curtain wall buildings. Commercial developers found in the emerging technology low-cost solutions for maximizing leasable square footage in a given building footprint. Unfortunately, most of these solutions lacked both the design sensitivity and the quality of the early Modernist work, becoming what Wigginton refers to as "a sort of 'International Style' without the style." The result was a proliferation of sterile-looking, water-leaking, energy-hogging glass towers redefining the skylines of the world's great cities (Figure 1.2). Regardless, it significantly boosted the glass and curtain wall industry.

Curtain Walls and SGFs

While closely related, there are distinct differences between curtain walls and SGFs. The primary difference is in the structural systems used to support them. Aluminum extrusions are generally used in curtain wall systems to construct a frame that secures some type of panel material, ranging from glass to composite metal panels and stone. The frame may be expressed or completely covered on both the inside and outside of the building. Curtain wall framing systems typically span only from floor to floor, the primary spanning member being the aluminum extrusion. Both the curtain wall and the SGF are separate from the building framing system but attached to and supported by it.

SGFs are often used in longer spanning applications where an aluminum extrusion as the primary spanning member becomes impractical or impossible. The technology embraces a design objective

FIGURE 1.2 The monoliths of highly reflective glass spawned by cheap curtain wall cladding systems did little to enhance the urban environment.

of high transparency and expressed structure incorporating some type of glass, most frequently clear glass often used without any framing elements, as the cladding material. A variety of structural options are available to accommodate a range of spanning conditions as described. The structure is exposed and thus becomes a dominant element of the facade design. Emphasis is often placed on the detailing and craftsmanship of the structural system. There has been a consistent evolution toward a dematerialization of structure, paralleled by an increasing refinement of the structural systems and components. Tensile elements have become increasingly predominant, leading to the development of pure tension-based structural systems like cable nets. Frameless glass systems, commonly referred to as *point-fixed* or *point-supported systems*, are most often used for the same reason. Framed panel or stick-type systems utilizing aluminum extrusions are also used quite effectively in SGFs but typically benefit from a design integration with the structural systems that support them, differentiating them from conventional curtain wall systems, although off-the-shelf curtain wall systems can be and have been used in SGF applications (Figure 1.3).

Another difference is in the strategy employed to provide the weather seal. Contemporary curtain walls typically employ a rain-screen strategy utilizing dry gaskets to provide the primary weather seal. These wall systems employ complex designs of aluminum extrusions that attempt to provide a pressure-equalized cavity, or cavities, as a barrier to water penetration and air infiltration. The design is intended to allow pressure differences to equalize within the extrusion cavities so that even if water penetrates the cavity, it will drain out of the system and not penetrate to the inside. Consistent with a minimalist approach, the weather seal typical of the glazing systems used on SGFs is a slender joint of silicone, field applied between adjacent glass panels; as with the structural systems, nothing is hidden. Today's silicone sealants are high-performance materials providing an effective, reliable, and durable weather seal.

Solar Architecture

A noteworthy parallel to the evolution of curtain wall technology, identified and developed by Wigginton, is the application of glass architecture as a potentially energy-efficient and environmentally responsive building form. This development also flows from the conservatory structures of Paxton and his contemporaries. Ecological function was their purpose; the enclosures were intended to sustain the botanical species collected from tropical areas of the planet in the less favorable climate of England and Northern Europe. These engineer-gardeners, or gardener-engineer in the case of Paxton, developed surprisingly sophisticated environmental systems including natural ventilation and thermal control, but the indispensable material was glass, which

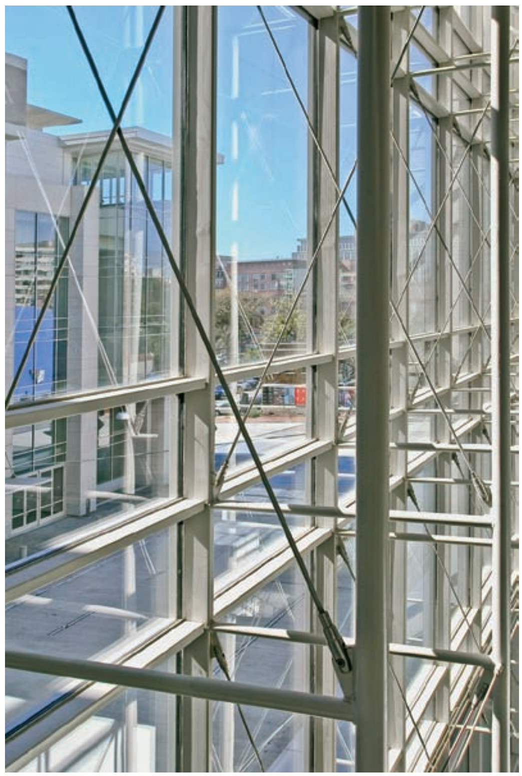


FIGURE 1.3 The Walter E. Washington Convention Center in Washington, D.C., 2003, is enclosed by an exposed truss system supporting an off-the-shelf stick curtain wall system. TVS-D&P-Mariani, PLLC JV architects.

enabled the construction of the solar collector otherwise known as the *conservatory*, *winter garden*, or *greenhouse*.

Designers who continued to experiment with solar architecture through the first half of the twentieth century were making use of the predominant attribute of glass, its transmittance, in quite a different manner than those architects who were pursuing transparency as an architectural concept. This group had recognized the powerful performance potential of glass, and thus utilized transparency largely for performance as opposed to aesthetic or conceptual reasons. The evolution of solar architecture quickened throughout the 1950s and 1960s, with many examples of solar homes and other buildings bringing increasing awareness of this building form even among the general population, especially after the renewed concern for conservation and energy efficiency in the wake of the 1972 oil crisis.

Thus, the development of transparency in the building envelope was pursued early on as a performance attribute, not just as an aesthetic intent or a conceptual principle. Glass in buildings has a long history of use for the purpose of harvesting solar energy. This has renewed the potential for high-performance contemporary glass products to play a key role in reducing energy use and even achieving net-zero energy consumption in today's buildings. Glass, as a mechanism for solar control, and SGF technology were parallel developments with little crossover in the early decades of the technology. Many SGFs were built with little or no regard to thermal performance and energy efficiency; heating, ventilation, and air conditioning (HVAC) systems were simply sized to compensate for thermal gain or loss. This is true even of prominent facades built in recent years in the United States. Increasing pressure for improved performance of the building envelope is now bringing long overdue change to facade technology, and the emphasis on energy efficiency and thermal comfort holds promise for better-performing future applications of SGF technology. In fact, the technology is increasingly being used in multistory double-skin facade systems, as is evidenced in the case studies in Chapters 7 to 17.[5]

The Atrium

Another building form deriving from the nineteenth-century conservatory structures and combining exposed structure and glass is the atrium, which emerged in the late twentieth century. Atriums were sometimes used to enhance the climate of an enclosed space, but most frequently they were used simply for the dramatic space they provided, such as the spectacular atriums that characterize the hotel architecture of John Portman. Richard Saxon maps the emergence and development of the atrium in detail in a book devoted to the subject.[6] SGF technology is ideal for application in atrium enclosures.

The Art of Structure

Long-span glass facade technology has resulted from the integration of a highly engineered glass material with elegant exposed structural systems. The rapid development of this technology over the past 40 years or more has been driven primarily by the pursuit of transparency in the building envelope, but this has enabled the development of the remarkable structural systems that have become the hallmark of SGF technology. Inventive structural systems have been the passion of creative engineers dating at least to the early to mid-eighteenth century and the work of J.C. Loudon, Joseph Paxton, and Richard Turner, who were each involved in developing structural systems and even patenting components. The great iron and glass conservatories of this period were most notable for the extensive use of glass, but this was only made possible by the transformation of the new wrought and cast iron materials into suitable structural systems—and quite elegant systems they often were.

The Crystal Palace set the precedent for the Universal Exposition, or World's Fair, as a showcase for structural innovation, followed by the Eiffel Tower at the Exposition Universelle of 1889 and the Ferris wheel at the Chicago World's Fair in 1893. The Russian engineer Vladimir Shukhov was designing and building gridshell structures before the turn of the twentieth century. Alexander Bell was experimenting with space structure geometries at approximately the same time. The Palace of Horticulture at the Panama-Pacific International Exposition in San Francisco (1915) followed, and so on to Expo '67 in Montreal featuring the iconic geodesic biosphere dome by R. Buckminster Fuller, which was a major coming-out party for space truss systems with several large pavilion constructs. Lev Zetlin's bicycle wheel roof for the New York Pavilion at the New York World's Fair (1964) stands among this lineage of novel structures, as does the British Pavilion by Nicholas Grimshaw with engineer Ove Arup at Expo '92 in Seville. The Olympic Games have also been a showcase for the art of the engineer, such as at the Munich Games in 1972 with the spectacular cable net structures by Gunter Behnisch with Frei Otto.

Most structure in architecture is ultimately concealed. These public venues have provided some of the few opportunities creative engineers have had to express their art. Then came the Modernists in the early twentieth century with their visions of transparency and a gradually emerging glass and structure technology to convert these visions into reality. By the 1960s, the infrastructure of materials and processes was in place to transform the building skin and bring a remarkable vocabulary of transparency to architecture. Structure started to show through the transparent envelope, and a new appreciation for the expression of structure as an aesthetic element of the design emerged.

The emergence of highly transparent glass facades that started in the 1960s and 1970s created one of the greatest opportunities ever provided the inventive structural engineer. What better way was there to showcase a structure design than to literally put it behind glass, like fine jewelry? Never mind that the overriding design intent was transparency and the dematerialization of the structure; this simply resulted in more refined and elegant designs. It was about transparency, but suddenly the budget was there for machined and cast stainless steel components. Transparency produced unanticipated side effects; the structure systems were getting smaller, yet more visible at the same time, drawing attention in their sparseness like a candle flame in the darkness. Almost imperceptibly, transparency focused on structure and the engineer had moved into the spotlight.

Ultimately, the design intent of transparency did dramatically dematerialize the structural systems, reaching its current minimalist expression with cable supported facades. But what has emerged simultaneously is a remarkable diversity of innovative glass facade and enclosure designs where the structure is showcased, what Nina Rappaport refers to as "the integration of structure as decoration," which she calls "deep decoration, or beyond surface . . . the structure has design emphasis."[7] Thus, a major aspect of the technology, the function, and the appeal of SGF is not transparency, but the structure itself; transparency becomes a means of showcasing structure. Consideration of the applications built to date reveals that the structural system used in support of the facade is, with some consistency, the most distinguishing component.

These divergent but related developments in architectural glass, steel structural systems, conservatory enclosures, atriums, solar architecture, and facade systems began to converge in the late twentieth century into a long-span glass facade building form. It is interesting to note that innovations in technology have consistently paced this building evolution. The introduction of wrought and cast iron, the production sources for glass and aluminum extrusions, and the development of structural steel framing systems all predated the development of curtain wall systems by several decades. The same is true with the development of glass as a structural material. The tempering or toughening process for glass was invented in 1928 in France but took several decades to gain traction in the marketplace. By the 1960s, the suspended glass mullion walls that presaged Foster's Willis Faber & Dumas Building (1975) had started to emerge as a building form. But it was not until Pilkington developed and engineered a warranted product for use on the Willis Faber & Dumas Building that this technology came into widespread use. This trend continues today; advanced interlayer materials, for example, are enabling ever-more-aggressive application of glass as a structural material.[8]

The Evolution of SGFs

To a notable extent, historical growth in the architectural glass market has been driven by a series of high-profile applications with widespread impact, including the great windows of the Gothic cathedrals in Europe followed by the transition to widespread secular use of glass in buildings and such milestones as Hardwick Hall (1590–7) by Robert Smythson and the new wing at Hampton Court (1689–96) by Sir Christopher Wren. Many if not most of these milestone projects were made possible or were inspired by advances in glassmaking technology, but it is ultimately the architectural manifestations that inspire broader adoption and use, as with the great burst of glass conservatory construction in nineteenth-century Europe and England that so strongly influenced architecture and set the bar for decades to come in glass structures.

Emergence

In a manner similar to that documented above, certain high-profile instances of SGFs mark the emergence and progression of the technology.

With the French invention of the process for heat-strengthening glass in the late 1920s, the material elements were in place for the initial emergence of SGFs: steel framing techniques and tempered glass. Yet, the exploitation of these materials was several decades away. By the 1950s the French, appropriately, had also conceived the long-span frameless glass facade. The Hahn system used at the Maison de la Radio in Paris in 1953 involved large glass plates two stories high. This is a very early example of a suspended glass facade. The glass is clamped and hung from the top edge. Glass fins set perpendicular to the facade at the glass joints are used to provide lateral stiffness.[9] This concept quickly diffused into the marketplace, resulting in the construction of many similar facades during the 1960s.

The progenitor of the immediate line of SGF technology may very well be the Willis Faber & Dumas Building in Ipswich, England (1975), by Foster Associates. Wigginton cites the landmark glass facade of this building as completing a "particularly thematic journey in glass architecture,"[10] referring to Mies van der Rohe's 1922 office tower concept model referred to above as the start of that thematic journey. The end of one journey can be the start of another, and such a case can be made here. Although other suspended glass walls were completed before this one, the Willis Faber & Dumas Building, for various reasons, became an icon inspiring future SGF innovation.

Sweeping walls of glass with little or no apparent means of support are so common now as to attract little attention. Such was not the case in the 1970s. Unlike the glass office tower, the facade for the Willis Faber & Dumas Building is not about transparency but rather reflection, at least during daytime. The glass is coated with a bronze solar control coating, presenting a solid, uninterrupted reflective exterior face (the weather seal is provided by a slender field-applied flush silicone joint). From inside the wall is almost entirely transparent, and at night with the interior lit, the glass wall virtually disappears. As with the Hahn system some 15 years earlier, the glass for the Willis Faber & Dumas facade is hung from above, only instead of a single sheet, six sheets are linked together in a chain from top to bottom, in this respect creating perhaps a truer "curtain" wall than the technology commonly referenced by that term. Glass fin elements set perpendicular to the glass plane on the vertical glass grid provide lateral support. The facade is 39 ft (12 m) high and follows an irregular curve in plan. In addition to Foster, Martin Francis played a role as glazing consultant in the realization of this facade, and Pilkington fueled design innovation by providing the suspended glazing system as a product, at a competitive price and with an unprecedented warranty. The early Pilkington system used a patch plate to accommodate the fixing of the glass. From this time on, mechanical point-fixed glass systems became a driving force in the evolution of SGF technology. This project is featured as a case study in Wigginton's *Glass in Architecture*.[11] Suspended glass fin facades[12] thus initiated the evolution of SGF technology and are to this day perhaps the most commonly found type of high-transparency facade.

Milestone Applications

The evolution of SGF technology can be viewed in a series of high-profile applications. A few of the most significant of these follow.

Willis Faber & Dumas Building; Ipswich, England
Glass Fin Facade
Foster Architects, designed 1971–2, completed 1975

The Willis Faber & Dumas Building (Figure 1.4) is significant in many respects. It is one of the very early examples of a frameless suspended facade incorporating glass fins as a stiffening element against lateral loads. It represents the productive partnership between industry and architecture, with the first application of a new product technology provided by Pilkington, a leading glass producer. It popularized this facade type, leading to a proliferation of applications. It is a viable candidate for defining the birth of SGF technology, as articulated in *Glass in Architecture*.[13]

Garden Grove Church; Garden Grove, California
Glazed Space Frame Enclosure
Johnson/Burgee Architects, designed 1977–8, constructed 1978–80

Popularly known as the Crystal Cathedral, this building obviously finds its roots in the great iron and glass conservatory structures of mid-nineteenth-century Europe. Predating the development of the lighter tensile structures that would emerge over the next decade in facade applications, this design makes use of a space frame structural system. The structure is clad entirely in reflective glass using a panel system in which the glass is structurally glazed to an aluminum frame. The

FIGURE 1.4 The Willis Faber & Dumas Building, Ipswich, England, Foster Architects, 1975. The glass facade marks the birth of SGF technology.

facade system includes operable vents that provide natural ventilation to this large glass enclosure (Figure 1.5).[14]

Glass Walls (Les Serres)
Parc de la Villette, Paris
Architect Adrien Fainsilber with Rice Francis Ritchie (RFR), designed 1983, constructed 1984–6

Les Serres was a seminal project for SGF technology incorporating many innovations and indicating the direction for future work. Peter Rice conceived of *cable mullions* as a means to achieve optimum transparency (Figure 1.6). Les Serres features horizontal rod trusses mounted on a steel pipe frame. The design team developed a special glass bolt called a *rotule*, which provides for unrestricted rotation at the point fixing, thus eliminating bending moments on the glass. This project is discussed further in Chapter 3.

The Pyramids at the Louvre, Paris
Grand Pyramid
I.M. Pei architect with Nicolet Chartrand Knoll, Ltd., and RFR, designed 1983–5, constructed 1986–8
Inverted Pyramid
I.M. Pei architect with RFR, completed 1993

The space grid structure was novel at the time in its extensive use of tensile elements.[15] The structure is clad with a fully perimeter-supported structurally glazed system in which the glass is fixed to the frame by a structural silicone adhesive with no mechanical attachment. The Louvre Pyramid served to popularize the emerging new SGF technology (Figure 1.7). The structure is one of the first to make use of a “superclear,” virtually colorless glass that is further discussed in Chapter 2 as low-iron glass.[16] RFR was subsequently asked to design the structure and glazing for the smaller Inverted Pyramid below the courtyard at the Louvre (Figure 1.8).

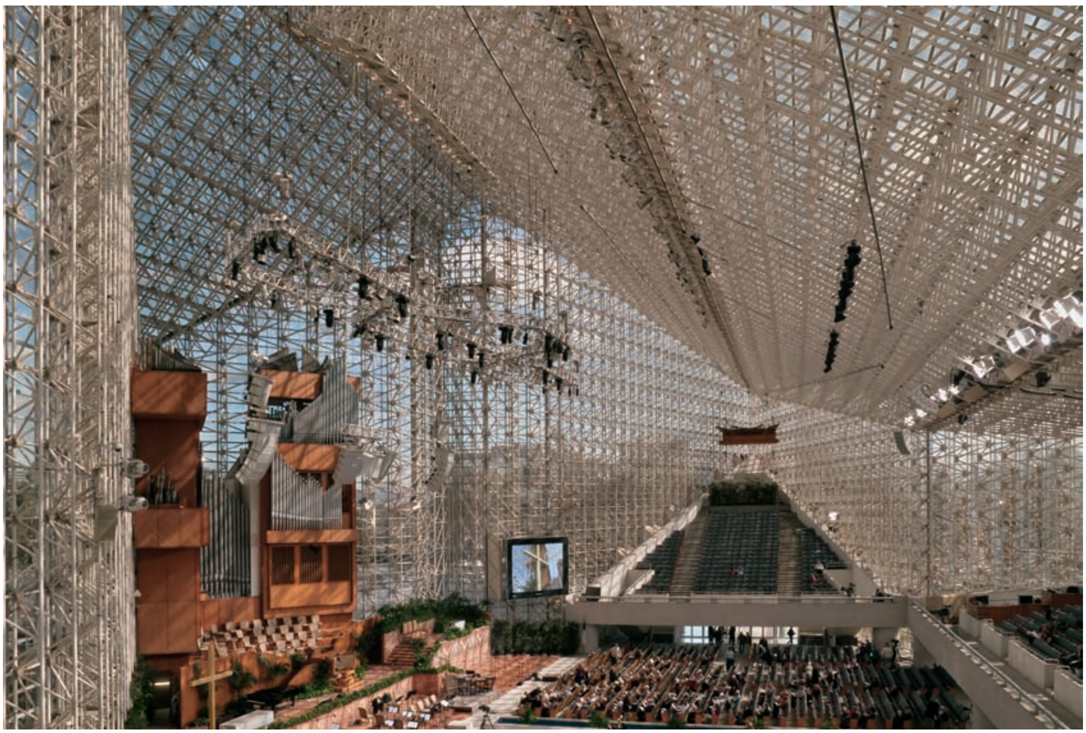


FIGURE 1.5 Crystal Cathedral, Garden Grove, California, 1980, Johnson/Burgee Architects. A reflective glass-clad space frame provides the enclosure for the Garden Grove Church.

FIGURE 1.6 Glass Walls (Les Serres), Parc de la Villette, Paris, 1986, Adrien Fainsilber, architect, with Rice Francis Ritchie (RFR). Peter Rice conceived the cable mullion as a means of optimizing transparency.

FIGURE 1.7 The Louvre Pyramid, Paris, Pei Cobb Freed and Partner with Nicolet Chartrand Knoll, Ltd., and RFR, 1988. The Pyramid did much to popularize the emergent technology of SGFs.

FIGURE 1.8 The Inverted Pyramid, Paris, 1993, Pei, Cobb, Freed and Partners with RFR.

Reina Sofia Museum of Modern Art, Madrid
Vertical Circulation Towers, completed 1990
Ian Ritchie Architects

After participating in the Louvre Pyramid and Les Serres designs with RFR, Ian Ritchie with Ian Ritchie Architects was asked to design three 115 ft (35 m) tall glass circulation towers as part of an effort to visually redefine this historic building, originally built in the eighteenth century as a hospital. Minimalism, transparency, and modernity were among the guiding principles of the design. The glass envelope encloses the vertical steel tower structure but sits well away from it, emphasizing the separation between skin and structure. The Pilkington Planar point-fixed glass is supported by an innovative tensile structure suspended from cable-stayed outriggers at the top of the tower. The tensile structure is outboard of the glass skin, and is comprised of stainless steel rods that anchor to large spring assemblies at the base of the tower to reduce the loads transmitted to the tower structure. The tie-downs support steel plate armature assemblies that reach out and support the glass fixings at the vertices of the glass grid (Figure 1.9). The towers were widely publicized because of the extraordinary degree of transparency achieved with the enclosure.

FIGURE 1.9 Reina Sofia Museum of Modern Art, Vertical Circulation Towers, Madrid, 1990, Ian Ritchie Architects. The innovative glass enclosures were widely publicized, influencing many of the advanced facade applications that emerged in the following decade.

Kempinski Hotel, Munich
Cable Net Facades, completed 1993
Murphy/Jahn Architects with Schlaich Bergermann and Partner

This is widely recognized as the first cable net facade, conceived by engineer Jorg Schlaich of Schlaich Bergermann and Partner, a leading engineering firm in the development of SGFs. Another bold and seminal structure, the cable net is comprised of prestressed vertical and horizontal cables in a planar configuration. The glass is clamped to the net and butt-glazed with silicone to provide the weather seal. The structures enclose opposing sides of the hotel lobby (Figure 1.10).

Messe-Leipzig Glass Hall and Bridges, Leipzig, Germany
Vaulted Glass Enclosure
Gerkan Marg & Partners and Ian Ritchie Architects, with IPP Ingenieruburo and HL-Technik;design started 1992, construction completed 1995

The monumental Messe-Leipzig vaulted glass hall is 780 ft (238 m) long and 262 ft (80 m) wide, with a maximum height of 92 ft (28 m). The vault structure is hierarchical, with primary arch trusses on 82 ft (25 m) centers supporting an orthogonal grid shell of welded tube steel. A low-iron glass skin is hung from the structure, point-fixed and tied back to the gridshell with long-fingered cast components (Figure 1.11). The project received international recognition on the opening of the facility in 1996 and spawned further applications of SGF technology.

This is just a small sampling of a few early milestone projects and a brief overview of the many fascinating applications of SGF technology.

FIGURE 1.10 Cable net facades at the Kempinski Hotel, Munich, 1993, Murphy/Jahn Architects. This is the first application of a flat cable net as a glazed facade structure.

FIGURE 1.11 Messe-Leipzig Glass Hall, Leipzig, Germany, 1995, Gerkan Marg & Partners and Ian Ritchie Architects. The monumental glass vault is another milestone in the evolution of SGFs, widely publicized and influencing future applications.

Innovator and Enabler

Implementers and enablers are found at the leading edge of any innovative and emergent technology such as SGF technology. Prominent among them is Tim Eliassen, a founder of TriPyramid Structures, a company specializing in the design and fabrication of rod and cable rigging systems and their application in SGFs.

Technology transfer is a well-established pathway for innovation. Tim Eliassen blazed a trail in bringing the technology of high-performance sailboat rigging to the architectural market. Since that time, there have been few milestone SGF applications with which he has not been involved.

Eliassen's undergraduate study was in aeronautical engineering, shifting to nuclear reactor engineering with his graduate work. But his passion was for sailboats. Recognizing an opportunity for improving the design of rigging systems, Eliassen cofounded Navtec and was immediately immersed in the world of large racing yachts, America's Cup boats, and sailing vessels whose sole purpose was complete circumnavigation of the globe in the shortest possible time. In the 1980s, Eliassen met Martin Francis, an architect and the F in RFR, the architecture/engineering firm he founded with Peter Rice and Ian Ritchie. Francis also happened to be a designer and builder of large sailing yachts. Their meeting was the beginning of an ongoing dialogue about the possibility of applying the rigging technology of high-performance sailing yachts to buildings. During the course of this dialogue and developing friendship, Francis took Eliassen to see the Glass Serres at Parc de la Villette, the seminal work designed by Peter Rice and RFR in 1983.

Then in 1987, Eliassen received a call from Francis telling him that there was a project in France that needed his involvement: the Louvre Pyramid by I.M. Pei. The project introduced Eliassen to architectural considerations of exposed structure and visual transparency with a focus on tension elements and, perhaps most of all, connection details. Under Eliassen's direction, Navtec ended up delivering what he refers to as "short pieces of yacht rigging," some 3800 of them, for the construction of the Pyramid structure. (The word *short* is a reference to the fact that the cold-headed rod rigging Navtec provided to the yachting industry was typically in lengths far longer than those required for the Pyramid.)

While not the first project to make predominant use of tensile elements, the Louvre Pyramid is a milestone SGF project important in two respects: it served to popularize the building form in the international design community and it revealed to Eliassen a compelling business opportunity. Eliassen had ended his ownership of Navtec by this time while remaining with the firm, focused on the design and engineering of the rigging systems, his true passion. On the successful completion of the Louvre Pyramid, he promptly recommended to Navtec's management that a new division be launched to pursue opportunities in the building marketplace. Management was less than enthusiastic about the idea ("roofs leak; you get sued").

Eliassen founded TriPyramid Structures in late 1989 with Michael Mulhern, who had acted as project manager for Navtec on the Louvre Pyramid project. Their first in a long line of high-profile projects was Moshe Safdie's Montreal Museum of Art. TriPyramid worked with Mero, then a provider of space frame structures, in developing an interesting hybrid space frame solution for a museum skylight in which many of the typical pipe elements were replaced with stainless steel tension rods and custom fittings, lightening the structure and enhancing the transparency.

Eliassen has a strong performance orientation deriving from his work with racing yachts; his success was measured not by the appearance of the work, but by the effect on performance. “It was simple with the boats,” comments Eliassen; “if you get the detail right, the boat goes faster.” This performance orientation served him well in his work on buildings, producing a performance-based aesthetic that was readily embraced by the design community. Well-designed exposed structures express a diagram of forces, providing rationality to the structural form that many find aesthetically pleasing. With Eliassen, this extends right down to the connection details, his particular passion. The component designs that characterize his work are elegant mappings of the functional requirements imposed upon the work.

TriPyramid was founded at a time when computer-aided design/manufacturing (CAD/CAM) technology was emerging, with companies like Navtec being far ahead of typical companies in the building industry. The ability to assemble a three-dimensional model and drawing package differentiated TriPyramid from other fabricators serving the construction industry at the time. Eliassen anticipated leveraging this capability in the marketplace as a means to supply rigging systems for buildings. But the business quickly changed.

New associations with such leading-edge glass designers as James Carpenter and Tim Macfarlane drove the business in the direction of art glass and other experimental structures, innovative explorations in steel and glass that pushed the materials and processes and increasingly involved Eliassen as a key collaborator in the design and development process. These investigations were most often driven by the pursuit of transparency and a dematerialization of structure that was greatly facilitated by Eliassen’s knowledge of and experience with the workings of high-strength tensile components. The business of TriPyramid became the integration of these elements into architectural structures.

Eliassen recognizes intense collaboration as a hallmark of innovation, referencing Peter Rice as an extraordinary collaborator. The details of the cable wall on architect Rafael Viñoly’s Kimmel Center for the Performing Arts in Philadelphia were developed in an intensive half-day collaborative session involving Viñoly, his facade wizard Charles Blomberg, Eliassen, and structural engineer and facade designer Tim Macfarlane. Dozens of projects later, with many landmarks among them, Eliassen still finds his music in the details. “The irony is that the lighter and more transparent you make a structure, the more prominent the details become,“ he observes. When considering pushing the boundaries, as often happens with SGF projects, there can be enormous value in having an experienced innovator on the team. That is why Eliassen has participated in many of the projects referenced in this book, including several of those described in the case studies in Chapters 7 to 17.[17]

Implementing Innovative Building Technology

The construction industry remains fragmented, highly conservative, and myopically risk-averse, showing little of the progress that has characterized other economic sectors, such as the automotive industry. This situation may finally be changing; such emergent and rapidly developing technologies as building information modeling, new strategies for prefabrication, and novel project delivery strategies may well revolutionize construction practice.

The relevant consideration here is the project delivery strategy. The evolution of SGF technology is documented in a series of highly innovative applications, each building on the antecedent work. The nature of current construction practice makes it an extremely challenging environment for innovation. Projects with innovative content—in design, materials, or processes— must embrace carefully crafted implementation strategies if they are to succeed. Central to any such strategy is the involvement of the appropriate experts for design, fabrication, and installation *as early as possible* in the design process. The prime motivation for alternate delivery strategies, at least when it comes to advanced facade technology, is to facilitate the earliest possible involvement of such experts.

The traditional design-bid-build process is seldom appropriate to even the simplest SGF applications. Years ago, a variation of the design-build process ultimately found favor in advanced facade projects where specialty design and engineering services were required. Rather than providing completed contract documents for the specialty system, the architect produced representative design development drawings and a performance specification, with final detailing and engineering falling to a specialty contractor. Today, even with a conventional design-bid-build project, the SGF work is most often broken out as a design-build package. However, this is often inadequate to a project's needs because the required expert cannot be properly engaged until the designer-builder is selected.

The design-assist strategy was developed by the American Institute of Architects (AIA) to address this shortcoming. Design-assist allows the project team to hire a material supplier, fabricator, or contractor early in the design process as a paid consultant. This practice is relatively new, and its use varies widely among projects. Many developers distrust it, fearing that it will compromise the provision of optimally competitive services. Many supply-side practitioners misunderstand the process, thinking that their usual presale services constitute design-assist. Nonetheless, this strategy is being effectively applied with increasing frequency, as many of the case studies in this book attest.

A design-assist strategy does not assure the service provider of securing a design-build contract for the work. Consequently, some specialty contractors are reluctant to provide such services unless they improve their prospects for obtaining a construction contract. One successful solution to this impasse is to guarantee a design-build contract to the design-assist provider if, at the completion of the design-assist phase, this entity provides a complete construction proposal that meets a preestablished budget. Other conditions are often incorporated in the design-assist agreement. Integrated project delivery (IPD) is a more sophisticated and comprehensive project delivery strategy being developed by the AIA that incorporates a significantly different contracting strategy intended to provide a collaborative project environment that fosters the early involvement of all required experts.

The important point here is that each SGF project must be carefully assessed for innovative content and relative complexity. As the technology matures, applications of low to moderate complexity with no significant innovative content are increasing, indicating that SGF technology is slowly diffusing into the marketplace as a new tier of adopters is enabled by the prior work. With simple applications and a design-build delivery strategy, little or no pre-bid involvement by a specialist may be required, although input from a specialty contractor, including preliminary pricing, is strongly recommended on even the simplest SGF projects. Most projects, however, will have enough complexity and novelty that the early involvement of the required specialties will be of significant benefit. Many SGF projects will continue to push beyond prior art, achieving a level of innovation that makes the early involvement of appropriate specialists critical to the success of the project.

The TKTS project, the case study presented in Chapter 17, is an excellent example. Architect Nick Leahy with Perkins Eastman characterizes an innovative SGF project, here the all-glass TKTS enclosure:[18]

> *As with any innovative project, it [TKTS] builds on pioneering concepts that are out there but either amplifies, refines or redefines them to produce a new product or uses, and in this way the technology and line of innovation moves forward a little. Structural Glass technology and architecture have advanced quickly over the last 15-years, and there are some beautiful structures built that served as precedents and drivers for design solutions. While working on the project, there wasn't a book on glass I didn't read or a new all-glass project I would not go to see and study the details.*
>
> *Structurally we started with calculations and based the design on built concepts and then pushed the boat out a little further. Dewhurst [the structural engineer] had recently completed a house with a load bearing glass wall supporting steel beams, so they had experience in the performance of glass under loads, and the precursors to the beam design were various glass fins and structural fins designed for curtain walls and roofs.*

The challenges of implementing innovative SGF technology are increased by the unique, one-off nature of each application combined with a frequent lack of significant resources for research and development, including mockups and testing. Leahy further comments:

> *In an ideal world we would have had an R&D budget for the project, but because of the nature of the project and the complex client structure, this wasn't the case. Architecture is a very different process than say product design, where you would build a prototype and then go to production; in architecture every project is a prototype.…*

Leahy attributes much of the success of the TKTS project to the early involvement of key consultants, material suppliers, and fabricators, as discussed in Chapter 17.

Organization of System Types

SGF technology is comprised of structural systems, glass, and the glass-fixing systems that bind structure and cladding. The facades are most usefully categorized by the integral structural systems used to support them. The elements of glass and glass systems are explored later, but are deemed subordinate to the structure system type with respect to facade type categorization. Thus, a long-span glass facade supported by a cable truss system becomes fundamentally a cable truss facade, regardless of whether it supports a spider-fixed frameless glass system or a framed unitized system, or whether it is clad in superclear or highly reflective glass. While the glass system is often tightly integrated with and even part of the structural system, it is generally the structure designs that represent the core innovative content of this building form.

Common Attributes

As a group, the structure system types that have been used in the construction of long-span glass facades frequently display certain general characteristics that help to define this class of building technology (Table 1.1).

TABLE 1.1 Common Characteristics of Structures Used in SGFs

Design aesthetics	Exposed and expressed structure Expression of membrane High transparency Dematerialization of structure
Materials, process, systems	Refined craftsmanship Machined and cast components Quality materials and finishes Lightweight structural systems Predominant use of tensile elements Use of tensile structures (all tensile elements)
Structural design and behavior	High structural flexibility High deflections Prestressed systems

Structure Types

The following structure types are considered because they have been used or could potentially be used in SGF applications:

- Mullion
- Glass fin
- Simple truss
- Guyed strut and mast truss
- Cable truss
- Gridshell
- Space truss/space frame
- Tensegrity
- Cable

The structural systems are not unique to the larger vocabulary of structural form, but their use in long-span glass facade applications has resulted in novel adaptations, and they can now be recognized as a unique class of structure types. The identification and comparison of the basic structure types are facilitated by their reduction to an elemental form, considered here in a simple vertical wall application. They are, however, derived from a rich body of innovative built facades of remarkable diversity and complexity, some of which defy such reductive analysis. This is symptomatic of a vital technology that is still evolving, recombining, and producing new forms.

Morphology

Morphology refers to the structural form that differentiates the system types discussed in the following chapters. While the real-world applications are diverse, each structure type displays a characteristic fundamental form and a unique general aesthetic. Table 1.2 groups the structure types into broader categories for purposes of organization.

Open and Closed Systems

Two distinct classes of structure systems are used in SGFs: closed and open systems. The attribute that differentiates them in this classification is the requirement for prestress, which must be initially determined as a parameter of the design process and must be realized on site during the installation of the structure. Prestress requirements have potentially significant implications for the design, engineering, fabrication, installation, and cost of an SGF, and thus become an important consideration in system evaluation, selection, and application.

- *Closed System:* A structure whose primary stability is achieved internally, independent of load transfer at the boundary structure anchorage

TABLE 1.2 Grouping of Basic Facade Structure System Types

Linear systems (Chapter 3)	Mullion systems	Linear open or closed section Glass fin
	Truss systems	Simple truss Guyed strut, mast truss Cable truss
Reticulated spatial systems (Chapter 4)	Space grid structures	Space frame with moment connections Space truss with pinned connections
	Gridshells	Quadrilateral gridshell Triangulated gridshell
	Cable-strut systems	Externally stabilized Internally stabilized, tensegrity
Cable systems (Chapter 5)	One-way membranes	Cable mullion
	Reticulated membranes	Cable net—flat surface Cable net—anticlastic surface

- *Open System:* A structure whose primary stability is achieved only through the application of pretension forces between the structure and boundary structure anchorage, thereby creating a condition of continuous prestress in the structure

Consider a simple truss, even one with internal cable bracing. Its morphology is independent of its inclusion in an overall structural system; it is internally stable and freestanding. The cable bracing may require pretensioning, but the basic structural form is not dependent upon it. A cable truss, on the other hand, has no such inherent stability. A cable truss released from the anchoring boundary structure against which it has been pretensioned by the development of prestress loads in the tension components immediately collapses into formlessness.

Spanning Behavior

Spanning behavior is an attribute of a structural system that affects the design, engineering, and anchorage requirements for a structure, as well as the potential efficiency of a structure. Two types of spanning behavior are considered here.

Unidirectional Spanning: Systems Spanning in One Primary Direction

Planar (flat) trusses can span in only one direction, and systems built of such trusses are referred to as *one-way systems*. Morphologically flat trusses of any kind are only capable of unidirectional spanning. This is also true of mullion, glass fin, and cable mullion structures (one-way cable net).

Multidirectional Spanning: Systems Spanning in Two or More Primary Directions

Additional spanning directions increase the potential efficiency of a structure, allowing for a more uniform stress distribution. Most common are two-way systems. Orthogonal grid space frames and cable nets are examples of two-way spanning systems. Triangular grid space frames and cable nets displaying three-way spanning behavior are also conceivable. More complex geometries, as can be developed with gridshell structures, are capable of complex, highly efficient multidirectional spanning behavior along multiple load paths.

Multidirectional spanning is not simply a matter of utilizing a two-way system; it is also a function of structure configuration. A square grid octet-truss space structure, rectangular in plan, will at some point, as the plan length increases relative to the plan width, span only in the short dimension and behave as a one-way system, with little or no increase in efficiency from the other potential spanning direction. A square plan will span most efficiently, evenly distributing stresses along both spanning paths. A one-way system will generally be the most efficient solution for a rectangular facade.

Categorization by Open/Closed System and Spanning Behavior

The structure types are categorized in Table 1.3 by inherent stability (open or closed system) and spanning behavior (unidirectional and multidirectional).

TABLE 1.3 Categorization by Open/Closed System and Spanning Behavior

Closed Systems	Open Systems
Unidirectional Spanning Systems	
Mullion (strongback)	Cable truss
Glass fin	Cable mullion[19]
Simple truss	
Mast truss	
Multidirectional Spanning Systems	
Space grid structures	Cable net Flat surface geometry Anticlastic surface geometry
Gridshell (triangulated or moment resistant)	Gridshell (pin-connected quadrilateral with cable bracing)
Tensegrity	
Cable-strut system (closed)	Cable-strut system (open)

Chapters 2–5 examine the structure system types categorized in Table 1.3. Readers who are intent upon exploring a particular structure type may choose to skip to the appropriate chapter. Glass and glass systems are discussed next so that the following chapters can describe the structure types within the context of these materials and systems.

Chapter 2

Glass and Glazing Systems

Glass as an Architectural Material

The organizers of the Engineered Transparency symposium at Columbia University in September 2007 asked a simple question at the outset: "What is glass?" A further question was "Is glass still glass?" The second question turned out to be more difficult to answer than anyone expected and the responses were more surprising, but in essence the answer was "Glass is not what it used to be."[1] Glass is recognized as a paradoxical material, displaying opposing attributes simultaneously; it is transparent and reflective, strong and fragile, material and immaterial. Developments in recent decades, however, have rendered the base material virtually unrecognizable amid the remarkable diversity of material variations commonly referred to as glass. It also became a ubiquitous material in commercial building construction during the second half of the twentieth century, despite certain properties that tended to compromise the thermal performance of the building envelope.

Unlike the relatively stable universe of metals (at least as used in building structure), glass has been an intense focus of research and development, with performance improvements occurring on a regular and ongoing basis. It is true, however, that raw float glass as a planar material in the building skin is an increasing rarity. Glass today is tinted, coated, fritted, laminated, insulated, layered, perforated, notched, wired, tempered, switched, and available in a vast array of these combined processes. The glass materials found on building sites today are profoundly different than those used in the early curtain wall systems. These differences attempt to address the problems and limitations arising from the use of plain float glass in the building skin.

While the structural systems may be the best means of categorizing structural glass facades (SGFs), glass is integral to the technology. A fundamental understanding of the various performance attributes of glass is imperative for the facade designer. Glass is a big topic, easily equal to its own book and the subject of many. A brief overview of the material is presented in this chapter because glass is one of the primary components of SGF technology.

Float Glass

Glass comes in a variety of forms as a function of chemistry and process. The basic ingredient, however, is silica, or sand, one of the most common and inexpensive materials on the planet. The addition of soda and lime, also very common materials, yields the most basic form of glass, generally referred to as *soda-lime glass* and the material used in the modern float process by which architectural flat glass is produced. The two largest users of glass are the construction and automotive industries, and here glass takes a more specific form.

Conceptually, float glass manufacturing is a simple linear process, the basic components of which are diagrammed in Figure 2.1. The raw materials are first mixed, heated to a melt temperature of approximately 1600°C (2732°F), and then floated in a continuous stream across a bed of molten tin. The molten glass, called the *float*, spreads across the tin surface until it reaches an equilibrium thickness of approximately 0.28 in. (7 mm). The thickness may be further manipulated by a system of conveyors and guides to within a range of 0.016 to 1 in. (0.4 to 25 mm). Float lines vary in width up to approximately 10 ft (3 m). As the material reaches the desired thickness, it is cooled to relative stiffness at approximately 600°C (1112°F) and moves from the tin bed to the annealing lehr. Annealing is a controlled cooling process that minimizes internal material stresses caused by uneven and rapid cooling. The annealed glass then moves to the cutting and storage area, the termination of the float line process. The float line process produces a highly uniform flat product with no wave or distortion and high optical quality with surfaces that require no additional processing (i.e., polishing). Over 90% of the world's flat glass is produced using the float process.

The slight greenish cast typical of conventional soda-lime glass is produced by the presence of iron oxide in the float chemistry. Small variations in the chemistry of the material mix can result in color variations, referred to as *body tints*, in the float product. Similarly, reducing the iron content of the float chemistry produces low-iron or superclear glass, discussed below.

A pyrolytic low-e (emissivity) coating is sometimes included as an inline component of the float process. A metallic oxide is deposited on the glass surface while still hot, effectively heat-fusing the material to the glass surface. Typically referred to as *hard coats*, pyrolytic low-e glass is tough and durable, and can be exposed to the environment without protection. Thin-film low-e coatings, or *soft coats*, are applied offline and are more fragile, requiring protection from direct environmental exposure. Pyrolytic coatings are generally cheaper because the process can be incorporated into float glass production. The thin-film low-e coatings, however, provide lower emissivity.

The process diagram in Figure 2.1 necessarily compresses the length of the typical float glass line, which can stretch to a third of a mile or more (roughly a half-kilometer). And once the start switch is flipped on a new float line, it runs nonstop for about 15 years, producing up to 1,100 tons (1,000 metric tons) of material per day. A float line is a costly investment. A new float line, which was inaugurated in September of 2010 by AGC Glass Europe, claimed to be the world's largest and represents a 150 million euro investment (approx. 206 million USD) according to the company's Web site. Recently completed and currently planned float glass plants range from 100 to 300 million USD in capital cost. The result is that float glass production is relatively centralized; some 260 float glass plants operate worldwide, but large distances between them result in extensive shipping requirements before the final material arrives at a job site ready for installation. The float glass process is also energy intensive. Some of the leading producers are attempting to reduce the energy consumption of the process by using natural gas as the primary fuel source.

The various material properties of glass—transparency, durability, resistance to corrosion and high temperatures—coupled with the huge production capacity of the industry and the relatively low cost render it a uniquely opportune material for application in architecture. The glass used in architectural applications begins as an annealed flat product of the float glass process, which is typically subject to modification through some form of postprocessing,

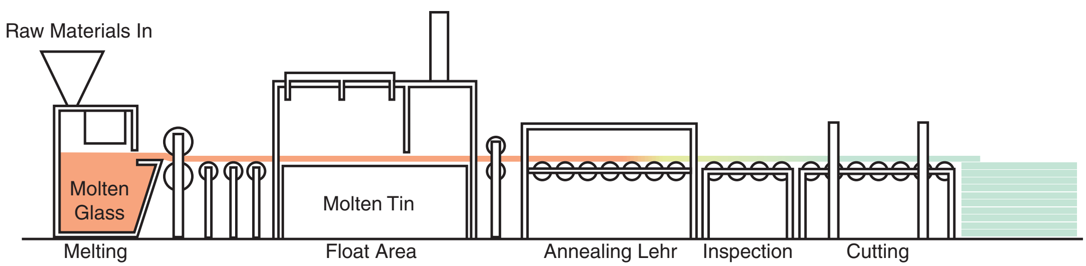


FIGURE 2.1 Diagram of the float glass process, which produces over 90% of all architectural glass.

thereby adding value. Secondary processes include various combinations of heat treating, laminating, fritting, coating, and panel fabrication.

Tinted Glass

Tinted glass, sometimes called *body-tinted glass*, is achieved through the addition of small amounts of metal oxides to the float. This provides useful changes to the solar, optical transmission and reflection behavior of the glass without altering its basic physical properties. The light transmission properties, and thus the color, can be changed within limits by this subtle alteration of the glass chemistry. Iron oxide, cobalt oxide, selenium, and other chemicals can be used in very small quantities to modify solar transmission properties. Bronze, green, blue, and gray are among the colors that can be produced this way.

The common performance objective in using tinted glass is to minimize infrared transmission with minimum reduction in the visible light spectrum. Green glass is most effective in this regard. There are limitations to the use of a simple body tint in pursuing this performance objective, however. Body tints are limited in their spectral selectivity, and their effectiveness in reducing solar heat gain is largely a function of the darkness of the tint. The darker tints quickly begin to reduce transmission of the visible light spectrum, a generally undesirable effect of tinted glass. Body-tinted glass can be combined with other coatings to enhance its solar performance and alter its appearance.

Performance Coatings

Mirror glass was an early industry response to the need for solar control in the glass building skin. Metallic coatings, including gold, silver, bronze, and titanium, were developed in the 1960s and 1970s to reflect solar thermal transmission. They were sometimes used in combination with body-tinted glass. Once some early performance problems were solved, mirror glass proved to be quite effective in reducing solar thermal loads and was used extensively in the cladding of commercial towers in urban centers around the world. The problem is that it reflects much of the visible light spectrum, resulting in darker interiors that require extensive artificial lighting to accommodate the needs of the workspace. The artificial lighting introduces its own heat contribution, increasing cooling loads on the building, in addition to increasing electricity consumption. The 1980s brought the introduction of the low-e coatings, which have evolved as the thin-film stars of today's glass coating technology. These coatings are spectrally selective, providing the powerful capability of reflecting specific ranges of the solar spectrum that carry the majority of heat energy while being transparent to most of the visible light spectrum.

Low-iron Glass

Low-iron glass is used extensively in SGFs. The low iron oxide content of the melt produces a glass without the slight greenish tint that characterizes conventional clear glass and provides a noticeably more transparent product. A cost premium of 10 to 20% over clear glass can be expected. The material is available under the industry trade names Diamont® by Saint Gobain, UltraWhite® by Guardian, Optiwhite® by Pilkington, and the first low-iron glass to be produced and introduced in projects like the Louvre Pyramid, Starphire® by PPG.

Monolithic Glass

Monolithic glass is a glass panel comprised of a single sheet of float glass. The glass can be tinted, coated, and otherwise processed, but it is used as a single sheet. Monolithic glass is frequently used in SGFs, as it provides for a distinctly smaller weather seal that enhances the overall effect of the facade's transparency. The side effect of this strategy is poor thermal performance. For this reason, insulated glass panels are often used, particularly in climate zones where solar heat gain or heat loss can present thermal challenges to enclosures with large areas of glazing.

Laminated Glass

Laminated glass consists of two or more pieces, or plies, of glass bonded together at the mating surfaces (Figure 2.2). This is typically accomplished through the use of a sheet material, called an *interlayer*, that acts as the bonding agent. Laminated glass assemblies can utilize tinted-glass, high-performance coatings, silk-screened patterns, and pigmented interlayers, alone or in combination. Glass lamination is primarily intended to improve the structural properties of glass by compensating for its brittle behavior. Laminated glass qualifies as safety glass in most situations. It is discussed at length in Chapter 6.

Insulating Glass Unit (IGU)

Insulating glass, as the name implies, is a strategy to improve the thermal performance of glass. The product, typically referred to in the industry as an *insulating glass unit* (IGU), is comprised of two glass lites separated by an air cavity and hermetically sealed around its perimeter (Figure 2.3). Air, compared to glass, is a relatively poor conductor and thus provides an effective insulation layer between the two glass lites. A facade or window utilizing IGUs is sometimes referred to as *double-glazed.* Double glazing need not stop with two lites; IGUs with three glass panels (triple-glazed, with two hermetically sealed cavities) have become increasingly common in window applications, and more layers are certainly conceivable, with cost being the practical limitation.

Alvar Alto is credited with being the first to use multiple-glazed panels in the 1930s. IGUs were standard industry products by midcentury. The primary reason for using multiple glazing is its enhanced thermal performance. The air cavity trapped between the sheets of glass acts as an effective insulator. Difficulty in maintaining the hermetic seal that created this trapped air cavity was the cause of early problems involving IGUs. A breach in the integrity of the seal resulted in moisture entering the cavity and condensing on the interior glass surfaces. This problem has been virtually eliminated with improved IGU production techniques. The

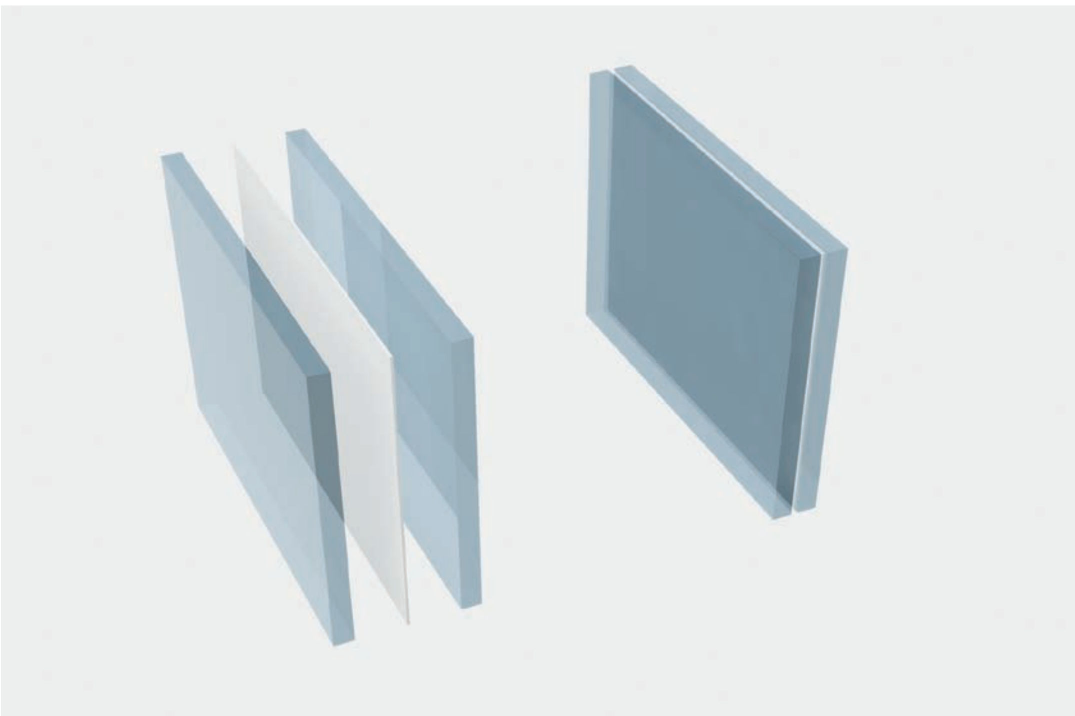


FIGURE 2.2 Laminated glass is two or more sheets (plies) bonded to a clear plastic interlayer in the presence of heat and pressure.

fabrication process is completely automated and able to accommodate a wide range of product configurations, which has both improved quality and reduced costs. The process involves bending an aluminum spacer bar to match the panel shape, pressing precut and cleaned glass sheets on either side of the spacer, and applying sealant around the entire perimeter. The perimeter seal is generally referred to as a *dual seal*, being comprised of two materials: a primary seal of polyisobutylene (PIB) and a secondary seal of silicone. The materials possess different properties and, used together, provide a superior barrier to both water penetration and air infiltration. Other materials are sometimes used as the primary or secondary seal. This may not be an issue with curtain wall systems where the weather seal is provided by a system of gasketed, pressure-equalized cavities. As the weather seal in most SGFs is provided by a field-applied silicone between adjacent glass panels, the silicone material must adhere to the edges of the IGU. It is therefore critical that silicone, or a material compatible with silicone, be used as the outer seal on the IGUs in such applications.

The aluminum spacer contains a desiccant material that works to absorb small amounts of moisture that may inadvertently enter the cavity. The spacers are typically anodized aluminum, and the aluminum color of the spacer is visible within the air cavity. Some manufacturers offer the spacer in black.

IGUs can be made of varying glass thickness and air cavity depth. A larger air cavity improves performance only up to about ½ in. (12–15 mm), beyond which further improvement is mitigated by convection within the airspace. A very common IGU for commercial facade and window applications is designated as ¼—½—¼ (6 mm—12 mm—6 mm), representing a ¼ in. thick outer lite, a ½ in. airspace, and a ¼ in. inner lite. Other techniques are also used to improve thermal behavior. Certain gases with improved insulation properties compared with air,

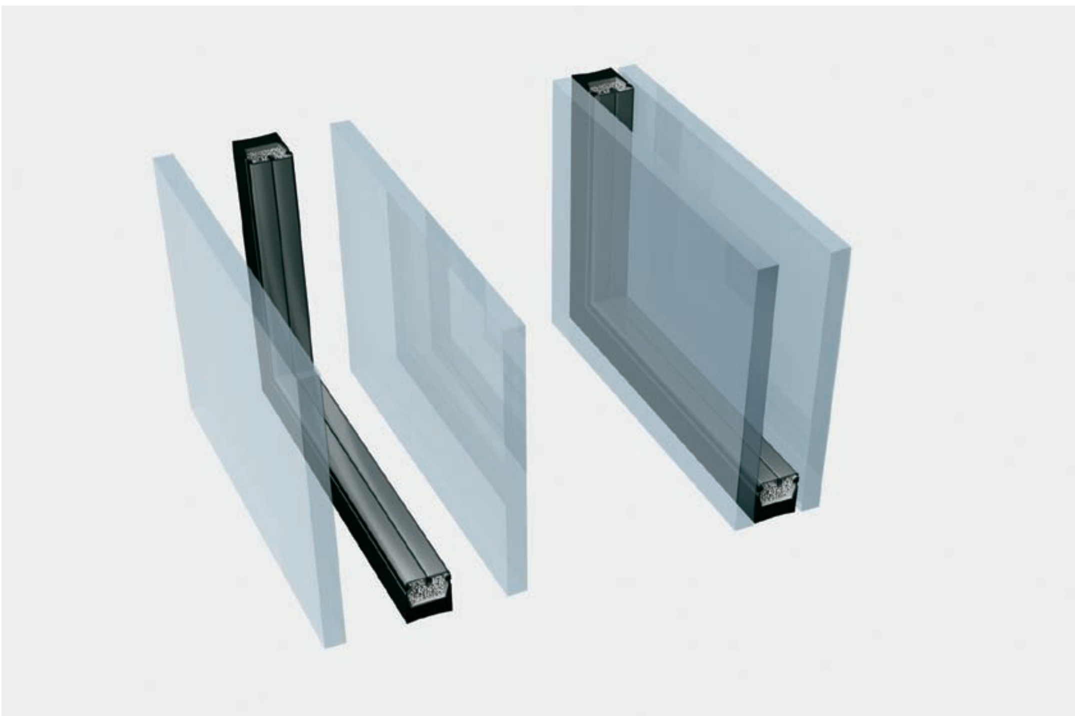


FIGURE 2.3 An IGU is two or more sheets of glass with a spacer between them to create a hermetically sealed gas cavity.

such as argon, can be used to fill the cavity of the IGU. Body-tinted glass can be used, and various coatings such as low-e, discussed below, can be combined in the IGU makeup. Various products use the air cavity to improve thermal properties and light transmittance: infill materials ranging from gels to special miniature venetian blinds. Research and development activities are ongoing, resulting in gradually improving performance. Some of these products are expensive, but as energy costs rise and their use increases in response, costs can be expected to drop.

As noted earlier, monolithic or laminated glass provides the highest level of transparency in SGF applications. While IGUs provide superior thermal performance and are often used for this reason, there is a price to pay in relative transparency. The edges of the spacer in the IGU are sealed to the glass with a black material, so there is a visible black band around the perimeter of an IGU that is the thickness of the spacer—about ⅜ in. (10 mm). An opaque sight line is formed between two glass panels, spanning from the inner spacer edge of one panel, across the weather seal between the panels, to the inner spacer edge of the adjacent panel. The weather seal is typically approximately equal to the overall thickness of the IGU. A common IGU makeup is two ¼ in. (6 mm) pieces of glass with a ½ in. (12 mm) airspace, for an overall panel size of 1 in.(25 mm). (Point-fixed applications may sometimes require a larger thickness in one or both pieces of glass, increasing the overall size of the panel.) Thus, the overall sealant site line (corresponding to the glazing grid) is over 1¾ in. (44 mm) wide. Framed glazing systems can approach this same dimension and are sometimes selected over point-fixed systems in these applications, as they may provide improved economy at little or no relative loss of overall facade transparency.

Laminated IGU

Glass panel fabrications can be both insulated and laminated. Insulating-laminated glass is an IGU in which at least one of the glass elements is a laminated panel. Most often, the exterior lite is a monolithic glass ply and the interior component is a two-ply laminate. If thermal performance demands necessitate the use of multiple glazing and the glass is to be used in an overhead or sloped application (15% or over from vertical), it must be both insulated and laminated as just described. The laminated glass is used as the inside lite of the panel to prevent a broken outer nonlaminated panel from falling into the building enclosure. A broken laminated panel is theoretically held in place by the interlayer, as described above in the section on laminated glass.

Laminated IGUs can quickly increase costs with point-fixed bolted glazing systems, as every IGU will require at least 12 machined holes. They do, however, offer greater flexibility in the application of frits and coatings because of the additional surfaces interior to the panel. Different frit patterns are sometimes silk-screened onto multiple surfaces to interesting effect (Figure 2.4). Laminated IGUs may be used for noise mitigation. Double-laminated insulating glass and other more rare configurations are also available for special applications.

Bent Glass

Hot Forming

Glass bending is a specialty field within the architectural glass industry, but the practice probably dates back to the beginning of architectural glassmaking. Heating float glass while in the annealed state is the basic process of creating architectural bent glass. As the material softens, it slumps or is pressed over a form and then is gradually cooled. Monolithic, insulated, and laminated bent units are all possible. Bends are generally limited to one direction, although double-curvature glass has been experimented with on some projects, such as the Condé Nast interior in New York City by Gehry Partners and the Glass Umbrella in Culver City, California, by Eric Owen Moss Architects. Special equipment is required to temper bent glass, and few architectural

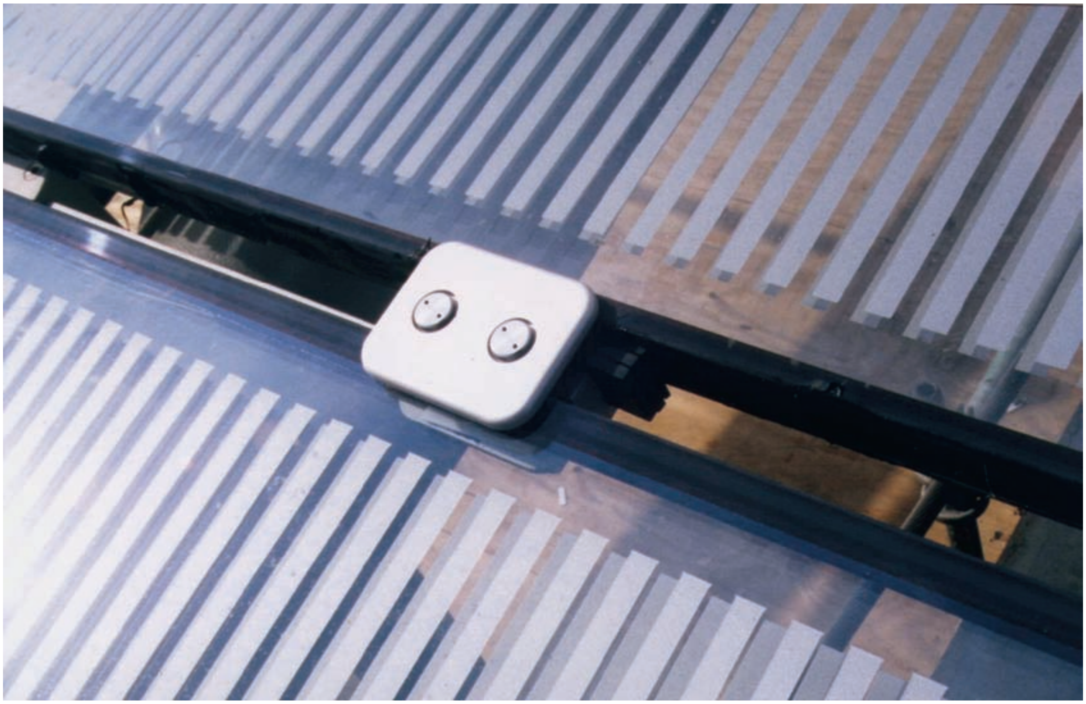


FIGURE 2.4 Laminated and insulated glass fabrications allow various coatings to be applied to the protected interior surfaces. Here a banded ceramic frit is applied to the no. 2 and 3 surfaces of this laminated IGU.

bent glass producers have this capability. Some bent glass may be difficult or impossible to temper, depending upon the surface geometry.

Specialty fabricators, many of them generational family businesses, provide glass-bending services. It is not unusual for bent glass on SGF projects to cross national borders. Two highly regarded architectural glass-bending specialists regularly deliver to a global market; Cricursa from its factory outside Barcelona, Spain, and Cristacurva from its plant near Guadalajara, Mexico, are both producers of high-end architectural curved glass. Glass-bending technology for automotive glass far surpasses that for architectural glass because of the large quantities of identical units that are characteristic of the former industry.

Cold Forming

Cold forming is a relatively new technique that involves bending the glass without heat. Two basic methods are used in cold forming. The first is to simply force the glass into a deformed position and secure it. This was the strategy employed in architect Frank Gehry's design for the ITC Corporation headquarters in Manhattan, New York City. Curtain wall producer Permasteelisa worked with Gehry to develop a system that could be deformed into shape during installation. The deformations were relatively moderate. The second method is to prebend the glass in a fixture and laminate the bent shapes, resulting in lower built-in stresses. The stunning new addition to the Strasbourg Terminal (Chapter 12) in France by architect ATEC with facade engineer RFR and contractor Seele uses this method to maximum effect. One of the motivations for cold-forming glass is that the material remains free of the surface distortions that occur during heat treatment. This technique is highly specialized and in the experimental stages, and few fabricators are currently capable of providing this service. However, some large glass fabricators are currently collaborating with advanced facade designers on several projects using cold-formed glass, such as Renzo Piano's Kimbell Art Museum Expansion in Fort Worth, Texas, with facade consulting firm Front.

Maximum Glass Sizes

The press for ever-larger individual lites of glass continues today. Higher transparency can be achieved with larger glass sizes. Supporting structural systems typically follow the glass grid, so as these sizes increase, the amount of structure decreases. This can quickly create complexity and add cost to the structural systems. There are a number of other practical considerations with respect to glass size, such as handling (glass is heavy, and large panel constructs can be difficult to handle in the fabrication and construction process) and transportation. Solving the handling issue for the larger sizes may provide some advantage, however, in that there are fewer pieces to install. These considerations aside, the facade designer often wants to know the limitations of size. Most glass used in SGFs has some secondary processing involved in its makeup (heat treating, insulating, laminating), and it is this processing that determines the maximum width a fabricator may produce as a function of the available equipment.

Float glass thickness ranges from approximately ⅛ to 1¼ in. (3 to 32 mm) for architectural purposes. The most common sizes used in commercial construction are ¼ to ½ in. (6 to 12 mm). Larger glass sizes may require thicker glass to accommodate the higher loads resulting from the large tributary area.

Most float lines have a ribbon width of about 10 ft (3 m). The available sizes may depend on handling and shipping limitations rather than on the manufacturing plant. Float sheet from the glass producer generally comes in two sizes: split in 96 by 130 in. (2438 by 3302 mm) and jumbo in 130 by 204 in. (3302 by 5182 mm). Working with the jumbo size requires special equipment that many smaller glass fabricators do not possess. However, efficiency can be associated with using the jumbo size, as less glass waste results from the fabrication process.

Heat treating, laminating, and IGU assembly all impose size limitations as a function of a glass fabricator's equipment. Heat-treated glass is limited by the width of the fabricator's tempering oven. As of this writing, Viracon indicates on their Web site a maximum tempered glass size of 84 by 165 in. or 96 by 144 in. (2134 by 4191 mm or 2438 by 3658 mm), indicating that the area, and not just the length or width of the glass lite, is a consideration.[2] Viracon recommends a glass area of 65 sq ft (6.04 sqm). Some manufacturers limit the size of heavier insulated IGUs to as little as 35 sq ft (3.25 sqm).

According to Joe Green, CEO of GlassPro, a regional glass fabricator in Southern California that specializes in glass bending and provides glass fabrications for point-fixed applications, the company can provide tempered glass up to 84 by 168 in. (2134 by 4267 mm), laminated glass up to 120 by 180 in. (3048 by 4572 mm; narrower widths can be made longer), and 96 by 130 in. (2438 by 3302 mm) for IGUs. Glass Pro also has a computer numerically controlled (CNC) machine, used for notching, drilling, countersinking, and other glass machining operations, that can handle sheet sizes up to 98 by 170 in. (2489 by 4318 mm). These capabilities are similar to those of other regional glass fabricators.

A small group of international companies have developed highly specialized capabilities that extend well beyond what can be found in a typical region or locale. Sedak GmbH & Co. KG in Gersthofen, Bavaria, Germany, a glass-to-glass and glass-to-metal laminating specialist and part of the Seele Group, has laminated lites of 10 ft 2 in. by 43 ft 7 in. (13.3 by 3.10 m) weighing several metric tons. The challenge at this level can be multifaceted; making these huge lites was only part of the problem. Vacuum-lifting equipment to handle lites of this size and weight did not exist and had to be developed to support this expansion of the glass-processing envelope. There are reports of glass designers working with tempered laminated glass in sizes up to 49 ft (15 m). Large-format furnace and autoclave combinations are either producing or coming online in China and Europe, making 30 ft (9 m) tempered, laminated, and insulated products "easy and common," according to structural engineer and facade specialist Michael Ludvik.[3]

An Aesthetic of Transparency: Glass as a Visual Material

While transparency is its most remarkable attribute, glass does manifest other visual behavior born of its application in the building skin. Clear glass is seen largely through reflections from its surface, which can render the glass conditionally opaque. In the absence of reflections, the glass becomes transparent. Designers intent on achieving maximum transparency in a glass facade have employed antireflective coatings with considerable success, minimizing reflections and thereby enhancing transparency. The pursuit of transparency in the building envelope has driven many of the developments in glass and glass facade technology in recent decades. Increasingly, however, designers are exploring the full range of light transmission from opacity through translucency to transparency and from specular to diffuse. The property of reflection is subject to similar experimentation. The plethora of material variations and techniques has resulted in a wide range of diverse product offerings, complicating glass selection.

In reality, transparent glass in the building facade is one of the easier options to evaluate from the standpoint of appearance. The varied effects exhibited by tinted and reflective-coated glass can be much more challenging for the designer to assess. Low-e coatings can produce subtle effects under various view and lighting conditions; reflected and transmitted light can combine to produce unexpected results. Add to this the effects of surface patterning and printing, as well as the plethora of colored, textured, and patterned interlayers, and glass selection becomes a major undertaking on many commercial building projects, requiring dozens of material samples in various combinations and even the construction of visual mockups that provide for the evaluation of different glass configurations under varied lighting conditions and environmental exposures.[4]

Specification and Standards

Specifying Glass

Specifying glass can be intimidating simply because of the large number of available options. Viracon offers over 350 different kinds of insulated glass alone. Fortunately, the various glass manufacturers and fabricators have excellent online technical support for this purpose.

Coatings and frits are specified by surface. Monolithic glass has two surfaces, two-ply laminated glass and insulated glass have four, insulated laminated glass has six, and so on. The no. 1 surface is to the outside of the building. Most frits and coatings are specified on the no. 2 or no. 3 surface, where they are better protected. The manufacturers offer recommendations based upon panel makeup, coating material, and function.

The *Specifier's Guide to Architectural Glass* is produced by the Glass Association of North America (GANA) and is available for free download from their Web site, along with many other technical resources.[5]

Many construction industry codes and standards apply to glass, glazing components, and the building facade, and should be thoroughly researched as part of any facade design development program. A few of the applicable standards include:

- ANSI Z 97.1 Glazing Materials Used in Buildings, Safety Performance Specifications and Methods of Test
- ASTM C 1036 Standard Specification for Flat Glass
- ASTM C 1048 Standard Specification for Heat-Treated Flat Glass–Kind HS, Kind FT Coated and Uncoated Glass
- ASTM C 1172 Standard Specification for Laminated Architectural Flat Glass
- ASTM C 1376 Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Glass

- ASTM E 773 Standard Test Method for Accelerated Weathering of Sealed Insulating Glass Units
- ASTM E 774 Standard Specification for the Classification of the Durability of Sealed Insulating Glass Units
- ASTM E 1886 Test Method for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials
- ASTM E 1996 Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes
- ASTM E 2188 Standard Test Method for Insulating Glass Unit Performance
- ASTM E 2190 Standard Specification for Insulating Glass Unit Performance and Evaluation
- ASTM F 1642 Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings
- CPSC16CFR-1201 Safety Standard for Architectural Glazing Materials

Glazing Systems

Glass systems are another of the three primary components of SGF technology; glass has been discussed and structures follow. Glass systems have two functions. The first is to fix the glass to the supporting structure. Curtain wall systems are used to hold glass and other cladding elements together and to secure them to the building structure. Alternatively, point fixings such as spider fittings are frequently used to secure glass to the supporting structure in an SGF. The second function of the glass system is to provide the weather seal for the facade through one of several means.

Glazing Methods

The glazing industry has developed several strategies for providing the weather seal on buildings. All of these have been utilized on SGFs; however, butt glazing is by far the method most commonly used. It provides the weather seal on virtually all point-fixed glass systems.[6]

Wet Glazing

Glass is sometimes wet-glazed into a frame using an elastomeric tape or a gunable sealant (meaning that it is typically applied with a caulking gun). This operation can be conducted in the field during installation of the glazing material or in the factory, as with the fabrication of curtain wall units. Curable materials are most commonly used; they undergo a gradual chemical reaction after application, assuming a dry, rubbery consistency.

Butt glazing is a special form of wet glazing.

Dry Glazing

The provision of glazing seals through the use of compression gaskets is referred to as *dry glazing*. The gaskets are extruded to a specific shape to suit the application, often mating to an aluminum extrusion profile. Silicone, neoprene, and ethylene propylene diene monomer (EPDM) are commonly used materials. Dry gasket systems have become increasingly popular because they minimize on-site glazing requirements where craftsmanship, weather, and labor costs can adversely affect wet glazing methods. Most contemporary curtain wall systems rely on compression gaskets for the primary weather seal. In practice, however, both methods are used in combination in most applications. Even dry gasket curtain wall systems typically require some strategic application of wet silicone to the units when assembled in the factory and when installed in the building skin.

Pressure-glazed Systems

Dry glazing is often used with pressure-glazed systems. The weather seal in these systems is produced by the compression of a dry gasket between a pressure plate and the glass surface. The large facade product companies all provide off-the-shelf variations of pressure wall or pressure-glazed systems. Failure to achieve adequate, uniform pressure on the gasket may result in air and water infiltration.

Butt-joint Glazing

Frameless glazing systems are invariably butt-glazed, and even the panelized systems sometimes used on SGFs are often butt-glazed (Figure 2.5). Pressure-glazed systems can capture the glass on two sides or all four sides. The two-sided version typically captures the glass along the horizontal edges. The vertical glass edges are left unsupported, and a wet silicone seal is applied to this joint. With point-fixed or frameless glazing systems, a butt-glazed joint is used as the weather seal throughout the system. This glazing strategy is sometimes referred to as a *barrier wall*; the skin provided by the glass and silicone seal is intended to be impervious to air and water infiltration. The operating principle is that if the seal is properly applied, it will provide a reliable and durable weather seal; it will not leak. Silicone is a robust and proven material with a lifespan in excess of 20 years.

Adhesive failure of the silicone material is avoided by proper substrate preparation; primarily, it is important to ensure that the glass in the joint area is clean and dry. In the case of glass substrate, this typically involves wiping down the surfaces with an appropriate solvent. Damp weather and cold temperatures may compromise adhesion. Cohesive failure of the seal can result from poor joint design; the joint width-to-depth ratio is critical. A width-to-depth ratio of 2:1 is most often recommended. This means that for thicker glass panels, such as laminated panels and IGUs, the silicone should usually not completely fill the gap from inside to outside between adjacent glass panels. A backer rod is used for this purpose. A length of compatible foam material round in cross section is compressed into the gap, providing a surface to control the sealant depth. Alternatively, a silicone gasket can be pressed into the joint opposite the side to receive the wet silicone material. Following the manufacturer's recommendations for both joint design and silicone application will ensure a quality seal. The systems are easily tested after installation of the silicone with a simple water spray. Any leaks are easily identified and repaired, something that can be quite challenging in a complex curtain wall system. The installation of the silicone seal is of vital importance in a minimal SGF system. Craftsmanship is critical; a well-tooled silicone joint is handsome, whereas amateurish application can result in a messy, inconsistent, toothpaste look that can detract significantly from the facade's appearance. Some waterproofing subcontractors specialize in the application of butt-glazed silicone. It is important that the specification documents adequately communicate the expectation of the designer with respect to the quality and appearance of the silicone seal.

The disadvantages of field-applied silicone are the requirement for expensive field labor, the potential for poor craftsmanship in the application, and generally adverse site conditions (adhesion issues related to temperature, moisture, and dirt).

Structural Glazing

The previously discussed glazing methods are all nonstructural; the sealant material provides a weather seal only and does not play a structural role. Structural glazing, which amounts essentially to gluing glass to the building's exterior, dates back to at least the 1970s and has since become a classic and commonly accepted glazing method, although some local building codes still prohibit it, Los Angeles's among them. The technique was originally developed to present a uniform glass surface to the building facade, uninterrupted by mullions or pressure caps. Today structurally glazed curtain wall systems are being used even in areas exposed to the extreme loading of hurricane-force winds.

Structural glazing is seldom used with SGFs. The point-fixed systems provide mechanical attachment of the glass to the structure. However, structural silicone material is often used for butt-glazed joints even though the primary function of the seal is not structural. The structural systems used to support SGFs are characterized by high deflections. Structures to be clad in glass were once designed to be rigid in an effort to subject the glass and seals to as little stress as possible from movement under design loading. Now it is recognized that structures and cladding systems that are *designed* to move

FIGURE 2.5 A butt-glazed joint is produced by the field application of wet silicone material to the gap between adjacent glass lites. The material gradually cures to a tough rubbery consistency. The technique produces a reliable and durable weather seal. Detail from a glass wall provided by Novum Structures, 2010, at the lobby of a downtown Los Angeles high-rise.

behave better under extreme loading conditions. The large elastic properties of the silicone joint make such large deflections workable in long-span glass facades.

Compatibility

The many materials that are often combined in a facade system make it necessary to consider their compatibility. This is critical in the case of structural glazing, where incompatibility can result in falling glass. In a book by that very name, Patrick Loughran devotes an entire chapter to the topic.[7] The close proximity of these many diverse substances can result in chemical reactions with deleterious effects ranging from compromising the integrity of the glazing seal to blemishing the facade's appearance. Glass is a neutral material, and frameless glass systems immediately simplify the problem by limiting the number of materials that can be in contact. Still, laminated glass has plastic interlayer material and IGUs have edge seals. The glass surfaces can be coated with a wide variety of materials ranging from ceramic frits to exotic metal oxides.

The more common compatibility problems with SGFs include the two glass types predominantly used: laminated panels and IGUs. Laminated glass is often used in frameless applications where a butt-glazed silicone joint provides the weather seal. This puts the interlayer material in contact with the structural silicone. There can be incompatibility between these materials causing a fogging of the interlayer that radiates from the edge of the glass inward as much as 1 in. (25 mm). Silicone materials have now been developed that are compatible with certain interlayers. The material suppliers must be informed of the intent to butt-glaze and requested to verify compatibility. They will often perform compatibility testing as a free service for material combinations about which they are uncertain. Fabricators of IGUs must also be informed of the intent to butt-glaze with a specific structural silicone material. They will then use a compatible material for the secondary (outer) seal on the IGU.

Staining is another problem that can result from the use of organic sealants. Plasticizers, oils, and chemical solvents can migrate from these materials over time and, if not frequently removed, can produce permanent stains on glass and other materials. The many glass coatings each react differently to exposure to these chemicals, so especially when using new or exotic materials, it is important to determine compatibility through testing. Other material finishes incorporated in the facade design must also be compatible with such exposure.

Compatibility issues are not limited to the glass and sealants. Dissimilar metals in direct contact can result in galvanic action, causing unsightly corrosion and even compromise of the structural capacity of the metals. The chemical reactions can be quite complex and are influenced by a variety of environmental factors, including air pollution, moisture, and a marine environment. Compatible stainless steel fasteners must be used with aluminum extrusions. Where aluminum systems are attached to mild steel structures, the materials should be isolated to prevent direct metal-to-metal contact.

SGFs often involve innovative designs and a novel use of materials. Compatibility issues should always be considered in such work, with the intent of isolating unknown or questionable material interfaces. A testing program should be developed for all such instances to determine compatibility.

Glazing System Types

The basic glazing types are categorized into framed and frameless systems (Table 2.1). Frameless glass systems include the two variations of point-fixed system types so often used in SGF applications. The other systems are also used and are briefly reviewed here, but with an emphasis on the frameless systems.

TABLE 2.1 Glazing System Types

Framed Systems	Frameless Systems
Stick	Point-fixed bolted
Unitized	Point-fixed clamped
Veneer	
Panel	

Curtain Wall Systems versus SGFs

Curtain walls are a glass system type typically configured to accommodate the short- to mid-range spans that occur between floor slabs of multistory buildings. The spanning member, most often an extruded aluminum mullion rectangular in section, may or may not be exposed. SGFs integrate a glass system type with an exposed structural system, often configured for mid- to long-span application. The spanning requirement of the glass system is often a relatively small increment, while the primary spanning capacity is transferred to the facade's structural system. The glass systems described here can be used in either curtain wall applications or SGFs, although in the latter case, their integration with a supporting structural system tends to differentiate them from conventional curtain wall systems. Framed systems dominate curtain wall applications, although frameless curtain walls of some interest have been completed and do have some potential advantages over framed systems. Conversely, frameless systems are most frequently used with SGFs, although interesting examples of framed systems can also be found.

SGFs often span longer distances than conventional floor slab spacing, with an upper range defined only by the limits of the structural design. While SGFs are also used in short-span applications, what primarily differentiates them is an exposed structural system employed to accommodate the span.[8] The curtain wall in this sense is limited to framing members consistent with the curtain wall used for the typical spans, although perhaps deeper, heavier, and reinforced.

Framed versus Frameless Systems

Any of the glazing systems categorized here can be applied in an SGF. While the frameless systems with point-fixed glass have propelled the development of SGF technology and are more frequently used, there are many examples of highly transparent SGFs that incorporate framed glazing systems. It is interesting to note the use of the glass systems in curtain wall applications on multistory buildings compared to their use in SGFs. Barrier walls with butt-glazed silicone joints dominate SGF applications but are rarely used in curtain wall applications. Even framed systems applied to SGFs often use butt-glazed silicone joints to provide a weather seal. Similarly, frameless systems find extensive use in SGFs but have rarely been applied to multistory buildings.

The application of frameless glass-system technology to high-rise building skins may present some interesting opportunities. There are certainly problems to solve, the accommodation of building movements not least among them, but there may be sound reasons to take the initiative. Frames can be problematic. They represent potential conduits for unwanted heat transfer, sound transmission, and smoke, not to mention moisture penetration and air infiltration. When moisture finds its way into a building, it is not through the glass but around the glass. Butt-glazed silicone joints have proven to be remarkably reliable and durable on SGFs.

There is a growing focus on thermal and acoustical issues in the building envelope. Glass fabrications have known values for thermal transfer and acoustical performance. Furthermore, improvements in glass performance have been dramatic in recent years, especially thermal improvements resulting from developments in spectrally selective thin-film coatings. The same developmental improvements cannot be claimed for framing systems, although leading curtain wall companies are working with renewed vigor to develop enhanced framing system performance because of the growing pressure for greater energy efficiency in buildings. One strategy might be to abandon the frame altogether and explore the application of frameless SGF technology to the enclosure requirements of high-rise buildings.

Framed Glass Systems

Framed systems include stick, veneer, unitized, and panelized systems.

Stick Systems

Early curtain wall installations were constructed from long vertical framing members called *mullions*, or *sticks*, spanning across supporting floor slabs (Table 2.2). Horizontal mullions span between the verticals. This system is sometimes referred to as a *mullion and transom frame*. The framing members are shop fabricated, factory painted, and installed one piece at a time. The glass or other cladding panels are then attached to the framing members. The systems are referred to in the industry as *stick-built*. This system type is site labor intensive, and site labor, especially in Western markets, is at a premium. Consequently, stick systems have been replaced by unitized systems in many applications.

TABLE 2.2 Stick System

- The earliest form of curtain wall technology
- Vertical extrusions span between floor plates
- Much of the fabrication and assembly work occurs on site
- Quality control and general conditions more challenging on site
- Appropriate for geographic regions with cheap site labor

Veneer Systems

The term *veneer system* is useful in describing a variant of the stick system sometimes used with SGFs. With a conventional curtain wall, the sticks must span between floor slabs. Structure systems used with SGFs, particularly the simple truss systems, may incorporate a high-tolerance flat face to provide continuous support to the glazing system. The aluminum stick that is used in such an application requires no spanning capacity; the supporting structure does all the spanning work. The glass system can thus be reduced to the minimum required to facilitate attachment of the glass to the structure (Figure 2.6). The system is similar in most other respects to the stick system described above. This integration of the glazing system and structure provides for greater economy, eliminating unnecessary redundancy between the structure and glass systems (Table 2.3).

FIGURE 2.6 The exposed steel structure includes vertical trusses and bolt-up horizontal mullions, providing a grid to which a minimal veneer-type glazing system is fixed.

TABLE 2.3 Veneer System

- A minimal approach borrowing the curtain wall technique
- Similar to a stick system, but nonstructural
- Requires almost continuous support to the extrusion receiving the glass
- Can be used with wet or dry seals
- Eases the demands on glass supply
- Very economical

Unitized Systems

Unitized system is a curtain wall term used to describe systems in which large framed constructs, or units, are built up under factory-controlled conditions, shipped to the site, and the entire unit lifted and set into position. Multiple glazing panels are typically incorporated within a single unit (Figure 2.7). Unitized systems strategically shift labor requirements from the site to the factory, which potentially allows improved quality and greater economy, at least in areas with high field labor rates. The unitized curtain wall is now the system of choice for most commercial high-rise building projects (Table 2.4).

TABLE 2.4 Unitized System

- Has largely replaced stick technology in large commercial applications
- Units are assembled in the factory and shipped to the field
- Shifts more labor to factory-controlled conditions
- Better quality and quality control from factory assembly
- May reduce expensive site labor

Unitized systems are rarely used with SGFs, although there is no technical reason to prevent this. The dematerialization of the facade structure, the expression of transparency, is the driving force for the predominant use of the frameless glazing systems most often employed on SGFs. Unitized systems are inherently framing intensive to provide for the structural integrity of the unit while it is handled in the factory and field. This complicates the high-level integration between the structural system and cladding that is typical of SGFs. However, the reasons for utilizing unitized systems can also apply to large SGFs, and

FIGURE 2.7 A large curtain wall unit containing over 30 glass panels being positioned for attachment to building anchors.

it is conceivable that a unitized approach could balance the considerations of aesthetics and efficiency.

Panelized Systems

Individual monolithic glass lites, laminated assemblies, or IGUs assembled with stiffeners to form a glazed panel are referred to as *panel systems* (Figure 2.8). This glass system type was adopted for use in SGFs to avoid the premium cost of glass for point-fixed applications. Domestic glass suppliers in the United States have been reluctant to provide a warranted product in applications where deflections of the glass unit may exceed certain levels. Some European suppliers willingly warranty their products for use at higher deflections, but also at a higher cost. The stiffeners provide structural properties allowing for their interim support by the truss system while still providing continuous support to the glass pane, thus minimizing deflections to the glass pane itself. The stiffeners can provide two-sided or four-sided support, and can mechanically capture the glass pane or be structurally adhered using appropriate structural silicone glazing material. When thermal performance concerns dictate the use of IGUs, panelized systems can be more economical solutions than point-fixed glass systems, with some loss of overall facade transparency (Table 2.5).

A cassette system is a variant panel system. The glass is fabricated with a minimal nonstructural frame that facilitates simplified on-site installation of the panel into either a stick or a unitized framing system.

TABLE 2.5 Panel System

- Provides moderate to high relative transparency, depending upon the glass type
- Glass surface can be lifted off the supporting structure
- Butt-glazed silicone joints can be used throughout
- Conventional glass fabrication requirements
- Facilitates the installation process
- Potentially more economical than point-fixed systems

Frameless Glass Systems

Point-fixed glazing systems require no frames and find most frequent use in SGFs. The glass panes are either bolted or clamped, with hardware systems providing attachment to the supporting structure. A common system type is often referred to as a *spider system*; a four-armed fitting, usually of cast stainless steel, supports four glass panes at adjacent corners on the glazing grid and ties back to the structure system. The spider fitting is designed to provide for glazing system movement under environmental loading, as well as to accommodate a specified field tolerance during assembly. A variety of spider systems are available from the many suppliers of cable and rod rigging systems. Cast stainless components can be quite expensive, especially if large, custom-designed spiders are required, as they often are in large glass grids. Alternative strategies can be lower tech, lower cost, and just as effective, depending upon the aesthetic goals of the project.

FIGURE 2.8 The panel system shown here consists of aluminum rails structurally glazed to two sides of an IGU. The system is butt-glazed.

Simple stainless steel spring plates have been used in place of cast fittings with excellent results.

There are two basic forms of point-fixed glazing; one requires perforations in the glass to facilitate bolting as the means of attachment, and the other employs a clamping strategy that requires no perforations in the glass material.

Point-fixed Bolted System

The point-fixed bolted system is the most popular and one of the most expensive glass systems used in SGFs (Table 2.6). Specially designed bolts are inserted through perforations in the glass material and mate with a fitting that ties to the supporting structure (Figure 2.9). There are variations of these glass fixings on the market, and the refinements of detailing and performance vary in important respects. The glass bolts are of stainless steel material. Pilkington's glass bolt used with their Planar system features a tapered bolt head that sits flush with the outer glass surface in a countersunk hole. It is a rigid connection transferring bending moment into the glass at the point fixing that must be accounted for in the glass engineering. Another type of glass bolt was developed by RFR, the French design firm whose principals were involved in some of the early milestone SGFs, like the Glass Serres at La Valette. This fixing is also countersunk, but the design features a bolt with a ball end that sits in a mating fitting that places the ball in the plane of the glass. This "articulated" bolt, sometimes referred to as a *rotule fitting*, allows the glass panel to deflect without creating bending moments at the fixing point. It also results in somewhat greater center-of-glass deflection than occurs with the unarticulated bolt.[9]

IGU panels presented a particular problem when the point-fixed glazing systems were first

FIGURE 2.9 A point-fixed bolted glass system using a spider fitting and perforated glass. A specially designed bolt penetrates through the perforation to fix the glass. The glass dead load is usually carried at the connections at the top of the panel.

used. A method had to be found to seal around the fixing component so as not to compromise the hermetic seal of the panel. Pilkington developed a ringed spacer that could be sealed around the holes for this purpose. As with virtually all aspects of advanced facade technology, European firms have led the way in systems development and application. In fact, it was not until 2006 that Viracon became the first major U.S. glass fabricator to provide warranted, perforated IGUs for application in point-fixed systems. Other glass fabricators have now developed this capability, and the sourcing of this product is becoming increasingly easy and the products more competitive.

TABLE 2.6 Point-fixed Bolted System

- Provides for optimum transparency with any given backer structure
- Glass plane is usually lifted off the supporting structure
- Hole drilling adds to system cost, especially with multi-ply panels
- Engineered and warranted systems are available
- Minimal butt-glazed silicone joints used throughout
- Creates demanding glass supply requirements
- Requires high-tolerance installation of backer structure
- Highest relative cost

This system presents a uniform glass surface with minimal interruptions in the form of butt-glazed silicone joints and countersunk bolted fasteners. Pilkington now offers a system with the glass bolt embedded in a laminated panel, providing mechanical capture with an uninterrupted glass surface that is otherwise attainable only in a structurally glazed system. A point-fixed bolted strategy combined with monolithic glass provides optimum overall transparency. Antireflective coatings can be applied to the glass to enhance the effect.

The joint size is a function of the glass thickness and should be determined in consultation with the glass provider. The number and location of holes depend on the glass size and design loads, and must be determined by a qualified engineer experienced with the use of glass. The bridging component that ties the glass to the backer structure can range from a custom cast stainless steel component, as with a spider-type fitting, to a simple spring plate fashioned from bent metal plate. It is important that the glass fixings provide for two requirements: (1) accommodation of field tolerances with respect to the location of the interface point at the backer structure and (2) accommodation of movement of the structure and glass under design loads.

Heat-treated glass is typically required in any point-fixed application, with fully tempered glass being most often used (see the discussion of tempered versus heat-strengthened glass in Chapter 6). In addition, laminated glass is required in any application sloped off the vertical more than 15 degrees.

At least two suppliers provide complete engineered and warranted systems, including glass and all hardware. These are good options, but they are expensive. With a qualified glass engineer on the design team, a viable alternative is to specify an off-the-shelf hardware system and a glass supplier offering a point-fixed glass product. Over the past decade, many fabricators of hardware systems including point-fixed glass components have emerged with catalogs full of products. Glass supply for drilled point-fixed applications has been more problematic. For many years, the large majority of point-fixed glass came from just a few European sources. However, more glass fabricators have entered this market in recent years, providing local and economical sources of perforated glass.

Facade system movements must be accounted for as part of the structural analysis, and the connection system must be designed to accommodate these movements. This sometimes requires the development of customized hardware systems. Tension structure designs for facade applications have grown consistently lighter and more flexible, resulting in greater deflections under design loads. Double-curved cable nets can exert significant warping forces on glass panes. Finite element analysis (FEA) of the structures must incorporate similar analysis of the individual glass panels.

The holes add to the cost, requiring drilling and countersinking of the glass panes, as well as the insertion of a sealing ring around the bolt hole to maintain the hermetic seal in the case of an IGU. Each laminated pane or IGU requires the drilling of at least eight holes. Insulated-laminated panes require a minimum of 12 holes. An alternative clamping strategy eliminates the necessity for perforations in the glass but presents other cost considerations.

Point-fixed Clamped System

An alternative strategy that eliminates the need for perforations and instead clamps the glass at the perimeter is the point-fixed clamped system (sometimes referred to as a *pinch-plate system*) (Figure 2.10). Clamped systems present certain advantages that may translate into greater economy. The additional glass fabrication processes associated with perforated systems are eliminated. Clamped systems also provide looser tolerances and are consequently easier to fabricate and install (Table 2.7). However, the resulting economies may be at least partially offset by the cost of the clamping hardware, which tends to be more complex and costly than the glass bolt systems. Off-the-shelf systems are less common, sometimes requiring the development of a custom hardware system that adds cost.

TABLE 2.7 Point-fixed Clamped System

- Provides transparency on par with point-fixed drilled systems
- Glass can be lifted off the supporting structure
- Eliminates the need for and cost of drilled holes
- Clamp plates may be visible on the exterior glass surface
- Off-the-shelf systems are less readily available
- Hardware cost may be higher than with glass bolt systems
- Butt-glazed silicone joints throughout
- Eases the glass supply requirements
- Eases the high-tolerance installation requirements for the backer structure
- Potentially lower-cost alternative to point-fixed perforated systems

FIGURE 2.10 A point-fixed clamped glass system requires no perforation in the glass. A blade penetrates through the silicone joint to support the glass dead load. An exterior cap plate secures to the blade to fix the glass.

The intent of this system type is to provide all the attributes of point-fixed perforated systems without requiring the holes. Although the means can vary, conceptually the spider component of the drilled point-fixed system is rotated 45 degrees such that the blades align with the glass grid. A thin web plate passes through the joint, which receives a top plate, effectively clamping the glass to the spider. There is a difference in the way the glass is supported. With the drilled point-fixed systems, the glass panel is typically hung from the top spider connection and allowed movement at the bottom. The reverse is true for the pinch-plate system; the pinch plates at the bottom of the glass panel support the dead load of the panel, while it is provided movement at the top.

Another clamping strategy, frequently employed on cable nets, is to set the glass into a specially designed vertex clamping component fixed to the supporting structure; a single component acts to clamp all glass corners at the vertex. A cover plate is then attached over the outside corners of the glass, effectively clamping adjacent glass corners. Neoprene pads are used on both faces of the clamp to isolate the glass from direct contact with the metal.

Glass specification and supply is a less important issue with this system than with drilled systems, simply because there is no requirement for special fabrication processes, such as drilling, countersinking, and the sealing of perforations in an IGU. The glass is still point-fixed in application, however, and subject to the same engineering analysis as a drilled panel, as well as the glass fabricator's requirements for point-fixed applications, including limits to deflection. Considerations of and requirements for heat treatment are the same as those for glass bolt systems.

Hardware systems range from machined and/or cast stainless steel components to simple metal plate systems. Care must be taken in the design of the clamping system to ensure that the designs conform to budget requirements. Custom hardware designs benefit greatly from the early involvement of the fabricator during the design process. No glass manufacturer offers an engineered and warranted pinch-plate glazing system, as Pilkington does with its Planar system. Facade hardware fabricators offer limited clamping-type systems, but their product lines are growing constantly. Novel SGFs may necessitate the design of a clamping system customized to the project's requirements. While this is also true of the glass bolt systems, there are currently few off-the-shelf options available for the clamped systems. Glass providers are more readily available than they are for bolted systems because of the elimination of the need for perforations in the glass.

Suppliers and Warranty Issues

Warranty considerations are important with point-fixed glass systems. Material warranties typically follow the supply chain from supplier up through the subcontractor chain to the general contractor and ultimately the building owner. Some of the warranties are accepted as *pass-through*, meaning that the building owner will directly hold a warranty from a material supplier. Increasingly, the owner is looking for all subcontractors in the chain to also warranty their scope of work. If facade glass proves to be defective and the glass supplier agrees to provide new glass, who pays for the installation? Many such questions emerge with warranty issues.

There is a difference between a product warranty and a system warranty. Many products may be involved in an SGF: a fabricated steel structural system, metal castings, glass panels, a glass-fixing system and components, and silicone sealant are common items. Several contractors may be involved in the installation of the facade: one for the steel structure, another for the glass, and still another to apply the weather seal. This can provide a confusing picture to the building owner contemplating his or her liabilities. The result has been an increasing requirement for one of the players in the implementation of an SGF to provide a system warranty.

A system warranty covers the overall performance of the glass system, or sometimes even the entire facade including the structural system. What is so compelling in this approach is that it eliminates the possibility of blame shifting, as when a glass panel breaks and the glass supplier blames a faulty installation. With a Pilkington system, everything is provided under a single umbrella warranty. Pilkington pioneered this approach with their Planar point-fixed glazing system, providing a 12-year system warranty covering the design, engineering, and material for the glass and fixings, as well as their application on the given project. This warranty stands as the best in the industry. Eckelt Glas typically offers a warranty of up to 10 years, as do some of the other Saint Gobain companies; these warranties have been known to equal Pilkington's warranty in certain instances. Alternatively, an increasing number of specialty subcontractors are willing to assume liability for the facade system's performance and provide their own extended system warranties. There are important qualifications and conditions to these warranties, and both manufacturers' and subcontractors' warranties should be carefully studied as part of the procurement process.

There is a certain premium cost associated with a system warranty, and a pass-through strategy is a cost-saving alternative. The risk profile of each individual project must be considered. An SGF project with innovative content may call for the additional expense of a full system warranty. For less aggressive SGF projects, locally procured materials and services and pass-through warranties of lesser duration may easily suffice.

Chapter 3

Linear Structural Systems

Mullion Systems

Mullion systems are built up from simple linear structural members employed as a structural mullion, or strongback (Table 3.1). The systems can range from elegant simplicity to extreme complexity, with considerable design diversity. While the inherent spanning capacity may be somewhat limited because of the relatively shallow member sections typically employed, novel design strategies such as cable staying of the structures have resulted in remarkably minimalist structures and elegant facades (Figure 3.1).

TABLE 3.1 Mullion Systems

- Simple open or closed steel sections or custom built-up sections are typical
- Transparency decreases as span increases and sections deepen
- If used in multistory applications, the glazing system must be able to accommodate the full range of building movements and deflections
- No prestress loads typically; tributary loading only
- Can be used in combination with long-span facade systems in shorter-span areas to provide a uniform building facade
- Efficiency decreases as span increases beyond approximately 20 to 25 ft (7 to 8 m)
- Potentially high relative value in shorter-span applications

Mullions are traditionally vertical members that separate glass panes, but today *vertical mullions* and *horizontal mullions* are commonly used industry terms in reference to the orientation of these framing elements in the building facade. They can be used in simple floor-to-floor spans, as required to support exterior facade elements, or as part of hierarchical framing systems involving other mullion or truss member types. Mullions can be comprised of plates, or simple steel or aluminum open or closed sections with provisions for the attachment of the glazing system and end connections. Square or rectangular tubes provide a useful flat surface for the attachment of veneer glazing systems. Steel plate mullions can be designed to present a minimal structural profile. Alternatively, aluminum extrusions can easily accommodate a unique section profile and be designed to facilitate the attachment of a glazing system. An example of an innovative facade product that has adopted this approach is the VS-1 system.[1]

Mullions can also be designed with improved sections having increased structural efficiency (Figure 3.2). Enhancements include multiple standard steel sections, such as two tubes or pipes, joined by continuous or, more likely, discontinuous web plates welded between the two sections. Developing truss action in the member moves it beyond a mullion and into the simple truss category described in the following section.

The glass fin system shares the basic morphology of a mullion system, although it is treated as a special case and discussed in Chapter 6. Glass fin systems are sometimes referred to as *glass mullion systems*.

As section properties increase with span, the strongback becomes increasingly inefficient from a material utilization standpoint in comparison to a simple truss. The designer must determine when to use a mullion versus a simple truss based upon the

FIGURE 3.1 A vertical mullion system using a thin steel plate mullion with a minimal sight line. The clips at the side clamp the glass in place.

FIGURE 3.2 Curved horizontal mullions are suspended from stainless steel rods located on the vertical glass gridlines.

variables of application, among them span, design loads, depth constraints, budget, and aesthetic considerations. Mullions of fabricated steel should receive a premium finish, and unless the interior surfaces are galvanized, it is advisable to hermetically seal tubular members with a welded plug at either end to prevent moisture from condensing in the tube, which can result in red rust dripping from the tube, staining nearby materials and finishes. This is not a problem with extruded aluminum, which typically requires no special treatment of the component cavity.

Truss Systems

Truss systems are structural designs utilizing trusses, most often planar trusses, as the primary structural element. A hierarchy of truss designs and sizes, as well as other structural components such as mullions, glass fins, and cables, may be incorporated into a truss system design. Traditionally, trusses have been used primarily in long-span roof structures, often hidden from view in the finished architecture. Their application in the support of structural glass facades (SGFs) is more recent, and the new context brings variation to the aesthetic and performance criteria driving form, producing a new class of truss system designs.

Trusses are an element of the building structures' vocabulary. In their most common form, they are a refinement of the more fundamental linear beam or column element, dividing the element in a direction perpendicular to the bending plane into two discrete top and bottom chords separated by interstitial diagonal elements forming a pattern of triangular openings. In fact, the most basic form of truss is a single triangle, the only geometrically stable simple polygon. Two poles anchored at one end to the ground and tied together at their tops comprise the primal truss, one that certainly predates recorded history. Refinements were a long time coming; such incremental improvements as king post and queen post trusses date from the Middle Ages, used in primitive roof and bridge construction. Truss bridges were illustrated by Palladio in his treatise *I quattro libri dell'architettura* (*Four Books of Architecture)* during the sixteenth century, and the evolution of the timber truss in the seventeenth and eighteenth centuries is largely rooted in this work.

It took the Industrial Revolution and the progress made in the development of materials, processes, and construction techniques during the nineteenth century to provide the technological basis from which contemporary trusses and truss-based structural systems would emerge. Iron and steel trusses were seldom, however, purposely used as expressive elements of building design. While their use as part of the building structure increased dramatically well into the twentieth century, they were most often hidden within the building envelope. Notable exceptions include the milestone Crystal Pavilion at the Century of Progress Exhibition in Chicago by George and William Keck (1934), which effectively presaged the so-called Hi-Tech architecture to emerge decades later, followed by the Eames House in Los Angeles (1949), where design innovators Charles and Ray Eames used off-the-shelf industrial components to such dramatic effect, including exposed planar steel trusses. Also in Chicago, the Hancock Tower, by Skidmore, Owings and Merrill (1970), provides a novel expression of the building structure as the diagonal bracing of the high-rise building is revealed (but not actually exposed) strikingly in the building facade. It was ultimately the European architects who brought the practice of integrating exposed structure into the building design to the forefront of architecture in the second half of the twentieth century with such landmark projects as the Center Pompidou in Paris (1977) by Renzo Piano and Richard Rogers and the Lloyds Building in London (1986) by the Richard Rogers Partnership.

Some of these early exposed structural systems were cable-stayed and suspended roof structures drawing inspiration from long-span bridge design and technology, such as in the Fleetguard Factory by the Richard Rogers Partnership (1980) and the Oxford Ice Rink by Nicholas Grimshaw (1984). Such high-profile projects began to introduce a vocabulary of cable-based structural systems to a broader audience of building designers. Ultimately, mast structures and guyed towers served as prototypical examples for facade designers looking for new techniques to support long-span glass facades.

Transparency

The pursuit of transparency in the building envelope has been a primary driver of SGF technology, although by no means the only one, and the relative importance and manifestation of transparency vary widely among projects. The result, in any case, has been an ongoing dematerialization of structure, achieved largely through an increasing predominance of tensile bracing elements in closed, freestanding systems and the extensive use of open systems comprised mostly or completely of tensile elements. More and more, however, the *control* of transparency as a means to manipulate daylight and view is becoming the predominant concern, and not simply the maximization of transparency with no regard to issues of thermal performance, daylighting, and glare. Nonetheless, the consideration of facade transparency remains relevant and the maximization of transparency a design intent on many projects. The structural system plays a defining role in the perceived transparency of any long-span glass facade design. Here the structural systems are characterized by their relative attributes of transparency.

Dematerialization of Structure

Transparency in the SGF has become strongly associated with the dematerialization of structure. The primary strategy in achieving dematerialization of the structural system involves the use of tension elements as part of the design vocabulary. This is consistent with a strategy of efficiency and sustainability: doing more with less material. The following steps were initially recommended as a means to improve the economic efficiency of a truss,[2] but they in fact describe a methodology characteristic of the progressive dematerialization of structure and the pursuit of transparency:

1. Minimize the length of compression members.
2. Minimize the number of compression members even if the number of tension members must be increased.
3. Increase the depth of the truss as much as is practical; this will reduce the axial forces.
4. Explore the possibility of using more than one material in the truss, one for compression and another for tension.

Transparency in this context is primarily a matter of reducing the structural profile of a facade design. A structural system designed such that certain elements encounter only axial tension forces allows those elements to be significantly reduced in section area from elements designed to accommodate compression and bending loads. A 4 in. (100 mm) diameter tube or pipe element can potentially become a ⅜ in. (10 mm) rod or smaller, significantly reducing the element profile. The overall effect can be quite dramatic. There are several theoretical reasons for this, but the simplest is that buckling disappears as a phenomenon of structural failure. The steps outlined above thus become a strategy for optimizing structural transparency. The cable-supported systems abandon compression elements entirely.

Expression of Structure

SGFs are not exclusively about the dematerialization of structure, however; far from it. Nor is the perception of transparency some linear function of the structural profile of the supporting system.

Many examples of SGFs, in the long tradition of the art of structure, as reviewed in Chapter 1, celebrate structure by developing the structural system as the focal expression of the facade design. The expression of structure tends to heighten the perception of transparency in the glass skin. Transparency becomes an effect of the interplay of light, structure, and membrane.

Structure and Membrane

A long-span glass facade is perceived in layers of membrane and structure. The glass skin, even a skin of the most optically clear glass, is not transparent after all, but a reflective, semitransparent luminescent membrane involved in a complex interaction with the surrounding environment: sky, buildings, streetscape, and people. This is the dynamic beauty of the material. Were it possible to make glass truly transparent, to make it disappear, the perception of membrane would be lost along with much of the engaging aesthetic of the glass facade. The glass does not disappear but is perceived as membrane, and is perceived as transparent because of the things that can be seen through it, such as the supporting structural system. Most SGFs register visually as a combination of structure and membrane. A deep truss system with dominant and expressive truss elements is perceived largely as a layered depth of structure. Even glass fin walls reveal a layered depth that speaks to both membrane and structure. Cable-supported structures, in contrast, become much more about membrane as the structure disappears into the surface.

Glass Selection

Glass selection is another design decision that significantly impacts facade transparency. Highly reflective glass coatings can render a facade completely opaque, with all of the view through the glass masked by veiling reflections. Such a facade will read as pure membrane from the exterior under most lighting conditions, as is the case with the Willis Faber & Dumas facade discussed earlier; as lighting conditions reverse to become brighter inside than out, glass transparency will also reverse, becoming more transparent from the outside and less from the inside. Antireflective coatings on superclear (low-iron) glass reduce reflections and maximize transmittance, thereby heightening perceived transparency. The use of laminated and especially monolithic glass minimizes site lines on the glass grid, also amplifying the effect of transparency.

Heightened transparency, however, is opposed to other important aspects of optimization in glass performance, thermal in particular. The designer must balance facade system transparency with the need for thermal performance, a balance that will vary considerably among projects as a function of use, local climate, and energy usage goals. An SGF can be an energy hog requiring oversized mechanical equipment to compensate for excessive heat gain or loss, or used as part of a whole-building energy strategy to minimize energy consumption. It is all a matter of design. More tools, materials, and techniques than ever before are available to the designer to achieve the desired balance between aesthetic and performance considerations. Unfortunately, too many highly transparent facades have been designed with no consideration of thermal performance beyond the sizing of the heating, ventilation, and air conditioning (HVAC) system. This situation is rapidly changing in the press of escalating energy prices, the spreading influence of the LEED program, and a growing mandate for reduced energy consumption in buildings.

The Serres at Parc de La Villette

Interest in the expression of membrane and transparency was growing in this same time period, as evidenced by the increasing application of glass fin walls inspired in large part by the Willis Faber & Dumas Building completed in 1975, as discussed in Chapter 1. In 1980, French architect Adrien Fainsilber won a competition for the design of the National Museum of Science, Technology and Industry at La Villette. The design included three large glass facades (*serres* in French) with which Fainsilber wanted to explore transparency and strength as material properties of glass, with the design intent of emphasizing the lightness and transparency of the facade structures in their entirety. His reference was the state-of-the-art suspended glass facade technology used on the Willis Faber & Dumas Building.

After winning the competition, Fainsilber invited Peter Rice to work with him in developing a solution for the Serres project. Rice was the engineer, with Arup at the time, who worked with Rogers and Piano in developing the structural systems for the Center Pompidou. Rice had just ended a partnership with Piano when he received the invitation from Fainsilber and agreed to take on the Serres project. He subsequently established the consulting firm RFR (Peter Rice, Martin Francis, and Ian Ritchie). Martin Francis had been the facade designer for the Willis Faber & Dumas Building. Ritchie was an architect who had worked with both of them. Together they assembled an ideal team to advance the state of the art in glass facade technology, which they succeeded in doing with the completion of these landmark facades. The firm continues to provide innovative facade designs today with a new crop of young talent, operating primarily in Europe and Asia.

RFR initially considered employing a variation of the system used for the Willis Faber & Dumas facade, a suspended system with a vertical glass stiffening mullion and patch plates at the corners of the glass panes to clamp them in place. The Serres team, however, recognized that the layering of glass elements acts to diminish perceived transparency in anything but a straight-on view and ultimately rejected this solution. They also sought to eliminate any attachment mechanism penetrating the glass plane, providing for a continuous, uninterrupted glass surface. Peter Rice recognized that a cable truss could be used as a stiffening element in place of the glass fin, what he referred to as a "cable mullion."[3] He also realized that the cable truss could be used as a horizontal rather than a vertical element, spanning between the columns of a stainless steel pipe frame structure, to further the transparency effect (see the case study in Chapter 8 for another example of this approach).[4]

The glass fixing was accomplished by the development of a novel fastener that included a ball-bearing fitting within the glass plane. Referred to as a *rotule fitting*, the ball bearing provides unrestricted rotation as the glass panel deflects under wind load, thus eliminating bending loads to the glass in the vicinity of the fitting. The glass was perforated and countersunk to receive the fitting, thus preserving an uninterrupted exterior glass surface. The glass in this facade design is used to provide rotational stability to the cable trusses, thus representing one of the early uses of glass as a structural material. This seminal work is covered in engaging detail in Rice and Dutton's book *Structural Glass*[5] and highlights the remarkable contributions of RFR to SGF technology, including many interesting case studies.

Truss Systems in SGFs

Planar trusses of various types and configurations can be used to support glass facades. The most conventional application is a single-truss design used as a vertical element, with the depth of the truss perpendicular to the glass plane. The trusses are positioned at the vertical seams of the glazing grid, which is frequently aligned with a building gridline or some uniform subdivision thereof. The truss spacing must be carefully determined as a function of the glass grid. Collectively, the trusses and related structural elements comprise a truss system. A truss system may include multiple truss types and embody a hierarchy of components.

Primary trusses, for example, can be separated by one or more cable trusses to heighten the system's transparency. A horizontal tensile system may be included to brace the primary truss elements against lateral buckling. Alternatively, lighter simple trusses or mullions may span horizontally between widely spaced primary vertical trusses, providing lateral support and attachment for the glazing system.

The pursuit of transparency combined with the expression of the structural system has produced increasingly novel and elegant truss system designs. Architecturally Exposed Structural Steel (AESS) specifications have been developed to control the visual quality of the steel fabrication work, including welds and surface finishes. Connection details are refined, with custom-machined stainless hardware or with joint designs that conceal the hardware. Employing a strategy of substituting tensile elements for compression members, minimalist planar truss designs have been developed in which triangulation is achieved by tensioned cable-crosses replacing larger-diameter tension/compression tube or pipe members. The truss systems are typically designed to carry facade dead loads and lateral live loads, but roof loads are carried by a primary building structure separate from the facade structural system. In some projects, trusses have even been hung from above to facilitate dematerialization of the truss system.

Steel truss systems are easily designed to accommodate any of the glass or glass system types discussed in Chapter 2. The integration of the two systems is a design consideration. Layering or stacking systems without thinking about how they will work together can result in a less efficient design. The capacity of the structural system to support the glass system and applied loads should be fully developed. The glass system can often be effectively integrated with the structural system to improve efficiency, thereby minimizing the structural requirements of the glass system. Glass curtain wall systems have been applied to exposed truss systems without fully utilizing the capacity of the structural system, resulting in a needlessly heavy glass system. For example, a square or rectangular tube can be used as the outer chord of a truss. The same or a similar section can be utilized as a horizontal mullion spanning between the trusses on the glazing grid. The resulting truss system presents a high-tolerance exterior grid of flat steel matching the glazing grid. This surface grid can then provide continuous support to a minimal veneer glazing system, thereby providing a high level of functional integration between structure and glazing systems. The result can be an economical solution to a long-span glass facade, and while this is not the most transparent of systems, effective relative transparency is achievable. A similar approach can be used with any of the planar truss types.

The glass system can also, however, be spatially separated from the supporting structure for visual effect. This acts to visually lighten the facade and enhance perceived transparency. Facade truss systems are most frequently vertical in elevation and linear in plan, but they can easily be sloped inward or outward and follow a curvilinear geometry in plan. Truss elements can also be manipulated to provide a faceted glazing plane. Truss systems can incorporate other structural elements, such as the horizontal mullion discussed above. Glass fins, cables, alternative truss types, and even cable nets can be incorporated as hierarchical elements within a facade truss system.

The application of trusses as part of a glass facade system brings other considerations; the glazing plane and grid will dictate certain geometric parameters of the truss system, deflection criteria must be considered, limitations in the design of boundary supports may eliminate certain system types, and the intended glass system must be evaluated in terms of the supporting structural system. However, aesthetic considerations are always in play and are often the primary design driver. Long-span facades make use of exposed structural systems. The trusses are typically custom steel fabrications with an emphasis on elegant structural system designs, highly crafted system components, and a general dematerialization of the structure in an effort to enhance overall system transparency. The basic truss types that will now be discussed include simple, mast, and cable truss designs.

Simple Trusses

The truss systems using simple truss types (Figure 3.3) are adaptable to a broader range of facade program considerations than the cable-supported systems. They can be expressed as highly crafted fabrications with refined connection detailing and material finish or present a more industrial aesthetic (Figure 3.4). A relatively high degree of transparency is achievable, with potential economic advantages over other system types (Table 3.2). Control of facade transparency is facilitated by the ease with which steel truss systems can accommodate louver and shade systems, integrated light shelves, awnings, and panels. These systems provide good design flexibility when it comes to the configuration and articulation of the overall facade system. See Chapter 7 for an example of simple trusses.

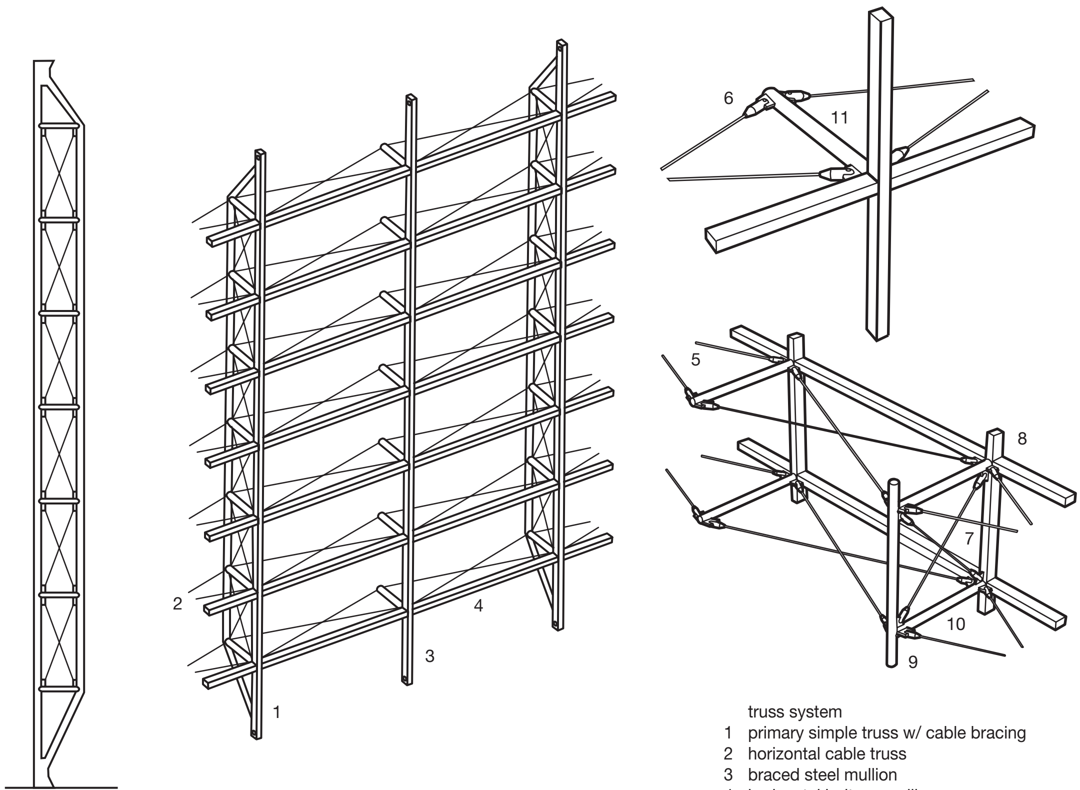


FIGURE 3.3 Truss system diagram with a vertical simple truss and a horizontal cable truss.

TABLE 3.2 Simple Trusses

- Aesthetic appearance varies widely, depending on truss and truss system design
- Moderate transparency relative to other structure types; varies widely based on truss and truss system design
- Highly versatile; system variations and hybrids are easily developed
- Very flexible in accommodating a variety of glazing systems, spans, forms, and form articulations
- Best system to accommodate loading and connection of add-on components (integrated sunshades, awnings, canopies, louver systems, entry portals, etc.)
- Mature technology
- Span/depth ≈ 15
- No prestress loads, tributary loading only
- Deflections = L/175 typical
- Reactions relatively low; systems can be hung or base-loaded
- Relative economy is largely attributed to ease of installation
- High relative value at a loss of some transparency compared to tension-based systems
- High potential for developing a low-cost solution

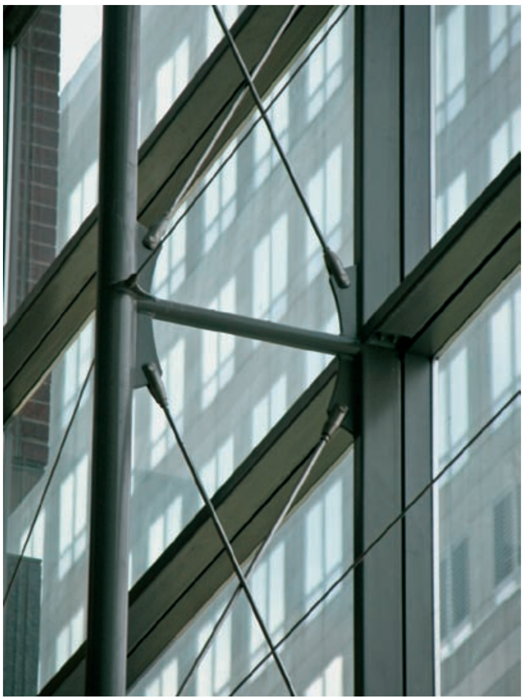


FIGURE 3.4 Detail of a simple truss system with cable bracing and an emphasis on craftsmanship.

Simple planar trusses in facade applications can assume a variety of geometric configurations, including variations of Pratt, Warren, and Lenticular trusses. The flat truss with parallel chords separated by interstitial web members is the most common in facade applications and can be used in a vertical or horizontal orientation. The arrangement of the web elements separating the truss chords can also vary. A lamella truss configuration is a common design for glass facades; a welded spacer strut perpendicular to the chord members forms orthogonal spaces that can be stiffened by a cable-cross, thus minimizing the truss profile. Truss design is a function of the structural considerations of span, loading, pitch, spacing, and materials.

Simple trusses and the truss systems incorporating them can range widely in complexity. Aesthetically, a truss system usually provides a more explicit expression of structure than a cable-suspended system, where the structure becomes so minimal that the expression becomes one of pure membrane. Strategies to lighten the structure and enhance facade transparency generally add to the system's complexity and cost, even as they reduce the total weight of material and improve facade structure efficiency. The detailing of trusses and truss systems also varies widely (Figure 3.5). Connections and hardware can be expressed as part of the structure design or concealed.

Truss system surface geometry is largely unrestricted, more so than with any of the other structure types discussed here. The simple trusses can be sloped, curved, faceted, dished, or stepped, all with relative ease, or developed into frames and arches to provide complete facade enclosures. Simple truss systems are the most flexible and adaptive to a range of design objectives, interface systems, and add-on components.

Trusses in the 30 to 70 ft (≈ 9 to 20 m) range are usually the most economical. Longer spans are achievable, but the cost increase that typically occurs as a function of span will often accelerate as the spans grow beyond 70 ft (≈ 20 m). Truss depth is optimized as a function of truss spacing, span, and design loads. Truss design becomes more complex if there is pressure to minimize the depth of the system. Most truss designs are statically indeterminate; the facade design must ultimately be analyzed as a whole system in the form of a three-dimensional computer model, utilizing an iterative process aimed at system optimization. The span-to-depth ratio for this structure type typically ranges from 10 to 15, with a deflection criterion of about L/175. Pretension requirements for tensile elements in simple truss systems are typically minimal and may merely include the snug-tightening of cable or rod components. Trusses can be hung or base-loaded. Hung trusses can be lighter but require heavy steel overhead support. Systems are typically base loaded and not designed to support the roof, meaning that the truss-top connection detail must be designed to transfer out-of-plane lateral loads from the facade to the roof structure but not pick up any vertical dead or live loads from the roof structure. Roof deflections relative to the facade must be carefully analyzed. Reaction loads are in the normal range for any long-spanning closed system as a function of the tributary area of the spanning elements.

Simple trusses are moderately efficient as structural systems. They tend to be stiffer than truss types that incorporate more tensile components. This stiffness reduces deflections compared to cable trusses or cable-supported structures, and provides more lateral restraint to resist wind and seismic loading.

Simple trusses are most often welded steel fabrications. Craftsmanship can be a significant concern; while many steel fabricators are capable of welding planar trusses, far fewer can provide the level of visual quality typically sought for the architecturally exposed structural systems included in SGFs. Craftsmanship requirements will vary from one facade application to the next as a function of the proximity of the exposed fabrication to the viewer, the aesthetic intent, the facade budget, and other factors. If craftsmanship is a primary consideration, a fabricator with experience in AESS practice should be sought and an appropriate AESS specification prepared to guide the fabricator.

Mast Trusses and Guyed Struts

Cable and rod rigging systems derive from the sophisticated structural technology of nautical architecture, especially as developed during the eighteenth and nineteenth centuries by the navies of England, France, Holland, Spain, and Portugal. Their influence first emerged in bridge design and later in architecture and continues today; the cold-headed high-strength stainless steel rods used as tensile elements on the Grand Serres and Louvre Pyramid structures are technology borrowed from the modern racing yacht

FIGURE 3.5 A simple truss system combining vertical truss elements with horizontal cable trusses.

industry. Mast trusses are visually reminiscent of these naval origins.

TABLE 3.3 Mast Trusses and Guyed Struts

- Mast trusses can be quite elegant as exposed structure
- Increased transparency over the simple truss achieved by lifting the glass surface off the structure and increasing the use of tensile elements in the truss design
- Diversity of form is trickier than with simple trusses but achievable within limits
- Considerably less flexible in accommodating interface systems
- Span/depth ≈ 15
- Pretension requirements limited to bracing elements and vary as a function of truss size and capacity
- Deflection = L/140 to L/175
- Reaction loading based on the simple tributary area of the truss element
- Trusses can be delivered to the site preassembled
- Trusses require care in handling, shipping, and installation
- Trusses require care during installation to achieve appropriate tolerances

Guyed struts or mast trusses are closed systems that use tensile elements to stabilize a central compression element (mast), usually a tube or pipe section (Table 3.3). The cables attach at or near the mast ends and incrementally at the ends of bracing struts or *spreaders*, compression elements attached at intervals along the length of the pipe. The spreaders increase incrementally in length toward the longitudinal center of the mast, thus giving the required shape to the cable run between mast ends (Figures 3.6 and 3.7). See Chapters 8 and 9 for examples of guyed struts and mast trusses.

Two, three, or four of these cable arches can be spaced with radial symmetry about the mast, increasing the buckling capacity of the mast and allowing for the use of a smaller mast section. The mast truss represents an incremental step toward greater transparency by resolving the compression loads in a single central element that is incrementally braced, thereby effectively reducing

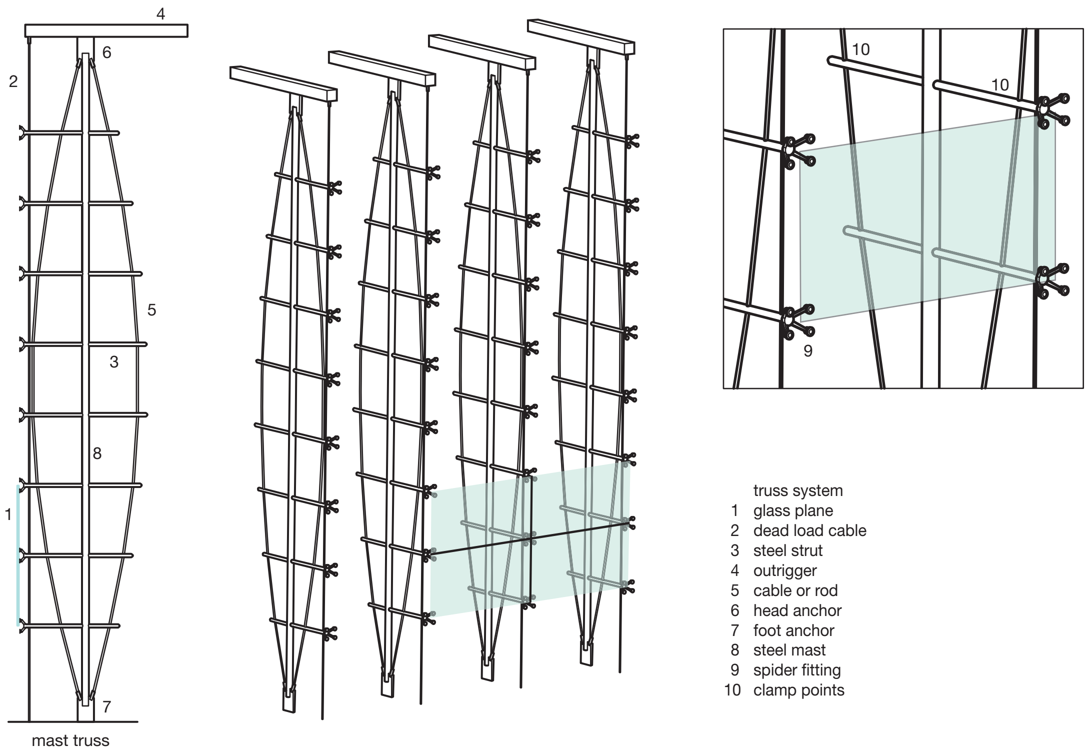


FIGURE 3.6 Truss system diagram with mast trusses.

the spanning distance and allowing for a slimmer profile.

A planar mast truss stiffened by two cable arches 180 degrees opposed can be used as a primary truss element in an SGF. The glass plane can be located in the plane of the masts, placing one of the cable arches on the inside and one on the outside. Alternatively, the spreaders on one side can be extended out to form a plane parallel to but offset from the mast plane, thus enclosing the entire truss system within the facade envelope. The glazing plane is most often located to the outside to provide the facade structure with protection from the elements. Facades have been built with the structures exposed, in which case materials and material finishes must be carefully determined with respect to exposure and maintenance requirements. It is possible to clad both sides of a mast truss system to create a double-skin facade. Some form of lateral bracing of the truss system, which may be as simple as a horizontal cable running through the system, can be fixed to the strut end opposite the glass plane and anchored at the facade perimeter.

This system was used in the construction of a dual-skin facade for the U.S. headquarters of a Japanese automobile parts manufacturer (Figure 3.8). In this case, the mast truss system supports only the outer skin of the cavity, with a simple window wall system comprising the interior skin. The 5 ft (1.5 m) cavity is conditioned to act as a thermal buffer to the building's interior and as part of the building's ventilation system. The same truss system is expressed in the building's lobby without the inner skin (Figure 3.9).

Mast trusses typically present a structural aesthetic somewhat less predominant than that of simple trusses but more so than that of cable trusses or cable nets. Some designers prefer strongly

FIGURE 3.7 Mast truss detail during construction.

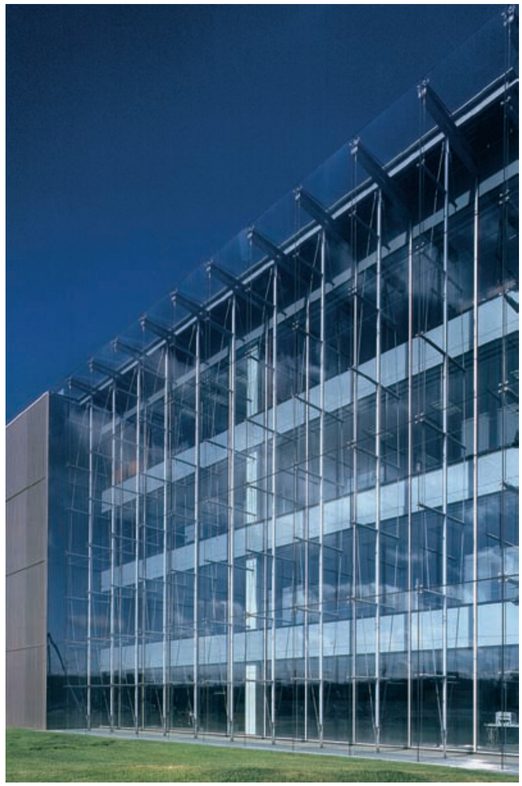


FIGURE 3.8 Yasaki North America, Canton, Michigan, 1998, Skidmore Owings & Merrill. The mast trusses support the outer skin of one of the first double-skin walls.

expressed structure in order to feature the structure rather than minimize it. This system provides an excellent opportunity for this kind of aesthetic treatment. The transparency of mast truss systems is generally higher than that of simple truss systems, largely resulting from lifting the glazing plane away from the structure mass, in this case the central mast element. This has the effect of lightening the structural system and increasing the perception of a transparent membrane.

Sunlight control issues become more problematic with this type of truss system, as mast truss designs tend to be somewhat less accommodating than simple trusses to integral add-on systems such as awnings and louvers. Form variation in the facade is also more challenging than with simple trusses. Consequently, most applications of this system are relatively simple in overall form; significant variation is achievable but with more constraints. Truss

FIGURE 3.9 The mast trusses are left exposed in the lobby area of the office building.

designs at the interface between geometry changes, as at corners where load transfers occur, can become complex.

Simple truss systems typically support the glass dead loads; the glass is hung from the truss structure. With mast truss designs, the glass plane is often located at the extent of a cable stay, with the spreaders extending out to define a glass plan parallel to the mast. The vertical dead load of the glass is typically carried by a suspended cable running immediately behind the glass plane and supporting the ends of the extended bracing struts. This *dead-load* cable is hung from the building structure or from an outrigger designed for this purpose. The glass is thus suspended and restrained against out-of-plane lateral movement by the truss. Deflection due to the weight of the glazing on the overhead structure should be accounted for in the design and installation of the truss system. The glass system generally fixes to the extended ends of the truss spreaders that define the glazing plane. A spider or clamp can be located here for a frameless system, or the strut ends can support a structural vertical or horizontal mullion.

Mast trusses tend to be more flexible than simple trusses of similar design, yet somewhat more rigid than cable trusses. A deflection criterion of approximately L/140 to L/175 is most typical, while the approximate L/d of 15 is similar to that of the simple trusses. Pretension requirements are usually minimal and are limited to truss assembly. No prestress loads transfer to boundary structure, as mast trusses are closed-system types. Lateral bracing and stay bracing of the structural system may require pretensioning. As with the simple truss, mast truss systems are typically base loaded and not designed to support the roof.

Fabricated steel masts, welded or pinned spreaders, stainless steel rod or cable bracing elements, and hardware comprise the bulk of these systems. Truss fabrication is somewhat more challenging than with simple trusses, and tolerances become more critical. Assembly and installation also tend to be more complex. It is important that the spreader ends supporting the glass fixings are located to high tolerances during installation. This is relatively easily accomplished with respect to vertical and in/out tolerances through proper detailing. The vertical position of the spreader end can be adjusted at the dead load cable. In/out tolerances can normally be accommodated by an adjustable interface between the end of the spreader struts and the glass fixing system, such as a threaded fitting that can be positioned and fixed in place. The horizontal position of the spreader ends can be more difficult to fix, as the truss and spreaders are less stable in this direction. In fact, the glass can be used to stabilize the trusses and locate the horizontal position of the spreader ends if a perimeter vertical course of lites is accurately fixed in position.

Trusses should be prefabricated in the shop to the greatest extent possible. Truss assembly can typically be accomplished more efficiently, more accurately, and with less damage to finishes than in the field. Cables or rods should be positioned and tensioned, taking care to control truss deformations. Very lightweight trusses may benefit from a fixture to facilitate truss assembly and to hold the components in place. This strategy may not be workable if the trusses are incapable of holding their shape when removed from the fixture. For this reason, cable and rod components are sometimes installed in the field. Shipping may also be simplified if the tensile elements are not installed. A functional compromise is to partially assemble the tensile elements to the trusses but without tensioning them; this simple strategy can significantly speed costly fieldwork. In any case, field tensioning must be done systematically to control truss deformations during assembly, and the strategy for so doing should be detailed in an installation method statement. A full section of the structure should be installed and accurately surveyed to determine conformance with specified field tolerances before commencing installation of glazing.

Cable Trusses

The next step in the dematerialization of a truss is to remove the big compression member, or mast, from the previously described truss category. This leaves the spreader struts as the sole compression elements. This step has been accomplished at a price; the remaining components are no longer stable and cannot even stand on their own, much less carry any load. The solution is to tension the truss against an upper and a lower anchor structure (Figures 3.10 and 3.11). This represents a fundamental change in truss behavior from those previously described. Cable trusses must be prestressed, or externally stabilized, to function as load-bearing structural systems (Table 3.4). This type of truss can be referred to as an *open system* (Table 1.3). The preceding truss types were internally stabilized, or closed systems; stability was provided as a function of truss geometry, requiring no interaction from the boundary. See Chapters 10 and 11 for examples of cable trusses.

TABLE 3.4 Cable Trusses

- Significant dematerialization from closed truss systems
- Increased transparency over the mast truss by removal of the center mast
- Spacer struts are the sole compression elements
- Significant diversity of form is difficult to accommodate
- Interface systems are difficult to accommodate
- Span/depth ≈ 8 to 12
- Prestress is important as a design and installation issue
- Deflections = L/140 to L/175
- Prestress forces transferred to the anchor structure; high reactions may require heavy boundary steel
- Additional installation complexity

Cable trusses evolved from the suspended structures developed to support long-span suspension bridges, with examples dating back to the early nineteenth century and with more primitive forms existing centuries earlier. By the mid-twentieth century the technique had been adapted to buildings; the Dulles Airport Main Terminal near Washington, D.C. by Eero Saarinen with engineering firm Ammann and Whitney is a well-known example, with a cable-suspended roof tracing a catenary curve between rows of concrete pylons. Suspended structures rely on gravity loads to resist uplift and

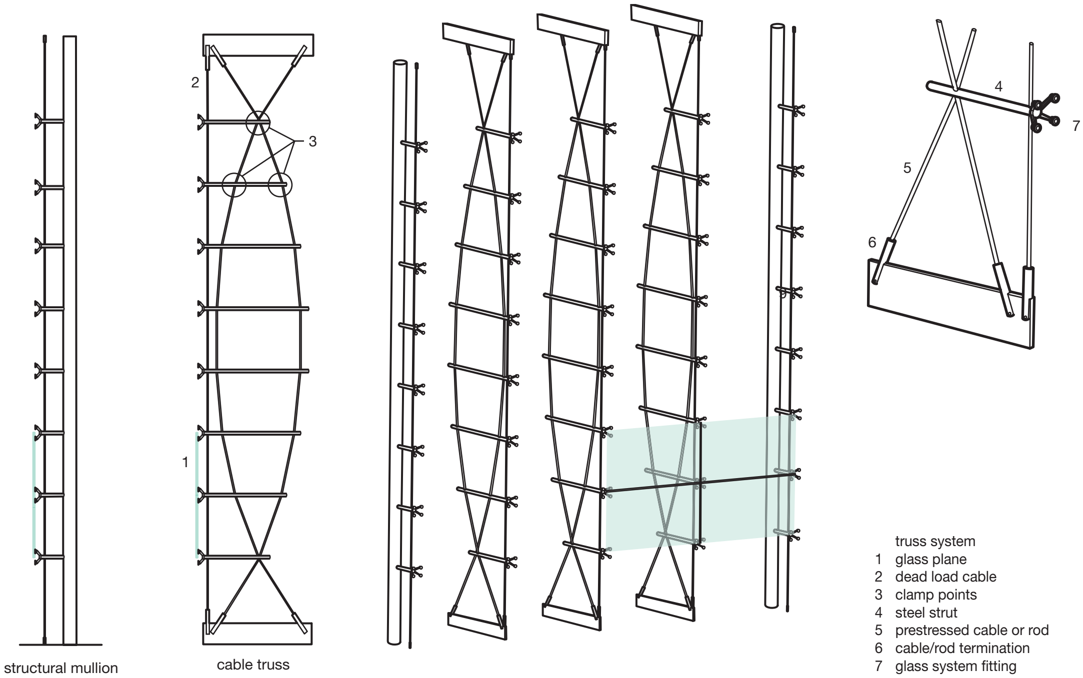


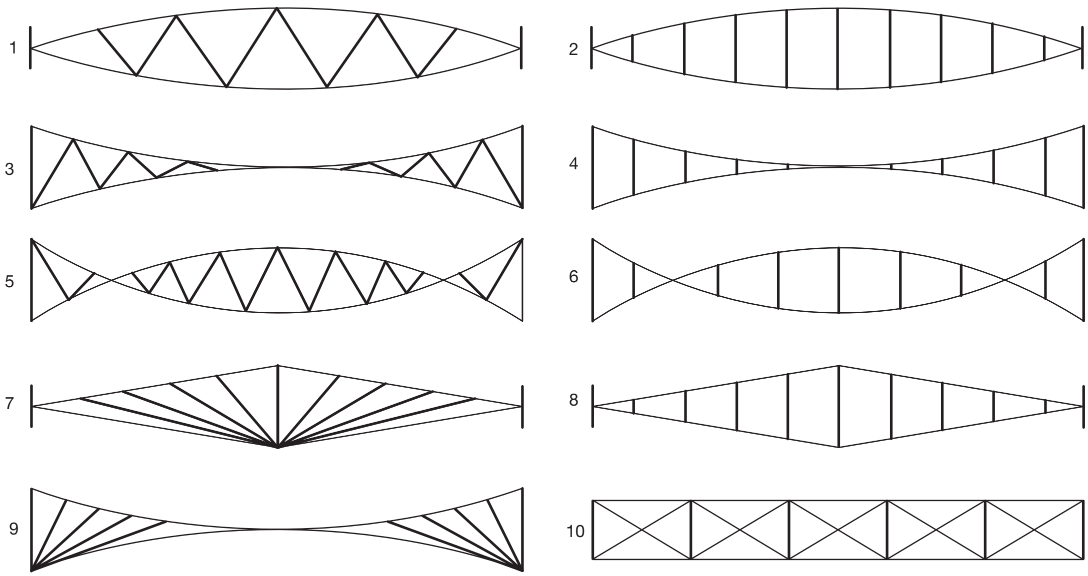
FIGURE 3.10 Truss system diagram with cable trusses.

FIGURE 3.11 Cable trusses span vertically between a pipe frame primary structure.

uneven loading conditions, and thus are unsuited for anything but horizontal structural designs. According to Professor G.G. Schierle, cable trusses were first developed in horizontal applications to stabilize suspended structures from wind uplift and unevenly distributed loads.[6] The tension cable line resisting dead load was duplicated, inverted, and integrated into the structure to form the cable truss. In the case of load reversals, as occurs with wind uplift, this inverted cable works to resist these loads. The cable truss thus becomes a structural system that functions independently of orientation and is applicable as a vertical structure. Variant derivations of this basic cable truss were in wide use as horizontal structures by the 1960s; in the United States, engineer Lev Zetlin developed cable truss roof structures for the Utica Auditorium (1959) in Utica, New York, and the New York State Pavilion at the World's Fair in New York City (1964), but it was decades before cable trusses were used in vertical applications as long-span glass-clad facade structures.

The cable truss provides enhanced transparency and a unique aesthetic to the facade as a minimalist expression of force. The only compression members remaining are the spreader struts that put the two tension paths into opposition. The inverted truss design (or *fish truss,* as it is sometimes referred to) effectively reduces the span and accommodates a shallower truss depth than that required by the mast truss. While alternative cable truss geometries are conceivable, lenticular and inverted geometries with horizontal compression struts are most common. Similar to the mast truss, spider or other fitting types can be positioned at the end of the extended spreader struts to fix the glass. More conventional panelized glazing systems can also be accommodated. Cable trusses are sometimes positioned horizontally (with the truss still perpendicular to the glass plane) between vertical mast trusses in a hierarchical scheme (Chapter 8).

Schierle identifies the variations in Figure 3.12.[7] Removing the primary compression element and backbone of the mast truss leaves an unstable and formless collection of cables and struts. The anchor structure must be capable of carrying the reaction



Cable Truss Types
1. Lintel truss with diagonal compression braces
2. Lintel truss with vertical compression struts
3. Concave truss with diagonal tension braces
4. Concave truss with vertical tension struts
5. Concave/lintel truss with diagonal compression braces
6. Concave/lintel truss with vertical compression braces
7. Concave gable truss with radial support and stabilizing cables and central strut
8. Concave gable truss with tension struts and central compression strut
9. Concave support cable and fan stabilizing cables
10. Parallel chord truss, vertical compression struts and diagonal tension braces

FIGURE 3.12 Cable truss variations as identified by G.G. Schierle.

loads resulting from the prestress forces required to stabilize the cable trusses under design loads. Lateral in-plane forces are typically handled by a minimal horizontal cable network.

There are several important considerations in designing with open systems. Appropriate prestress forces required to stabilize the truss and control deflections under design loading conditions must be determined as part of the system design. These prestress forces must be balanced against the reaction loads that will be transferred to the boundary structure. The more deflections are limited, the higher will be the required system prestress and the higher the resulting reaction loading transferred to the boundary structure. Perhaps the predominant consideration in the design of an open truss system is ensuring that the boundary structure is designed to handle the reaction loads and that the effect is factored into the budget early in the design process. It is important to note that the loads generated from the prestress requirements are not intermittent loads, like wind or seismic loads, but continuously applied loads similar to dead loads.

Geometry transitions as occur at facade corners can result in significant complexity; corner trusses must resolve the in-plane lateral forces coming from each direction. As the systems become progressively more minimal, each element becomes increasingly important as an expressive structural element. As the sole compression element in the system and as a visually predominant component, the spreader provides an opportunity for expression. Truss head and foot configurations, as well as the spreader–cable connection, become prominent details.

The actual truss shape will be defined by prestress forces acting on the truss configuration and the mechanical properties of the components, and thus can only be exactly determined through a form-finding process. However, the exact shape of the trusses is usually of no particular importance with respect to the conceptual development of a cable truss system.

Facade surface geometry is more constrained than with simple truss systems. Surface form variations are possible within limits. More aggressive variation may require the development of a hierarchical structural system involving combinations of structure types (Figure 3.13).

Cable truss systems share topological similarities with mast truss systems. Spreader struts extending out to define the glass plane, similar to the mast truss systems, most often provide the glass system interface. The glass plane can be located on the inside or outside face of the truss system. A suspended dead load cable tied to the extended spreaders is used just behind the glass plane to support the weight of the glass. A spider fitting can be affixed to the strut end for the attachment of point-fixed glass as a transparency-enhancing option. Adopting a strategy discussed with the simple truss systems, a continuous square or rectangular tube section can be fixed to the strut ends to accommodate the attachment of a veneer system or virtually any of the glazing system options (Figures 3.14 and 3.15).

Cable trusses are the first example given here of an open, tensile-resistant system, in which tensile stress plays the predominant role in stabilizing the truss and resisting applied load. Compression elements are included in this system type as the spacer or spreader struts that give shape to the cable trusses. These compression elements are subject to buckling, and perhaps bending and shear, depending upon the system design, but the tensile forces are dominant and are the source of the increased efficiency of this structure type. Enhanced transparency accompanies this increased efficiency.

Span/depth (L/d) is typically in the range of 12 to 15, depending on load combinations, truss, and truss system geometry. These systems are sometimes designed for greater deflections; deflection ratios ranging from L/140 to L/175 have been used in past projects. Design prestress forces must be determined through analysis of the truss system, and will vary as a function of the truss system span and depth, the load requirements, deflection criteria, and boundary stiffness. These prestress forces will be realized in the field through a process of pretensioning the cable trusses. The prestress both limits deflection and prevents any of the tensile elements from going slack under design loading.

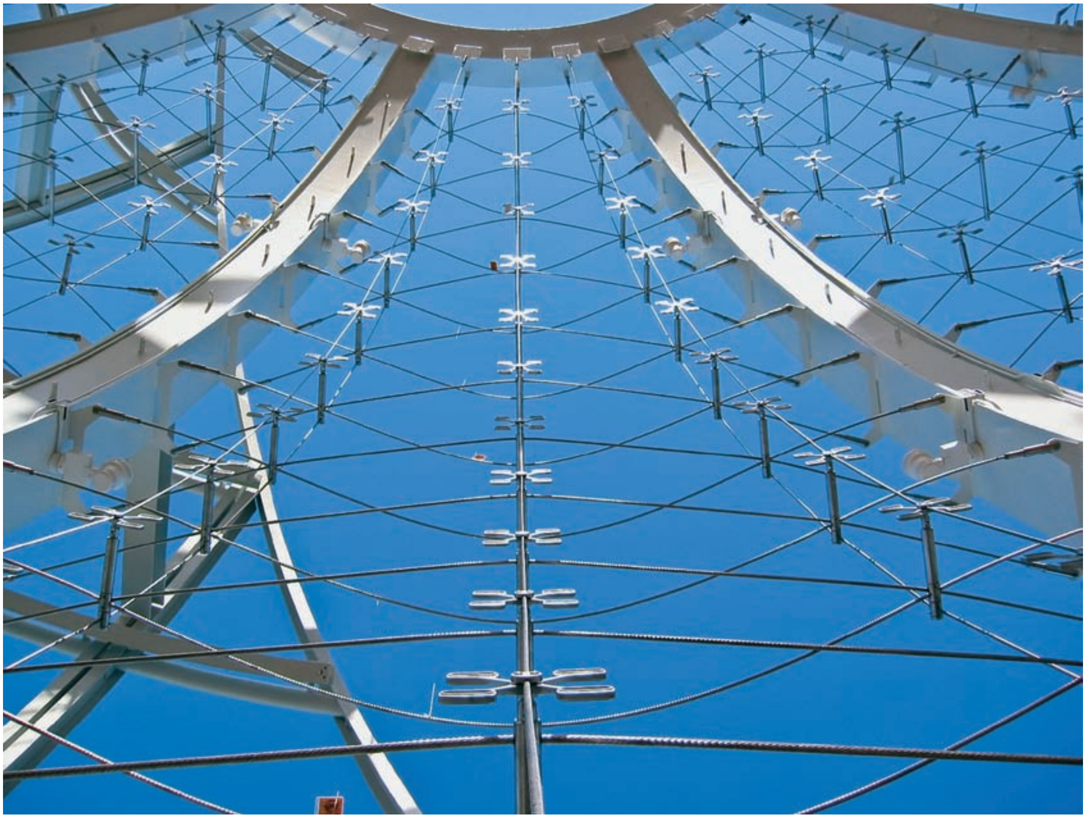


FIGURE 3.13 Cable trusses span between steel arches to form a dome.

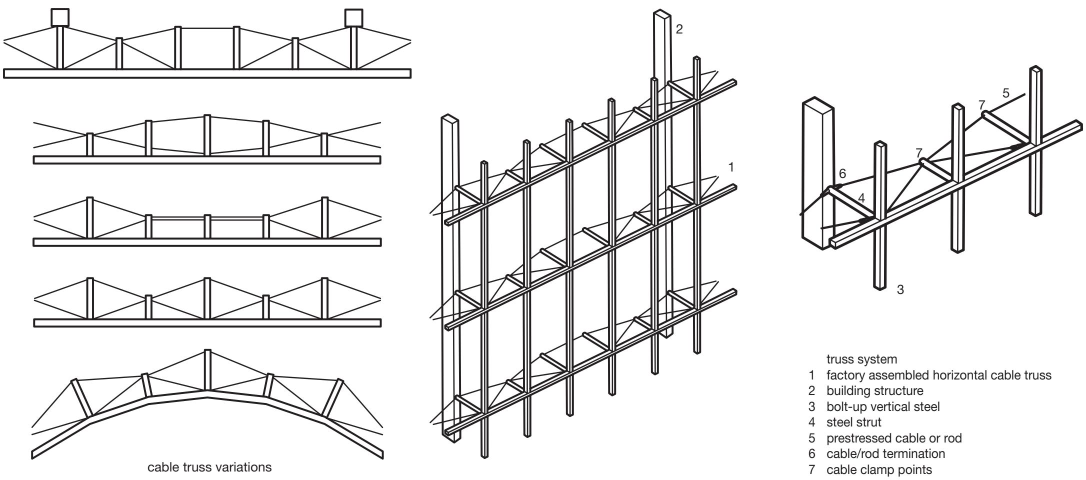


FIGURE 3.14 Truss system diagram using a horizontal cable truss as the primary structure.

FIGURE 3.15 Detail of horizontal cable trusses in a curved facade.

The pretensioning applies a constant reaction load to the anchor structure. These reaction loads can be quite high, depending upon the facade design. It is important to determine a close approximation of these reaction loads early in the design process so that the building engineer can account for the impact on the anchoring boundary steel of the building.

Cable trusses are efficient systems and are quite lightweight on a span/weight basis, but this efficiency is achieved at some cost to the boundary steel, as discussed above. Primary design objectives become managing the prestress loads and mitigating the impact on the anchoring building steel. Systems designed to accommodate large movements perform well under seismic loading. The ability of these highly flexible systems to absorb energy provides a potential advantage when they are subjected to extreme loading, as represented by impact and blast loads. The glass-fixing system must be designed to accommodate the movement.

Materials are minimal. Spreaders can be hollow mild-steel sections of simple and economical construction. However, designers frequently elect to develop this component in stainless steel, or even in cast stainless, which frees the component from the constraints of a uniform section. Spreader end fittings can be machined or cast, designed to fix the spreader end to the tensile elements and to accommodate the attachment of the glass system. If budgets permit, advantage should be taken of these minimal material systems by specifying materials of premium quality, thereby maximizing longevity and reducing maintenance requirements to little more than periodic cleaning.

Truss assembly considerations are similar to those discussed for mast trusses. Partial assembly of the trusses under factory-controlled conditions is recommended. This will require a racking and shipping strategy that protects the partially assembled truss and facilitates handling and installation on the building site. Cables should be prestretched and marked for clamp locations in the factory. If trusses must be assembled on site, an appropriate staging area should be prepared. A welded steel fixture can be designed to facilitate multiple functions: truss assembly, transport of the truss from the staging area to the installation location, and positioning of the truss as it is attached to the supporting structure. This typically involves transferring the top anchor connection of the truss from the fixture to the support point on the building structure. The truss is then attached to the bottom anchor and is ready for tensioning and adjustment. Multiple fixtures may be required to support the truss installation workflow. An alternative strategy is to stage the assembly immediately below the top support point. Using a winch and pulley, an assembly crew working from the ground can piece the truss together in increments, hoisting the truss periodically as assembly progresses until the base of the truss is reached. If the truss anchor points are properly detailed, the truss head and foot can be secured with the installation of a simple pin connector. Regardless of the strategy, great care must be taken to protect the expensive material finishes throughout the duration of fabrication and installation activities.

Chapter 4

Space Structures and Gridshells

The structural system types included in this chapter are variations of reticulated spatial structures: space grids, gridshells, and cable-strut systems, characterized by a combination of tension and compression elements and by an integral development of three-dimensional geometric form, either through cellular repetition or surface curvature (or both). The truss systems discussed in Chapter 3 are undeniably three-dimensional, but they are built up from linear primary elements, which differentiate them from the systems discussed in this chapter.

Space Grid Structures

Space grid structures are another unique option for use as the supporting structure in a long-span glass facade. This structure type has been employed in architectural applications since the 1930s and 1940s, peaking in popularity during the 1980s, and largely falling out of favor with facade designers as the more transparent systems became available. While occasionally used in glass wall applications, space trusses are more commonly employed as long-span roof structures and occasionally as complete building enclosures (Figures 4.1 and 4.2), clad in a variety of materials ranging from glass to metal decking. The use of a space structure in a vertical wall application presents some unique considerations in comparison to the other structure types that may render it more or less appropriate, depending upon the many variables of context. It is a viable solution when considering a complete glass enclosure, particularly a long-span enclosure. Space grid structures are inherently less transparent than the other structure options discussed in this chapter because of the layering of structural components (Table 4.1).

Space grid structures include *space frames* and *space trusses*, terms used somewhat interchangeably in the industry, with *space frame* being the more common term. Professor G.G. Schierle[1] comments that *space truss* is the more appropriate term for the componentized systems because of the truss action created by the pin-connected axially loaded struts. *Space frame*, according to Schierle, is the more appropriate term when moment-connected joints are used, as when the structural bars are welded together in a manner that will combine axial and bending stress in the bar. It is the former prefabricated and componentized systems that are the subject of this section, the welded systems seeing far less use because of their intensive site labor requirements.[2] Nonetheless, this text will defer to common usage in an effort to avoid confusion and facilitate communication across the various user groups and employ the term *space frame*.

TABLE 4.1 Space Grid Structures

- A unique aesthetic of exposed multilayer grid structure
- Least transparent of the structure types
- Complex structural geometries and resulting surface geometries are possible
- Strong cellular modularity can either constrain or facilitate form generation
- Mature technology, but few system providers
- Span/depth ≈ 15 to 20
- Typically very rigid and lightweight structures with low deflections
- Most efficient when used as multidirectional spanning structures (spanning directions must be close to the same dimension)
- Fabrication is a specialty with relatively few producers
- Erection facilitated by system prefabrication

Alexander Graham Bell is apparently the first to have experimented with three-dimensional triangulated structures in the very early years of the twentieth century, and is generally acknowledged as the inventor of the space frame as a structural system type. There was little practical application of this structural form until the German inventor Max Mengeringhausen[3] developed the first componentized space frame product in the 1930s for application as a scaffolding system. The system was comprised of a steel-forged "ball" node with machine-threaded holes, and with steel struts that attached to the node via bolts in the strut ends. The unique aesthetic of the system combined with the compelling geometric structure it was capable of producing eventually captured the attention of building designers, who became interested in using it as exposed structure in roof and canopy applications. Konrad Wachsman was among those who recognized the potential of the space frame as an efficient, lightweight, long-span structural system, developing concepts for mobile aviation hangars for which he built detailed scale models.

It was not until the 1970s that space frame structures found any significant commercial application. The early experimentation and development reached a milestone with the Montreal Expo in 1967. Many space frame structures were present, including the Dutch Pavilion and Buckminster Fuller's famous dome, now called the Montreal Biosphere. Another enabling development roughly coinciding with this event was the increasing sophistication of the analytical tools required if this building form was to achieve practical application. Finite element analysis techniques were developed by the National Aeronautics and Space Administration (NASA) as part of the Apollo space program, and the computing devices to drive such analytical software were just beginning an ascent of their own that continues today.

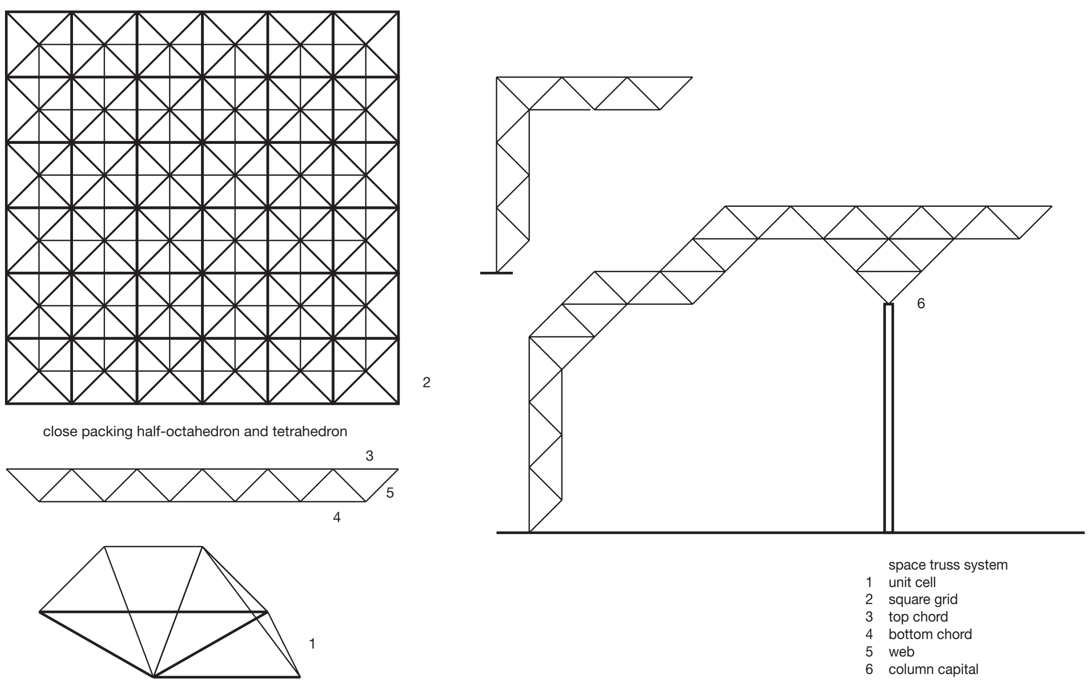


FIGURE 4.1 Space frame system diagram showing the basic square-on-offset-square grid.

Space frames gained popularity in architectural circles in the late 1970s and saw many applications through the 1980s. They were most frequently used in exposed structural applications because of their unique aesthetic. Some of the more high-profile applications include the Javits Convention Center in New York City; the Biosphere 2 Research Center in Oracle, Arizona; and the Long Beach Arena at California State University in Los Angeles. In each of these applications, the entire building enclosure is constructed of an exposed space frame structure. As this structure type was used in a series of high-profile applications, the aesthetic novelty diminished and interest in the space frame as a stylistic element of architecture soon waned. Applications tapered off throughout the 1990s and remain infrequent.

The real potential for the space frame is not as a stylistic element, but as an efficient and economical means to provide long-span column-free space. Space frame designs have been developed as alternatives to conventional truss designs with as little as half the weight of material. In most cases, however, the higher installed cost per pound of material, including all costs from design through fabrication and erection, more than offsets the savings in straight material cost. This material cost simply reflects the current low cost of steel. As energy prices inevitably increase, so will material prices, and at some point meaningful value will be found in reducing the weight of material required to enclose a large space.

Another phenomenon unique to the space frame is the intense interest it has inspired in generations of inventors and entrepreneurs intent on developing and patenting a novel space frame product, as represented by the connection mechanism

FIGURE 4.2 The Crystal Cathedral (1980), Garden Grove, California, is a space frame structure clad in a curtain wall system incorporating reflective glass. Operable vents provide natural ventilation.

employed to connect the struts together. Dozens of patents have been awarded, and well over a dozen different space frame systems have been introduced into the commercial marketplace over the decades. Few still survive, and of these, the original forged ball and tube system first developed by Mengeringhausen has, arguably, yet to be improved upon, at least in terms of economic practicality. In any case, it is apparent that the success of any space frame enterprise has as much or more to do with the mundane aspects of contract administration, project management, and sound business practices as it does with the connection design. For this reason, more providers can be found for the forged ball and tube system, or some relatively minor variation thereof, than any other.

Space frames are three-dimensional multilayer truss systems, most often constructed with prefabricated components; struts that are joined at their ends to nodal components with bolted connections provide for ease of assembly on the building site. The truss networks are capable of two- or three-way spanning, depending upon the geometry and configuration, a behavior that can significantly increase structural efficiency on a strength-to-weight basis and provide for large column-free spaces. They also provide a uniform grid to high tolerance that can facilitate the attachment of a glazing system and other facade system elements such as shading components and service catwalks. While seldom used, space frames are a viable facade structure option, and perhaps because they have seen relatively little use in this application, they may present an opportunity for the adventurous facade designer seeking a different expression of structural form. Space frame structures do present unique opportunities for the generation of nonplanar form through the spatial repetition of a three-dimensional space-filling unit cell or a pairing of space-filling unit cells. Various geometries are possible, most taking maximum advantage of triangulation to achieve very stiff and efficient structures. Space frames can be form-active when configured as a vault, dome, or pyramid, but they are always geometry-active, taking advantage of the stability and stiffness provided by triangulation.[4]

Space frames create a pronounced aesthetic dominated by some level of geometric intricacy. Their appearance is unique enough that it has often been the determining factor in the selection or rejection of this structure type in any exposed application. While they are often considerably lighter than conventional truss systems in the same application, their relative density of members and continuous depth of structure affect the perceived transparency of the structure (Figure 4.3). Even simple truss systems can provide more perceived transparency than space frames.

Space frames are comprised of repeating geometric unit cells that combine to form a three-dimensional truss network. The most common is the so-called square-on-offset-square, a repeating combination of close-packed half-octahedrons and tetrahedrons that form two layers of a square or rectangular surface grid separated by interstitial web members. This grid is derived from the same basic geometry as the octet-truss patented by R. Buckminster Fuller. Interesting forms can be generated by the repetition of a three-dimensional space-filling unit cell. While many space frame structures have been built since the 1970s, very few building designers have really explored their potential, most applications being planar and orthogonal in form. Componentized space frame structural systems are potentially an ideal mate to the parametric-driven form-generating tools currently being explored by architecture's avant-garde. These designers, however, often resist being limited to the geometric constraints of a single space-filling unit cell or pairing of unit cells. Unit cells that morph parametrically can provide dramatic form and surface geometries, but current manufacturing technology lags considerably behind any practical application despite the ongoing development of computer-aided manufacturing technology. Even with a workable solution to the manufacturing component of these designs, erection on the building site presents the most formidable hurdle of all. Site assembly and installation procedures are a long way from being automated to any significant degree.

Componentized space frame systems utilize pin-connected joints that eliminate local bending. Struts resist loads by accommodating axial tensile

FIGURE 4.3 An interior view of the Crystal Cathedral clearly shows that space frames are not the most transparent structure type.

and compressive stress only. The lack of bending provides for the optimization of strut member sizing. To prevent bending moments, loads from interface systems and structural anchor points must be transferred at the node points only. The surface members in a double-layer grid are called *chords*, the interstitial members that join the two layers, called *webs*. The chords resist global bending and the webs resist global shear. Frequent perimeter support at some uniform grid interval provides for more anchor points with smaller loads at each point. It is important to optimize space frame performance by developing the most uniform distribution of forces through the strut network. This provides for minimum diversity of part types and associated favorable economies.

As vertical facade structures, space frames are subjected to uniformly distributed wind load (load case requirements typically include a combination of negative and positive wind pressures over areas of the facade). They are generally anchored at some uniform interval at the top and bottom nodes. The structure is most commonly base loaded, with the bottom anchors taking the dead load of the facade. Both top and bottom anchors resist lateral loads, with the top anchors resisting only lateral loads. Alternatively, it is conceivable that a space frame structure could be hung from anchor points above, inverting the support scheme above. It is also conceivable that a space frame structure could be designed to support roof loads, although this would likely complicate the space frame design considerably.

The multispanning capacity from which the space frame derives its efficiency can be compromised by configurations that effectively limit the spanning direction of the system. A square grid space frame structure built to a rectangular plan of 50 by 100 ft (approximately 15 by 30 m) will effectively span only in the 50 ft (15 m) direction. The optimum width-to-length ratio for such structures is 1:1 and generally should not exceed 1:2 so as not to completely negate the two-way spanning action. Where the ratio exceeds 2:1, a simple truss system is likely to be a more effective solution. It also follows that for a space frame to provide an efficient structural solution to a vertical facade design, perimeter anchors will be required at the sides of the facade as well as at the top and bottom. Again, if this is not possible or desirable, a structural type with one-way spanning action will likely provide a more efficient solution.

Space frame depth is another primary design consideration. The span-to-depth ratio is high, often in the 15:1 to 20:1 range for facade-type structures. However, the minimum and maximum depth of a space frame are also determined as a function of geometry and the spatial requirements at the node to accommodate the connecting strut ends and hardware. Assuming an orthogonal grid with *x* and *y* dimensions falling within the ratio of 1:1 to 1:2, a general rule is a minimum depth of one-half of the largest surface grid dimension and a maximum depth equal to the smallest grid dimension.

In the majority of applications and in the absence of extenuating variables, space frames are typically most efficient in the range of an 8 to 10 ft (2.5 to 3.0 m) grid. In a vertical facade application, it is most desirable for the space frame grid to mirror the glazing grid. This may require a somewhat smaller grid than is optimum for the space frame, but economies may be found in an integration of the glass and glazing system with the space frame. As space frames are best loaded at the node, any glazing system capable of spanning from node to node can be used, including point-fixed systems. The outer-face surface nodes can act as anchor points for clamped or bolted glass fixings. Alternatively, framed glass systems can be designed to attach at the same node points. Veneer systems are also conceivable, with a special chord strut designed to resist bending loads and provide continuous support to the glazing system.

Space frame engineering is a specialty practice most often provided by a specialty contractor in the form of complete design-build services who acts as the engineer of record for the space frame facade system. Given this arrangement, while the development of an appropriate conceptual space frame design is easily within the capabilities of most facade designers, it may be advantageous to involve a specialty contractor early in the design development process. Most of these contractors are willing to perform considerable work gratis if they perceive that by doing so, they may improve their chances of being awarded the project. It is even better if the project delivery process allows for the early qualification and contracting of a design-build provider.

The typical space truss is comprised of many pieces, each prefinished in the factory. This procedure is superior to field painting in any case, but it would be extremely impractical to field paint a space frame structure of the type discussed here. As a further consideration, in the event that the finish is compromised for any reason to the extent that widespread refinishing is required, the space truss can be very challenging and costly to repair. The dense geometry of the three-dimensional structures prevents easy access to the component surfaces for necessary preparation and paint application. This fact, combined with the large number of parts, can make refinishing costly. Even cleaning of the structure can present a challenge, and the space frame can constrain access to the glass from the structure side for cleaning purposes. The simple truss systems can provide potential advantages in this regard. These realities make it imperative that a top-quality high-performance finish appropriate to the application is specified and realized; that this finish is not compromised during the shipping, assembly, and erection activities; and that an effective maintenance program is defined and implemented to prolong the life of the finish.

Constructability issues with a space frame structure are somewhat different than with the other structure types discussed here. The other systems typically involve the application of a custom design with components and connections designed in direct response to the varied project requirements. Employing a space frame structural system will seldom involve the design of the system itself, meaning the design of the typical mechanism by which the struts are interconnected. Rather, the facade designer will select an existing space frame product and product provider. Details where interface systems connect to the space frame system will be carefully coordinated with the space frame provider. The earlier this is done in the design process, the less likelihood there will be of disruptive changes as the design progresses through the implementation phase.

The manufacture of space frame components is accomplished with varying levels of automation under factory-controlled conditions and to very high tolerances. Space frame struts, for example, are typically held to ±0.030 in. (1 mm) or less over a 5 ft (1.5 m) length. There are very good reasons for such tight tolerances. A primary advantage of the componentized systems is that they can be assembled in the field by simply bolting the components together, eliminating the expensive site labor cost associated with positioning and field welding steel tube. There is no mechanism for adjusting the overall tolerance as the frame is built, however. With the typical ball node and tube system, accuracy of the assembly derives from the accumulated tolerances of the struts from end to end plus the machined faces across the node where the strut ends mate. Because the space frame is built up from the incremental repetition of these strut and node components, dimensional variations have the potential to stack over the lengths of large structures. It becomes evident why the manufacturing tolerances must be tight. Even so, there is the potential to exceed the tolerance provisions for structural steel and encounter a problem at the interface of the space frame with the supporting structure. This problem can generally be addressed by designing anchor components to provide the necessary flexibility. All systems interfacing with the space frame must also be studied in this regard.

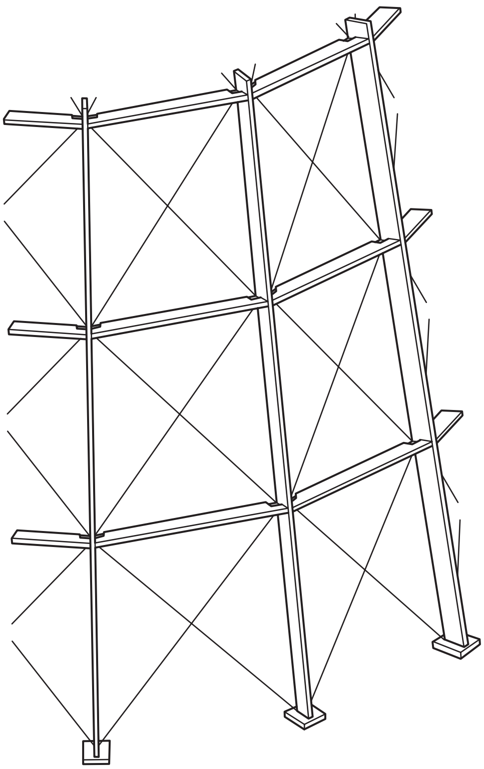
Space frames can be built in place, but it is almost always more efficient to build subassemblies on the ground in a staging area reserved for the purpose; the subassemblies become the building blocks of the space frame structure. After enough subassemblies are prepared, erection operations can proceed in placing them. This typically involves some type of crane positioned to lift, swing, and set the subassemblies. The subassemblies must be sized within the weight capacity of the crane, given the reach involved in each pick. Subassemblies are tied together with infill struts that have been left out of the subassemblies. The rigidity of the space frame facilitates the erection process by minimizing shoring requirements as frame assembly proceeds. The space frame can accommodate large cantilevers during the erection and before cladding systems are applied.

Gridshells

Gridshells are a unique structure type (Table 4.2). They also represent an entirely different means of generating form. Gridshells are form-resistant structures, as opposed to tensile-resistant structures such as the cable truss, although a hybrid form makes use of integral tensile structure. Despite a predominance of bending and compression elements, gridshells possess remarkable transparency as a function of their thin shell properties. It is this lack of system depth, the single layer, that so dramatically differentiates the aesthetic and transparency of gridshell structures from multilayer structures, such as space frames. Gridshells have been used as complete enclosures as well as vertically oriented facade structures (Figures 4.4 and 4.5).

TABLE 4.2 Gridshells

- A unique form-active thin shell aesthetic with an emphatic definition of surface
- Excellent transparency, depending upon the geometry and the glazing system
- An interesting form generator; gridshells can be vaulted or domed, comprised of regular and irregular conical and toroidal sections or free-form, double-curved surfaces
- Complex surface geometries are more easily realized than with multilayer structures
- One of the newer facade structure types with relatively unexplored design potential
- Multiple spanning paths and shapes provide long-spanning capacity and structural efficiency
- Relative depth of the structural system is significantly reduced compared to that of truss systems
- Glass grid typically follows the structure grid
- Fabrication and installation can be complex



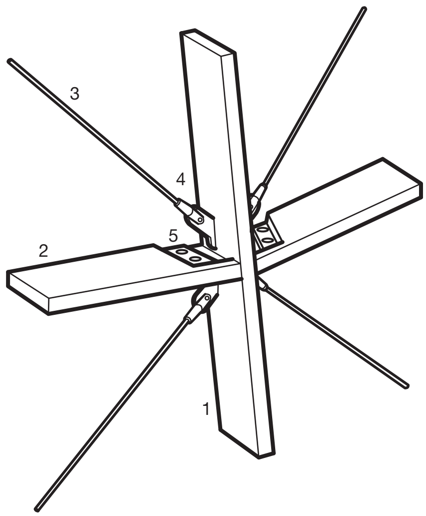


FIGURE 4.4 Diagram of a simple gridshell system.

The brilliant Russian engineer Vladimir Shukhov pioneered the design of gridshell structures, developing the world's first double-curvature steel gridshells constructed as exhibition pavilions for the All-Russia Exhibition in Nizhny Novgorod (1896). His work also included innovations with metallic thin-shell and tensile structures and the first hyperboloid structures. Shukhov's work later inspired the German architect and engineer Frei Otto, who also did pioneering work with gridshells, including the design for the Mannheim Multihalle in Germany constructed in 1975.

Relatively few gridshell structures have been constructed, and most of these have been roofs, canopies, or full building enclosures. Gridshells have seldom seen application as a facade system. One of the few examples is the John Joseph Moakley United States Courthouse in Boston (1998) designed by Pei Cobb Freed & Partners with LeMessurier Consultants (Figure 4.6). The dramatic glass facade faces the waterfront and employs a unique structural system developed by LeMessurier. The structure, with geometry derived from a conoidal surface, is constructed of vertical ladder trusses laid side to side, parallel to the glass plane and welded together at nodal intersections. Stainless steel tension-rod bracing cuts a diagonal web through the stacked steel grid of isosceles trapezoids. The rods required pretensioning to 90 kips (400 kN). The ladder trusses were factory welded and shipped to the site, where the rods were installed and tensioned prior to being lifted and set in place. The high tensile forces made the individual ladders extremely unstable and prone to warping, requiring that each truss be secured to a strongback along its entire length as a kind of fixture to stabilize the ladder during the tensioning and installation

FIGURE 4.5 This system was used to enclose the lobby of a corporate office building.

process. Once a ladder was welded to its neighbors, the shell action became active and the strongback could be removed and reused on another ladder. This innovative design produced a structural system with a depth of less than 11 in. (279 mm). A conventional truss solution with trusses set perpendicular to the glass plane would have required a truss depth of at least several feet. The structure provided support for a conventional stick curtain wall system.

Since the late 1980s, the engineering firm Schlaich Bergermann and Partner, working with various architects, has designed a number of glazed roofs and canopies using gridshell structural support, and has developed novel techniques for developing grid geometries that facilitate fabrication and construction. Their work clearly demonstrates the versatility of this structural form and its application as a building enclosure. Similar to the Boston Courthouse, the systems employ a network of in-plane cables to provide stability and shear resistance to the minimal shell grid.

Of the many gridshell structures completed by Schlaich Bergermann, all are roof or canopy structures with the exception of a small sculptural structure done with James Carpenter Design Associates for the Bank of America. The "Luminous Gridshell" features an elegant double-curved system design with laminated dichroic glass. The construct is hung in a vertical orientation, and an extrapolation of the design to a facade structure takes no great leap of imagination. Regardless of their infrequent use as facade structures, gridshells are a viable option for consideration, as the examples here attest. This structure type remains rather underexplored in this context, and there may be some interesting potential in future work.

Schlaich Bergermann was also involved in the New Milan Trade Fair gridshell canopy designed by Massimiliano Fuksas, completed in 2005. This undulating double-curved surface is fully triangulated, requiring no integral tensile bracing system, as with the nontriangulated grids, but also somewhat denser because of it. A number of similar structures have been completed in recent years.[5]

Gridshells are a subset of shell structures. Rather than being monocoque shells, they are comprised of a grid of discrete structural members forming triangles or quadrilaterals that define the shell geometry. Single- and double-curved surfaces are both possible. Unique shapes can be developed with gridshells that benefit from the combination of shell and arch action. Both welded systems, like the Boston Courthouse facade, and componentized systems, like the Schlaich Bergermann roofs, are possible.

Gridshells invariably provide a unique aesthetic of curving or undulating form. Simple geometric forms are most common, but curved shapes with endless variations are possible. As with membrane structures, flat and nearly flat shapes will not work as gridshell structures, and adequate surface curvature is a key element of the design program to ensure an efficient structure. The Messe-Leipzig Glass Hall discussed briefly in Chapter 1 is a hierarchical vaulted structure with a gridshell of welded steel pipes spanning between arched trusses.

Facade transparency is a largely subjective phenomenon affected by many variables, the structural system being but one of these. Nonetheless, thin-shell structures have an advantage here, being single-layer structures of minimal depth. This difference is apparent when a thin-shell structure is compared with a multilayer structure like a space frame. The perception of transparency, however, is influenced by other factors, among them the integration of structure and membrane, as discussed in Chapter 3. Merging the glass into the structural grid tends to emphatically define the structure as membrane. While the glass-clad gridshells discussed here are of remarkable transparency, the effect is strikingly different than that provided by certain variations of the truss systems, especially the cable truss. A point-fixed glazing system with monolithic glass and butt-glazed joints can virtually disappear from view in the absence of prominent reflections. The structure behind the surface commands visual attention, enhancing the transparency of the surface by engaging the eye beyond that surface. The structural lattice of the gridshell, on the other hand, focuses attention on the surface, defining the membrane regardless of the appearance of the glass.

Shell structures have long been recognized for the superior efficiency deriving from their shape.

Thin-shell structures in reinforced concrete have been used in many long-span structural applications. While the design, engineering, and construction of these form-active structures remain challenging, they have found use because of their efficiency and unique aesthetic. The strength of the shell derives from the curved or double-curved (synclastic or anticlastic) surface geometry.

There are two generic structural forms of gridshell. The closed system relies on either moment connections or a fully triangulated geometry to achieve stability; the open system employs a quadrilateral grid stabilized by perimeter anchor locations and cable bracing intersecting grid modules. The cable bracing system is pretensioned and anchored at the perimeter. A clamping mechanism clamps the cable bracing at the vertices.

As with any shallow domed structure, global buckling is a concern, and the designer must take care to provide adequate surface curvature and to avoid flat or nearly flat areas unless adequate support is provided. Curvature can be optimized as part of an iterative process to maximize structural efficiency. The grid will define the geometry without the need for analytical form-finding, but such a process is very useful if an optimal shape is desired. In addition, if cable bracing is used to stabilize the structure, the design will include a prestress requirement. With gridshell structures, it is advisable to involve a specialty consultant or design-

FIGURE 4.6 Boston Courthouse, 1998, Pei Cobb Freed & Partners. This gridshell facade is similar in concept but much grander in scale, approximately 300 ft (90 m) across and spanning 100 ft (30 m) from top to bottom, with a system depth of only 11 in. (279 mm).

builder as early as possible in the design process to assist with the development of the form and the determination of reactions to the supporting structure for the benefit of the building engineer.

The glass grid typically follows the structure grid, with attachment taking place at the vertices of the structure, or with the glass continuously supported at the surface of the gridshell's structural members. Large grid structures require a secondary glazing system to accommodate an appropriate glass grid. Any glass system type can be used, but it is most commonly integrated with the structural system.

Spanning capacity is most affected by surface curvature; the greater the shape, the higher the spanning capability. A curvature ratio of 1 ft (0.3 m) of sag over a 10 ft (3 m) span is roughly equivalent to an L/d of 10. A typical deflection criterion is L/175. Depending on their geometry and construction, gridshells can be the most efficient structural systems because of the combined effects of shape and multidirectional spanning. Gridshell structures of complex geometry can exhibit unusual behavior under seismic loads, and the seismic behavior of these structures needs to be carefully considered as a function of shape. Gridshell flexibility depends upon geometry and system design: fully triangulated systems are quite rigid. Some systems are more flexible than others and thus may perform differently under extreme loading conditions.

Gridshells can be built as welded steel fabrications or from componentized systems: kit-of-parts bolt-up products that can be configured to custom designs. Componentized systems are welded steel tube struts that bolt together at their ends or bolt into node components at the grid vertices. The componentized systems are similar to space frame systems and share many of the issues identified previously with them. Gridshells built up from the assembly of relatively small components require special attention to tolerance issues. The facade design needs to be analyzed during design development to ensure that enough adjustability is provided to the structure and the glazing systems to accommodate material, fabrication, and installation tolerances. Few structural steel fabricators are qualified for the precision production work required for the componentized structures, so care must be taken to identify fabricators that have experience in working to the prescribed fabrication tolerances. There are a few specialty design-build contractors with experience in the fabrication and erection of gridshell structures. They may perform their own fabrication or work with fabricators who have been qualified on previous work.

Welded steel gridshells require a different approach. The fabrication strategy is typically driven by transportation and erection considerations. Nonplanar subsections present a challenge in shipping. It is usually desirable to shop fabricate as large an assembly as possible to minimize field labor. The subsections are then positioned and welded or bolted together on site to provide the final structure. The size of the subsection is most often limited to what can be shipped on flatbed open trailers. Whatever the determination, the size limitation will dictate how the overall structure will be divided into subsections for fabrication purposes. The complexity of fabrication of these nonplanar structures will further reduce the number of vendors qualified for the work. The Desert Bloom is an example of a gridshell that is fabricated in large subsections in the factory and then shipped to the building site for assembly (Figure 4.7).

The componentized systems provide certain advantages in terms of fabrication and erection. The components are much smaller and easier to handle than large welded assemblies. As with space frame systems, the “intelligence” of the system is built into the design of the components. As long as the fabricator is capable of providing the required accuracy, the challenge of complicated layout and fit-up of complex, large, heavy steel fabrications is avoided. The benefit of scale extends to the building site, where the materials are easily handled and positioned. Again, the intelligence is designed into the system, and the requirements of the installer are limited to bolting the end of part A to the end of part B and so on, and as the assembly proceeds, the design of the parts automatically provides the correct shape. This eliminates the need for a highly skilled installation crew to accurately position large, heavy subsections of complicated curved geometry under generally adverse site conditions and then spend many hours welding or bolting these subsections together.

Either approach will require analysis to determine an appropriate strategy for shoring the gridshell as assembly proceeds. Unlike space frames, which tend to self-stabilize as assembly proceeds and typically require minimal shoring, gridshells can be unstable during assembly until the structure is complete between support points. Few erectors have experience with the assembly and installation of gridshell structures, which do involve a range of special considerations. As with any of the systems requiring pretensioning and complex assembly methods, the erector should be required to submit a detailed method statement outlining the assembly and erection procedures. With a gridshell structure, it is of particular value to have the input of a qualified erector during the design process so that critical issues of constructability can be addressed.

Cable-strut Systems

Reticulated cable-strut systems combine cable and strut components in a spatial geometry stabilized by prestress of the tension network. They fall within the larger category of tension systems and can be either open or closed system types. Closed system

FIGURE 4.7 Desert Bloom, Casino Morongo, Cabazon, California, 2004, Jerde Partnership. The leaves of this triangulated gridshell span 90 ft (27m).

types include tensegrity structures and tension-grid structures derived from the application of tensile components to space structure geometries. Open system types include multilayer cable nets and cable-strut dome systems (Table 4.3).

TABLE 4.3 Cable-strut Systems

- A unique structural aesthetic combining tension and compression components to form reticulated spatial structures
- High potential transparency, but structure can predominate
- A broad range of high geometric complexity
- Stability considerations and load transfer mechanisms are paramount and can be highly complex
- Can be designed as traditional closed systems or as hybridized open systems
- Form-finding is required and can be challenging as a function of geometric complexity
- Prestress is required for system stability
- Prestress in open systems will transfer to anchor structure
- High installation complexity, depending upon the geometry

Cable-strut structures vary considerably in form and application, but have in common the combination of strut and tensile elements to achieve three-dimensional form. Tensegrity and tension-grid structures are two types of cable-strut structures.

Tensegrity represents a unique and interesting subgroup of the broad class of cable-strut structure types that combine tensile and compressive elements in a distinctive manner. However, it is fair to say that early tensegrity structures inspired many of the structure types and applications that make up this class. *Tensegrity* is a term often but incorrectly applied to any structure type with a predominance of tensile elements. The factors that differentiate this subgroup are poorly understood outside of a relatively small group of researchers and designers specializing in complex geometric structures. A concise and generally accepted definition of tensegrity has proven elusive, but certainly not for lack of trying. The term was coined by R. Buckminster Fuller to label a class of structures discovered by Kenneth Snelson. Fuller ultimately redefined the term, generalizing the fundamental principles to a philosophy of tension and compression and applying it to a broader range of structures, including geodesic domes[6] possessing no tensile elements at all. This philosophy of tensegrity subsequently even transcended the realm of structure and has been used to describe physical and biological systems such as the skeletal-muscular system.

Tensegrity structures were first identified and explored by sculptor Kenneth Snelson in 1948. Snelson introduced Buckminster Fuller to his findings, and in the mid-1960s Fuller coined the term *tensegrity* as a contraction of *tensional integrity*.[7] A true tensegrity is a balanced construct of complementary forces, with continuous tension elements and discontinuous compression elements. Fuller's original definition for tensegrity was of compression elements that do not touch, but exist as "small islands [of compression] in a sea of tension."[8]

The original definition of tensegrity derived from the work of Snelson included only closed-system geometries with very specific attributes. Fuller, over time, broadened his definition in several confusing respects. Since then, many attempts have been made to define the term. Rene Motro has made the most rigorous attempt at nailing a definition.[9] He started with an analysis of the three patent holders relevant to the roots of tensegrity systems: Nelson, Fuller, and David Georges Emmerich. From this he developed what he terms a "patent-based" definition, but he recognized the need for an extended definition based on the application of the perceived intent of the patents to the evolution of work inspired by these patents. He identified the core concept of "islands of compression in an ocean of tension" and adapted one of the many previously offered definitions as follows:

> *A tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components.*

There are few examples of tensegrity structures in the built environment. Snelson himself expressed doubts regarding the practical application of tensegrity structures in architecture. However, an insistent group of researchers and engineers remain committed to exploring the properties of tensegric form and may very well provide unique solutions for facade structures. Many geometric forms have been explored by Snelson and others, and mathematicians have cataloged variations of tensegrity geometries that remain largely unexplored in architectural applications. Tensegrity structures have been built from repeating cellular units, such as the Needle Tower (Figure 4.8). Models have been built of tensegric grids. It is not difficult to conceive of geometries such as these being developed into quite interesting facade structures.

Cable-strut Structures

Fuller went on to develop structural dome concepts inspired by his work with tensegrity structures. In 1964 he patented the *aspension dome* system. The concept was later used by David Geiger to develop a tensile roof structure for the Seoul Olympic Gymnastics Arena in 1986 (among other structures), representing the first architectural application of cable-strut structures. The fabric-clad structure weighed in at just 2 psf (9.8 kg/m^2). Matthys Levy of the engineering firm Weidlinger and Associates developed a similar structure that was used on the Georgia Dome. While typically referred to as tensegrity structures, these dome systems do not conform to Motro's patent-based or extended definitions. Motro cites the primary reason as the large, continuous compression ring that lies outside "the ocean of tension." Applying the terminology used here and applying Motro's definition, tensegrity systems are invariably closed systems. This remains, however, a matter of some

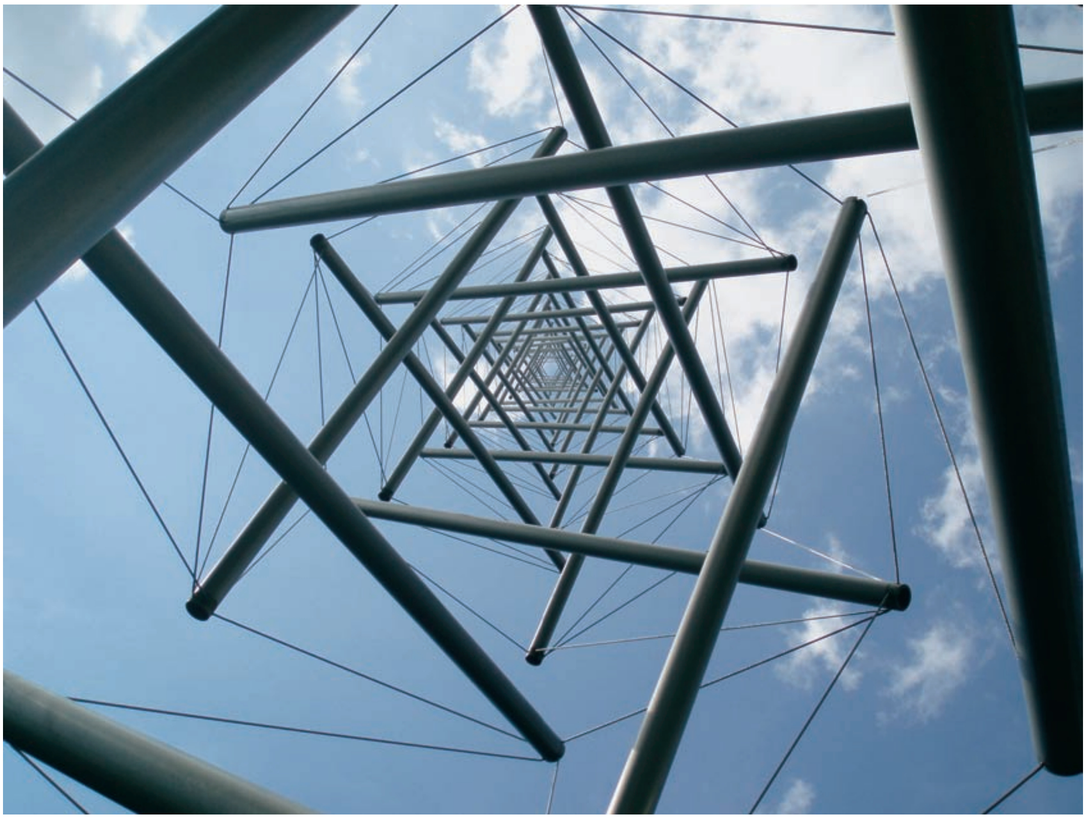


FIGURE 4.8 Needle Tower, Kenneth Snelson, 1968. This tensegrity sculpture resides at the Hirshhorn Museum and Sculpture Garden, Washington, D.C.

contention. Robbin[10] has argued that these dome systems can fairly be classified as tensegrity structures. Motro's definition is more recent and rigorous and is used as the basis for the system categorization included here.

Unfortunately, there is an insubstantial body of work to draw on for evaluation; few cable-strut structures have been employed in facade applications. Cable-strut facade structures are most closely related to cable trusses and gridshells with cable bracing since they combine complementary tension and compression elements in the basic structural form. If cable trusses are developed as spatial systems with multidirectional spanning behavior, they qualify as cable-strut structures (Figure 4.9). Double-layer cable nets are conceivable, with compression struts separating the nets, and could be regarded as cable-strut structures in this categorization scheme.

Tension-grid Structures

A hybrid form of space structure emerges as another cable-strut structure type as tensile components are integrated into various space structure systems. What may be referred to as *tension-grid* structures derive from the strategy for structural dematerialization (discussed on pages 48–49) applied to various geometries used as space grid structures. Unit cell geometries incorporating tensile elements are being used by researchers and designers to generate stable space grids, a geometric articulation of tension and compression that yields unique structural forms with certain characteristic properties.[11] As with space frames, unit cells can be defined and repeated in space to create linear, planar, and articulated form. These systems tend to be highly complex, with stability and load transfer issues a matter of some subtlety. Tension grids are largely unexplored as facade structures.

FIGURE 4.9 Lloyd D. George United States Courthouse, Las Vegas, 2002, Dworsky Associates. A cable-strut skylight encloses the entry lobby to the courthouse.

While tension-grid structures could be classified as a subgroup of space grid structures, they are fundamentally different in their requirement for prestress as a prerequisite of stability, and consequently are included here as a subgroup of cable-strut systems. There is also an overlap with tensegrity structures, as some but not all tension grids can be classified as tensegric grids.

Cable-strut structures are visually distinct. Tensegrity structures in particular present a compelling aesthetic. Compression elements appear to float, as they are suspended within a tensile net. The systems can be very transparent, but that is often not the point with this structure type. As attention is naturally drawn to the often startling visual effect of the floating compression components, the structural system is frequently expressed at the expense of optimum transparency.

The determination of an appropriate cable-strut geometry that will meet the various requirements of a facade structure is complex and challenging, and is beyond the capability of most facade designers. Those wishing to explore the potential of this structural form will either have to familiarize themselves with the various geometries or engage the services of a specialist. Detailing will also be challenging, with little precedent. The connection detail between the cable and the strut end will be of particular importance. Robbin points out, from his study of the work of David Georges Emmerich, that the ratios between strut and cable lengths are important in determining the structure's efficiency. Compression elements need to be minimal in length. (Again, this is consistent with the dematerialization strategy introduced on pages 48–49.) The glass system interface must also be considered as the system geometry is developed. An obvious approach would be to develop geometry with a compression element ending at the intersections of the glazing grid. This strut could then be treated as with the mast and cable truss structures. Long spans are possible, as with the cable-strut roof structures used to span stadiums as discussed above, but such structures would require significant adaptation for glass facade application.

Prestress is an integral part of cable-strut systems and a prerequisite for stability. In the open system types, prestress loads are transferred to the anchor structure. Closed systems also require prestress as a condition of stability, but the prestress forces remain internal to the system. Reaction loads are high with open systems because of the prestress loading, and anchor structures must be designed to accommodate these loads. Cable-strut structures appropriate to glass facade applications will likely perform similarly to cable-truss or mast-truss systems, and share similar material and process considerations. Some tension grids and tensegrity designs embody considerable geometric complexity, increasing the importance of constructability considerations and intensifying the challenges of assembly and installation.

Chapter 5

Cable Structures

Tensioned cable structures represent a relatively new structural form (Table 5.1). Frei Otto was the seminal figure in the development of this structure type, introducing it to the world in the 1960s and 1970s with his dramatic work for the German Pavilion at the 1967 Montreal Exposition and then with the equally daring Olympic Roof and various enclosures and structures for the 1972 Olympic Games in Munich (Figure 5.1). Drawing on an extensive study of natural form, Otto developed anticlastic membrane surfaces exhibiting structural properties that were promising for their use as architectural structures of unique and elegant form. Structural fabrics were not available at the time, so Otto developed a technique of employing intersecting prestressed cables of opposing curvature to construct prestressed nets of cable to define the surface geometry. The cable nets were then used to support a cladding material: a polyester fabric at the German Pavilion and a complex glazing system of polycarbonate panels at the Olympic Park structures.[1]

TABLE 5.1 Cable Systems: General Attributes

- Elegant minimalist aesthetic
- Highest transparency
- Flat, curved (i.e., a plan radius), and double-curved system geometries are possible
- Newest of the facade structure types
- Cable-supported structures generally exhibit high geometric flexibility and are characterized by large deflections
- Typical deflection criterion L/40 to L/50
- Critical prestress requirements for design and installation to control deflections
- Prestress loads generate high boundary reactions
- Installation pretensioning can require sophisticated jacking systems and complex installation technique
- High cost

The Olympic Park structures are especially remarkable given the lack of automated analytical tools and techniques to provide for the form-finding and engineering analysis of their complex designs. Frei Otto developed his own sophisticated empirical techniques to determine the geometry of the membrane structures without the help of computer automation. Today, off-the-shelf computer programs are available to facilitate form-finding, nonlinear analysis, and even pattern generation for membrane structures. Contemporary membrane structures typically make use of a fabric membrane and forego the cable nets; structural fabric materials comprised of polytetrafluoroethylene (PTFE)-coated fiberglass or polyvinyl chloride (PVC)-coated polyester fiber are capable of acting as a structural membrane without the necessity of a supporting cable net.

It was only much later that cable structures found application in building facades. The push for transparency resulted in the employment of cable net structures for the support of long-span glass facades. The first such structure was built for the Kempinski Hotel in Munich and completed in 1993. Architect Helmut Jahn called on renowned German engineer Jorg Schlaich[2] to develop a highly transparent facade system to enclose opposing sides of a large, open atrium. This seminal structure defined a new level of transparency and a new building technology for long-span glass-glazed structures. One thing that differentiates the Kempinski cable net from the referenced prior art is that it is a flat surface and thus does not benefit from the surface stability provided by the opposing curvature of an anticlastic membrane. It was also one of the very first cable structures to support glass as a cladding element. The structure spans 82 ft (25 m) vertically by 131 ft (40 m) horizontally, with a square mesh grid of 5 ft (1.5 m) formed by $\frac{7}{8}$ in. (22 mm) diameter cables. Monolithic glass panels $\frac{3}{8}$ in. (10 mm) thick match the cable net grid. The entry portals are cantilevered from the floor, with a gasket between the cable net and the portal structure accommodating the movements of the facade under wind load[3] (see Figure 1.10).

This remarkable structure was presented shortly after its completion to an appreciative audience of engineers at an International Association of Shell and Spatial Structures conference in Atlanta, Georgia, in 1994. Following his presentation, Schlaich called for questions and was immediately asked the maximum deflections under wind load. His response was, "Approximately one meter." It took a full minute for the assembly hall to settle down. It is almost difficult to recall now, but this was a time when highly flexible structures were not widely used or understood and were rarely considered to support glass. Rather, the strategy with structures supporting glass was to make them maximally rigid, exposing the glass to as little movement as possible. Space grid structures were often used to support glass walls and skylights by reason of their rigidity. Gradually it was recognized, helped by the completion of such high-profile facades as that of the Kempinski Hotel, that glass panels attached to flexible structures and sealed with a rubbery silicone were not only viable but had certain distinct advantages; when extreme loading conditions create movement, it is advantageous to have systems in place that are capable of accommodating significant movements.

The next step in the move toward dematerialization of the structural system is to completely delete the struts, the last of the remaining compression elements in the structural systems discussed previously, thus

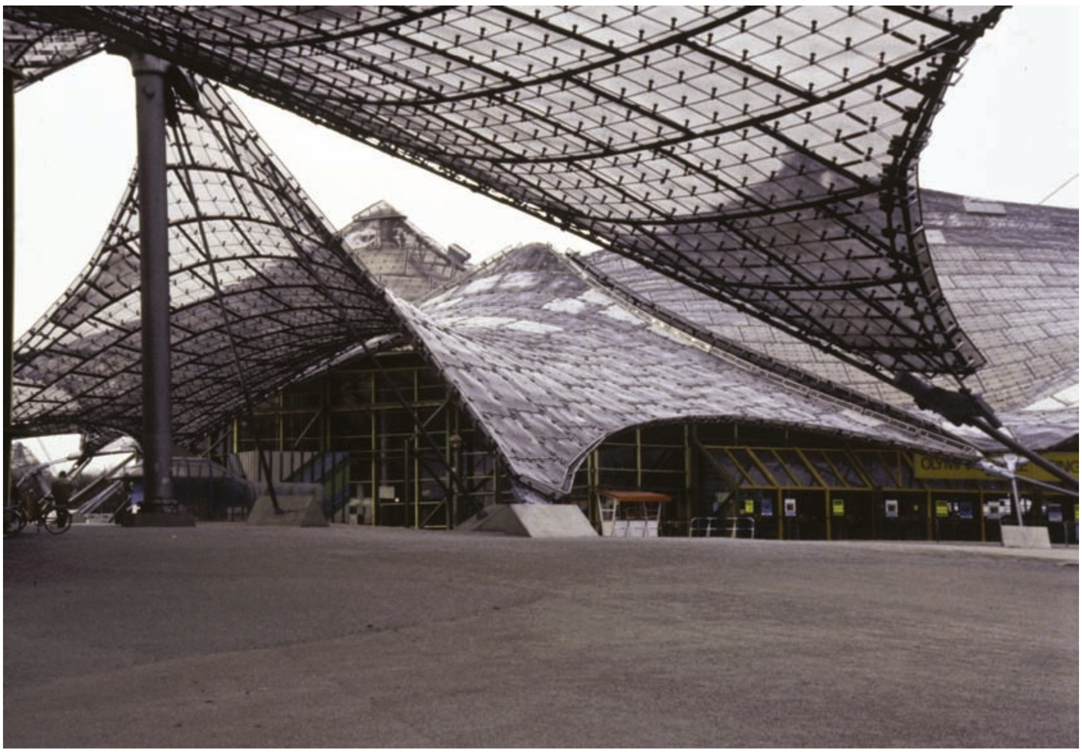


FIGURE 5.1 Olympic Park, Munich, 1972, Behnisch and Partners with Frei Otto. The 1972 Olympic Games brought the attention of the world to the dramatic structural forms created by cable net structures.

yielding this new category of open system structure that is entirely tension based. There are many variations on the cable structure theme, both in form and in application. The most popular system type, because of its simplicity, is the cable mullion structure.

Cable Mullion Systems

In cable structures, all that remains from the former system types are the tension components (Table 5.2). Cables can be tensioned vertically against top and bottom boundary structure, resulting in an open structure with one-way spanning behavior. If adequate prestress forces can be achieved, the cables can be used to support glass while controlling deflections. Dual-function clamping components that clamp first to the cables can then be used to clamp the edges or corners of adjacent glass panes on the glazing grid. The glass plane can be straight or curved in plan (Figure 5.2).

TABLE 5.2 One-way Cable Mullion Systems

- Most minimal and most transparent cable system
- Designs can range from very simple to complex
- Systems can be flat, or curved in plan
- Geometrically simple
- The shallowest of all systems
- Flat systems are the most flexible, with the largest deflections
- Deflection criterion as low as L/35
- Long spans require high prestress loads and generate high boundary reactions
- Can be used in simple floor-to-floor spans (see Chapter 13)

FIGURE 5.2 This cable mullion system enclosing the lobby of a 53-story tower at 111 South Wacker in Chicago by Lohan Caprile Goettsch Architects (2005) is curved in plan and encloses the lobby of a downtown Chicago high-rise.

A narrow glazing grid will result in a higher density of cable elements, thus lowering the prestress requirements for each individual cable. High prestress forces may be required to control deflections. Nonetheless, the cable mullion structure is being utilized with increasing frequency because of its relative simplicity. In its most fundamental form, the cables merely span floor-to-floor and become a very basic expression of what Peter Rice referred to as a "cable mullion" on Les Serres. The Newseum case study (Chapter 15), in contrast, is a complex design using one-way horizontal cables. See Chapters 13, 15, and 16 for examples of one-way cable systems.

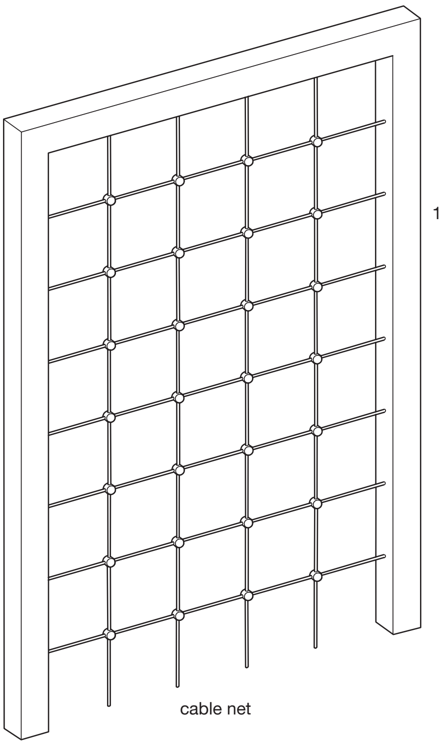
One of the earliest cable structures built in the United States was designed by Dewhurst Macfarland and Partners with TriPyramid Structures for the Kimmel Center for the Performing Arts in Philadelphia, designed by Rafael Viñoly Architects. The cable mullion system encloses the end of a glazed vault. This novel design employs a system of lifting weights at the cable ends to resist lateral loads. It was completed in 2001.

Flat Cable Nets

The addition of horizontal cables to the system described above yields a cable net, reticulated, an open system capable of two-way spanning behavior (Table 5.3). Adding the horizontal cables to a straight plan geometry of vertical cables produces a flat net with an orthogonal cable grid defined by the relative spacing of vertical and horizontal cables (Figure 5.3).

TABLE 5.3 Flat Cable Nets

- Flat nets are geometrically simple, typically with an orthogonal grid
- Flat nets and cable mullions are the shallowest of all systems
- Potential for reduced deflections compared to cable mullions
- Typical deflection criterion L/40 to L/50
- Potential for lower prestress loads and boundary reactions than with one-way cable systems
- Additional material and more complex components, fabrication requirements, and installation requirements may add cost compared to the one-way system, depending upon many variables



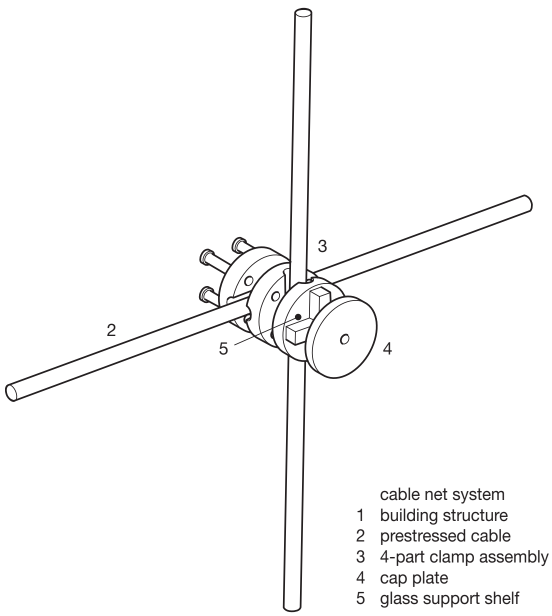


FIGURE 5.3 Cable net system diagram for a flat two-way structure.

In a long-span structure, the addition of the horizontal cables makes the control of system deflections easier, assuming an effective spanning distance, resulting in reduced prestress requirements in the cable elements. Simple flat cable nets, as described here, have been constructed with spans of 150 ft (46 m) or more. Among the first to be built in the United States in the same general time frame as the Kimmel Center was the two-way cable net for the UBS Tower in Chicago, designed by Lohan Caprile Goettsch Architects (Figure 5.4). A series of cable net bays designed by ASI Advanced Structures with Schlaich Bergermann and Partner wrap the public street-level lobby area in a membrane of transparency. The monolithic glass features a special antireflective coating provided by Schott Glass. The spans here were moderate at 35 to 40 ft (10.6 to 11.2 m). This was soon followed by a much larger cable net at the Time Warner Center in Manhattan, designed by James Carpenter Design Associates with architect SOM (Figure 5.5). The cable net structure, design-built by ASI Advanced Structures, with W&W Glass providing the Pilkington Planar point-fixed glazing system, spans 150 ft (45.7 m) vertically and 90 ft (27.4 m) from side to side. The wall features an integrated ground-floor entry portal and canopy. Another cable net designed by SOM with ASI Advanced Structures[4] incorporates a more complex faceted geometry using a hierarchy of cable sizes. In China, the New Beijing Poly Plaza cable net spans an opening 295 ft (90 m) tall by 226 ft (69 m) wide and was completed in 2005.[5]

FIGURE 5.4 UBS Tower, Chicago, 2001, Lohan Caprile Goettsch Architects. A series of flat nets enclose the lobby of this high-rise tower, among the first to be completed in the United States.

See Chapter 14 for an example of a two-way flat cable net.

Double-curved Cable Nets

The cable net can be manipulated to produce a double-curved membrane (Table 5.4). If the horizontal cables are aligned to a curve in elevation and the vertical cables are aligned to an opposing curvature in plan, the horizontal and vertical cables can be tensioned against each other to form a double-curved (anticlastic) surface with unique properties. The anticlastic surface provides stability to the cable net that a flat configuration does not possess, significantly limiting deflections under wind load and thus requiring lower prestress forces in the cables. Lost, however, is the facility of the orthogonal grid; the double-curved net produces a more complex geometry that complicates assembly and installation of the net and increases the requirements of the glazing system (Figures 5.6 and 5.7). Depending upon system geometry, the corners of some grid modules may not even lie on the same plane, resulting in the possibility that glass panels could require cold-forming during installation to conform to net geometry, thereby inducing warping loads to the glass panels. These potential effects can be mitigated by careful design of the net geometry and otherwise accounted for in glass engineering.

TABLE 5.4 Double-curved Cable Nets

- Great diversity of form possible, with many unexplored possibilities
- Present a unique aesthetic
- High geometric complexity
- Double-curvature membranes provide a more stable structure with the potential for considerably lower deflections than flat cable nets
- Double-curved nets require form-finding to determine shape
- Deflection criteria of L/40 to L/50 can be accommodated with lower cable prestress and boundary reaction loads
- Exacting prestress requirements to provide the correct membrane shape
- Highest relative cost

The Central Terminal at Sea-Tac International Airport in Seattle includes what is believed to be the first double-curved cable net wall built in the United States. The facade was designed by the Central Terminal architects Fentress Bradburn with consultant ASI Advanced Structures, and was completed in 2005 under a design-build contract by facade contractor Architectural Wall Systems, with Mero Structures providing engineering services and cable net supply (Figure 5.8). The cable net includes five double-curved cable net segments comprised of ¾ in. (20 mm) stainless steel cables and clamp fittings. With 449 panes of triple-insulated glass, the wall is 60 ft (18 m) high and 350 ft (107 m) across. The nets span approximately 75 ft (23 m) between columns subdividing a radius. The three central net bays are approximately 60 ft (18 m) high, with the two end bays stepping down to approximately 50 ft (15 m). The Sea-Tac cable net was designed to deflect up to 11 in. (280 mm) under peak wind loads.

Cable net structures are remarkably minimal—cables, clamping elements, and glass fixing components comprise the entire structural system—and are easily the most transparent of the facade structure

FIGURE 5.5 Time Warner Center, New York, 2004, Skidmore Owings & Merrill. This flat cable net is 150 ft (46 m) tall and 90 ft (27 m) wide.

system types. However, this material advantage is at least partially offset by the necessary strengthening of the supporting boundary steel to accommodate design loads and full-time prestress forces.

Design Considerations

Cable net design and engineering is a specialty, and while there is now a selection of specialty firms providing such service, few conventional building designers or engineers have this capability. Given the high prestress loading to the boundary steel, it is important that the cable net designer be involved early in the design process. Boundary stiffness is a key element in the design of the cable net, and is best negotiated between the cable net designer and the building engineer. The cable net designer can then model and analyze the cable net design and provide reaction loads to the building engineer as needed for the design of the building structure supporting the cable net. An iterative design process and back-and-forth communication between the design teams is the best manner in which to arrive at

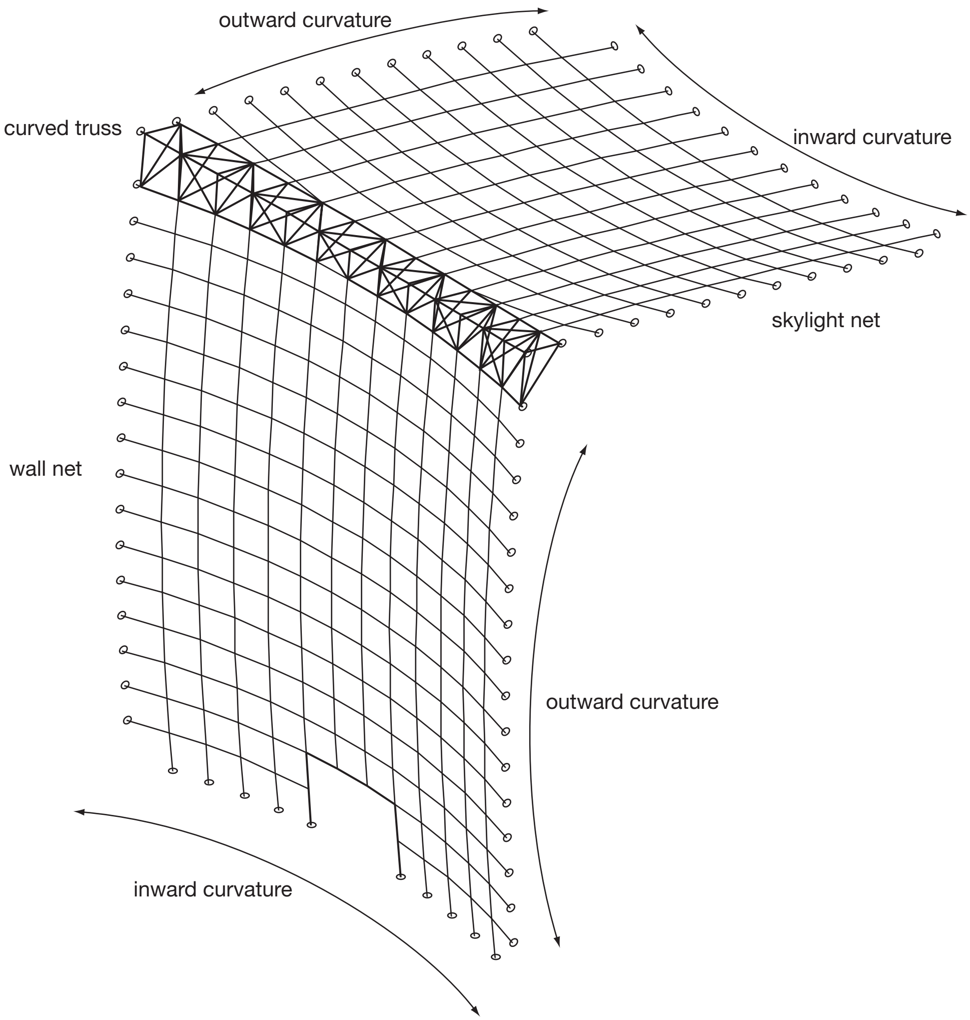


FIGURE 5.6 SEC Station Place, Washington, D.C., 2003, Kevin Roche John Dinkeloo and Associates. Diagram of the double-curved cable net and skylight that enclose the building lobby.

an optimized design having the least impact on the structural design for the building. If the design of the cable net is delayed until late in the structural design of the building—or worse, until the structural steel is under construction— significant disruption to the work of the engineer or the construction of the building is possible. Unfortunately, this occurrence is not as uncommon as might be expected.

Grid module definition is a concern with both flat and curved cable nets. The grid must be sized in the context of an often competing set of variables. While there is great latitude in the determination of a grid module for a flat cable system, there is less leeway with a curved cable net, as the final grid size will be a function of the form-finding process as determined by the net geometry, the mechanical properties of

FIGURE 5.7 The slight curvature in the placement of the perimeter anchors is key to providing form to the cable net.

the components, and the pretension forces designed into the system. The net grid typically matches the glazing module. Unless the building grid or some other consideration is driving the glazing module, a good place to start is with the type of glass to be used and the approximate area or size of the largest glass panel. The glass will be heat-treated, and may be laminated and/or insulated. Suppliers should be confirmed and budget pricing considered before finalizing the grid module.

Pretension requirements should be anticipated during the system design process, and the perimeter support conditions should be designed to facilitate this important installation activity. If hydraulic equipment is required to achieve prescribed cable tensions, then a convenient mounting for the cylinders must be integrated into the perimeter anchor design where the pretensioning will take place (see Chapter 14).

Cable systems may not be an appropriate system choice for renovation work because of the high prestress loads unless additional boundary support can be provided around the perimeter of the facade. As the glazing grid typically coincides with the structure grid, determination of the module is an important consideration that will affect prestress requirements, reaction loads, and system deflections.

Double Curvature

Given the early application of cable nets as anticlastic membrane structures, it was only a matter of time before designers began developing double curvature in cable net–supported glass facades. This can be accomplished by defining an appropriate geometry to the boundary condition of the net. Curvature in plan, for example, can be defined by vertical cable anchors fixed to a curved overhead

FIGURE 5.8 Sea-Tac International Airport Central Terminal, 2005, Fentress Bradburn Architects. The double-curved cable net facade supports a point-fixed drilled glass system.

truss and with the location of base anchors following the same or similar curvature. Opposing curvature can be provided by the location of horizontal cable anchors on either side of the structure. When tensioned, the cables pull against each other, resulting in a saddle-shaped surface that acts to provide the inherent geometric stability lacking in the flat cable nets, exactly as takes place with tensioned fabric membrane structures. A flat, square fabric awning, for example, will flap in the wind; such flapping is moderated only to a limited extent by applying tension to the fabric. However, if one set of opposing corners is pulled in one direction normal to the plane of the fabric and the other set of corners is pulled in the opposite direction, a saddle shape will result and the membrane will be stable under significantly higher wind loading.

The primary advantage of this design strategy in glass facade applications, in addition to providing a more interesting surface geometry to the facade, is that the enhanced stability of the double-curved net significantly reduces the high deflections associated with the flat systems and thus requires less pretensioning to control those deflections. This lessens the requirement for heavy boundary structure to resist these loads.

The development of the geometry of double-curved cable nets is an important consideration; they are sensitive to relatively minor changes in net geometry, material properties, boundary support, and design loading, and the final shape of the net must be determined as a function of performance. Adjustments to these variables during design development can have a significant effect on net performance, including the required cable prestress as well as cable forces under design loading. In addition, coordinated manipulation of the net geometry can consolidate the variation in glass panel sizes required to glaze the net. Without this design coordination, and depending upon the symmetry of the net geometry, it is possible that a different size may be required for each grid panel of the net. These factors can significantly increase costs, both of the glass itself and for the additional handling required in the manufacturing and installation processes.

Form-finding

Cable nets are part of a class of flexible tension structures that includes fabric membranes. Like membrane structures, double-curved cable nets present something of a challenge to many designers since the shape of such surfaces cannot be arbitrarily imposed. Form in these truly performance-based structures is a function of anchor locations and stiffness, net geometry, mechanical properties of the materials, and the pretension forces defined as a function of the design. The shape of such a structure is determined through a process called *form-finding*, an iterative and interactive process that can make use of both physical and computational modeling. While various computational programs are readily available to accommodate the form-finding and further analysis of cable net structures, such tools are not typically a part of the work process of most building designers, architects, or engineers. At least for now, this remains a specialty technique and the province of a small but growing group of consultants and design-build firms specializing in this and related technology. Most building designers are therefore left with the frustrating circumstance of being unable to definitively describe the shape of the structure during the design phases, and even an approximation can be a challenge. In cases where a close approximation is not possible or adequate, a specialist should be included in the design team.

Structural Behavior

In practice, cable structures are remarkably resilient and accommodating, designed to absorb significant movement without damage to structure, glass, or weather seal. They can deform to many times the deflection criteria of conventional steel or aluminum structures without permanent deformation or failure. Deflection criteria for flat cable structures typically fall in the L/40 to L/50 range. The cable mullion system for Alice Tully Hall, included as a case study in Chapter 16, has a deflection criterion of L/35. Contrary to being a problem, these deflection criteria provide the resilience to best withstand the extraordinary loadings resulting from seismic events or bomb blasts by absorbing and releasing the energy with mitigated impact to the structure itself.

One thing is apparent in examining the completed works with cable facades: their use of material is minimal—some type of cable, clamping fittings to secure the vertices and fix the glass to the structure, and perimeter anchor assemblies to attach the cable ends to the boundary structure are the primary elements beyond the glass itself. This material efficiency does not generally translate into economic competitiveness with more conventional systems, a subject discussed at the end of this chapter.

While individual projects can become quite complex, as evidenced by some of the case studies included in this book, the basic elements of a cable system are simple and few. Cables are the primary structural material. There are choices concerning cable type and end fittings, or *terminations*, as they are referred to in the industry, clevis and threaded fittings among them. The choice is influenced by such factors as the visibility of the cable terminations in the final installation, or it can be dictated by the tensioning strategy to be used in installing the structure. As a rule of thumb, a cable tension of over 8 kips, or 8000 lb (35.6 kN) of force, will require some form of hydraulic jacking. Lesser tensions in a properly designed anchor condition can usually be generated by the turn of a nut on a threaded termination fixed to a simple anchor assembly, with leverage provided by a large wrench or a spud wrench and breaker bar. At some point, as the tension increases, the nut will begin to gall on the thread and further tightening may damage a threaded termination. The point of galling is not simply a function of the tension, but also of the size of the threaded assembly and, more particularly, the material and material finish of the termination assembly. The actual galling point is best determined empirically based on the specific project parameters. It is far better to determine this value as a mockup or prototyping exercise than in the field during installation, where the discovery of a galling problem can be quite costly to remedy.

Cable systems typically require a clamping component to fix the cables at the cable intersections, or vertices. The cable clamp must be designed to provide enough clamping force to ensure no movement of the cable within the clamp under peak design loads. This component generally does double duty by also facilitating the fixing of the glass system to the cable structure. In such a minimal system, the components tend to become more visually prominent as a function of the overall material scarcity. It is desirable, therefore, that these components are of high visual quality, and most designers bring great attention to the development of the clamp assembly. For this reason, stainless steel is often employed as the material in a machined or cast fitting. It is also important that the surface finish of a stainless steel component be properly considered and specified.

One common design for a cable net fitting is a four-part component (Figure 5.9). The inner three parts secure the net at a vertex. The outer third part also incorporates an integral shelf that supports the dead weight of the glass. The glass sits on a setting block of high-density silicone used to cushion the glass against direct contact with the metal. Thin strips of silicone are also used to sandwich the glass between the third clamp part and the final exterior clamp plate. The designs may vary in appearance, but the basic function remains the same. This style of clamping component can be easily designed to accommodate any of the various types of fabricated glass panels, which are effectively point-fixed in this design, but through the mechanism of clamping rather than bolting.

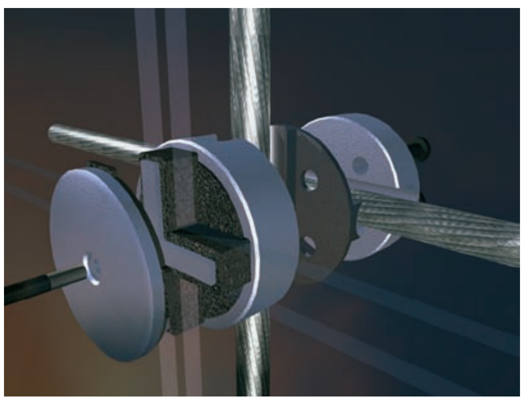


FIGURE 5.9 A schematic rendering of the four-part clamp typical of a cable net. Note the dead-load plate where the glass rests.

Bolted point-fixed glass systems can also be integrated with a cable structure, but they require perforations in the glass to accommodate the bolts. Figure 5.10 shows a clamping assembly designed to receive a spider-type fitting that provides the fixing points for the corner bolts that fasten the adjacent perforated corners of four glass panels. The application shown here is on a double-curved cable net. The cable net clamping assembly works in the same manner as the previous design, with three cast stainless steel pieces that act to clamp intersecting cables at a vertex point of the net. The outer component of the clamp assembly integrates the glass connection fitting.

Constructability

The tolerances in this type of system are demanding. The net is typically installed to a high level of accuracy, with each clamp requiring positioning as close as ± ⅛ in. (3.2 mm) from its theoretical position, depending upon the amount of adjustability designed into the clamp and spider components. Hole positions in the fabricated glass with respect to the glass edge are another consideration, as is their tolerance from the theoretical position. The accumulation, or stacking, of tolerances must also be evaluated. These tolerances can vary among fabricators, and need to be rigorously defined and analyzed to determine the maximum out-of-position locations for each component. These accumulated tolerances must then be accommodated in the design of the clamping assembly and/or spider fitting. The glass system must provide for two critical functions beyond simply securing the glass panels to the supporting structure: it must provide for any out-of-position components within the specified

FIGURE 5.10 An H-type spider fitting supported by a double-curved cable net. Note the large silicone joint between the insulating glass units (IGUs).

tolerances, and it must provide for the movement of the system under dynamic loading conditions, including racking loads that might occur as a function of seismic events.

In some cases, novel panelized or unitized framing systems have been developed that can be bolted to a modified cable clamp assembly. The frame is thus point-fixed rather than the glass, avoiding entirely the premium cost associated with point-fixed glass systems.

Glass fabrication for flat cable structures presents no particular challenge, with any glass makeup readily accommodated. Higher deflections than those for fully perimeter-supported glass may require thicker lites. The glass manufacturer's warranty requirements typically limit the allowable deflections on IGUs to L/140, although this restriction is loosening. Some European glass fabricators warrant deflection limits to L/90. Even lower limits may be possible, but it is important to have an early dialogue with the potential suppliers during design development. Code requirements, thermal performance, acoustics, and other considerations may dictate the use of laminated and/or insulated glass panels. Heat-strengthened or fully tempered glass is typically used in any point-fixed glass applications. The cable structure is a dramatically dematerialized structure. In keeping with this, and where other considerations permit, monolithic tempered glass panels are often used as the most effective for maximizing transparency. Low-iron glass is employed to maximum effect in such an application, at a premium of approximately 10 to 15% over the cost of conventional clear glass, with its slightly greenish tint. For the ultimate in transparency, an antireflective coating can be applied to the glass surface, which significantly reduces reflections from the surface, especially when viewed at a low angle of incidence. The monolithic panel also benefits from the smallest practicable silicone joint between panels to provide the weather seal. The use of monolithic glass is not recommended where poor thermal performance will significantly compromise energy efficiency, as is often the case. However, cable-supported monolithic glass has been used as the outboard skin in double-skin facades (see Chapter 14).

Glass panel fabrication for double-curved cable nets can be more of a challenge. The geometry of these nets often results in a grid of trapezoidal shapes. The glass fabricators are accustomed to orthogonal shapes: squares and rectangles. Deviations from this are referred to as *pattern glass*, with a premium of approximately 15 to 20%, or more if the pattern results in an abundance of waste from leftover pieces. The pattern cuts often cannot be processed by automated facilities, hence the resulting cost increase. The cost impact of the patterns is highly process dependent and is not uniform from one fabricator to the next, so it pays to solicit quotations from multiple sources.

The double-curved cable nets generate not only patterns, but often an abundance of unique patterns as well, resulting in a large number of different part types. The various part types must be carefully and clearly marked by the fabricator to provide for easy identification by field personnel, indicating orientation (inboard/outboard, which may not be visually apparent in the field) as well as type. Whatever the material or component, geometric complexity results in a high multiple of part types, which serve to propagate the complexity through the processes of fabrication and installation, representing a significant management challenge to the firms that undertake this demanding work. Even if automated systems can solve the problem of fabrication complexity, when the part gets to the field a construction worker still has to identify and handle it, ensuring its correct positioning in the prescribed sequence, and a large variety of part types can have significant impact in the absence of careful installation planning.

In addition to point fixing, which places certain structural demands on the glass panel, double-curved cable net applications may present other challenges. Depending upon the geometry developed for the net, some designs may result in grid modules in which the four corners that define a module are significantly out of plane. This condition can require warping of the glass panel in the installed condition, sometimes referred to as *cold forming*. Furthermore, deflections of the cable net under design loads may result in localized warping of glass panels, or further warping as the case may be. Each glass panel must be engineered to withstand the loads it will experience, including the warping load. This is of particular concern when using IGUs, where warping forces stress the bond providing the hermetic seal to the airspace between the two pieces of glass.

A related consideration here is the warranty; the glass fabricator must be willing to provide their warranty in full consideration of the warping and other loads that are a function of the application. While the cable clamp designs easily accommodate any glass makeup, warranty can be an issue. Point-fixed glass panels experience higher deflections than two- or four-side supported panels, and some glass fabricators will not warranty their product, or even sell it, for such an application. This is largely a reflection of the highly conservative and risk-averse building environment in the United States. European fabricators have been providing glass in point-fixed applications for over 30 years and typically offer warranties of 10 to 12 years. Viracon, a leading glass fabricator in the United States, began in 2006 to provide product for point-fixed applications (including a drilled IGU) under a 10-year warranty. The European suppliers, however, typically allow higher deflections in their insulated glass products. In any novel or extreme application of glass, the issue of warranty is best addressed with the glass fabricator during the design phase of the project, when accommodations to the fabricator's specifications may be easily implemented.

The stainless steel materials for the cables and components typically have the highest quality, the greatest durability, and the most minimal maintenance requirements. The cable system is generally located within the weather envelope and is not exposed to the elements. If the structure is exposed to the outside, environmental factors such as proximity to the ocean and industrial pollutants become important considerations in material and finish selection. Stainless steel cables and components, properly specified and handled, should have life spans approaching 100 years or longer, with minimal maintenance. Galvanized cables and painted or plated components will perform in direct proportion to the quality of the finish material and its application. Material finishes are easily damaged on site during assembly and installation, and care must be taken to protect them so as not to compromise the long-term performance of these components.

Installation

The simple planar geometry of flat cable systems make them relatively easy to install. Nonetheless, the key to maximum efficiency in the installation of any cable-supported glass facade or enclosure is precision. If the vertex clamps of the structure are accurately located, the glass installation will progress efficiently.

Cable nets can be assembled in place at the building site or preassembled under factory-controlled conditions. Considering the high cost of field labor in the U.S. construction marketplace, cost savings can probably be realized in a factory assembly strategy. It is also usually easier to control tolerances under factory conditions. A large layout and assembly area may be required, and the factory assembly of a double-curved net may require an area at least as large as the net itself. A simple hydraulic fixture can be assembled to facilitate cable marking, with each cable loaded to pretension requirements and carefully marked for vertex clamp positions. Care must be taken to establish a starting point for the marks at the top or bottom of a cable. This point then needs to be accurately calibrated in the field. Cables should be marked to facilitate positioning of the cable clamp; a center mark will likely be of limited use if it is not visible as the clamp is positioned. Marked cables can then be laid out and the vertex clamps installed. Twisting or kinking of the individual cables during the assembly process must be prevented. Nodes must be handled in a manner that avoids damage to the components and their finishes. After assembly, each vertex clamp should be wrapped in a protective packaging material. The net can then be carefully folded, or preferably rolled upon a metal drum or similar fixture. If it is folded, the cables should be protected at the folds to avoid damage. A drum roller can be effectively employed to incrementally roll up the net as the assembly progresses, thus minimizing the assembly area size.

Depending upon the degree of curvature, double-curved nets too can be folded and rolled, although they are considerably more difficult to handle. Also, fixing of the cable vertices on a double-curved net without positioning and pretensioning the entire net may result in rotational misalignment of the cable clamps that can result in cable twisting when the net is installed and tensioned. For these reasons, some builders prefer to install double-curved nets in place. A sound but more complex factory assembly strategy appropriate for double-curved nets is to build a boundary fixture to support the entire net, ideally one that replicates the theoretical boundary stiffness of the actual structure as used in the computer model. This is the preferred method for factory assembly of a double-curved net. This strategy can also be used with flat nets, minimizing cable-marking requirements; when the cables can be properly positioned and tensioned, the vertex clamp locations are defined simply by the cable crosses. Double-curved nets may require cable marking prior to pretensioning, depending upon the geometry. Once pretensioned, the clamp assembly positions should be surveyed on both the flat and double-curved nets, the latter being far more difficult because of the three-dimensional position.

The preassembled rolled or folded nets are deployed at the site, lifted into position using multiple hoists as required, and the end fittings secured and positioned. Alternatively, field assembly of the nets is facilitated by installing the vertical cables first, followed by the horizontals. Cables are usually marked and numbered in the factory prior to delivery to the field. Extensive use of man-lifting equipment is often required with this technique for the purpose of installing the vertex clamp assemblies prior to pretensioning. An alternative technique is to stage the net assembly from the ground immediately below the top anchor ties for the vertical cables. Multiple hoists or multiple feeder lines tied to a single hoist can be rigged through pulleys located at each top anchor location. The feeder lines tie to the top termination of the vertical cables. Horizontal cables are laid out along the base of the wall. The uppermost horizontal cable is first fitted to the verticals with the installation of the clamp assemblies by the installers working at ground level. The vertical cables are then hoisted incrementally to the position of the second uppermost horizontal cable. Proceeding in this manner, the entire net is assembled at ground level, where worker productivity is maximized. Man lifting is required only at the perimeter to secure and pretension the net.

Cable tensioning requirements range from simple to extraordinarily complex, largely as a function of prestress loads and system geometry. One-way and two-way flat cable systems are geometrically simple, but prestress loads can be quite high if spans are significant. Much technique is involved in the tensioning of the more complex cable net shapes. Appropriate theoretical cable pretensions must be determined during the design of the structure in a manner that yields the most efficient shape to the net, and then these exacting tensions must be realized in the field. Pulling a uniform *x-y* grid into a varying *z* dimension provides a spectrum of challenges at the building site. In order to achieve the proper shape in the net, clamps must be accurately positioned on the cables, and the procedure may require that all cables, vertical and horizontal, be tensioned simultaneously. This will require a rather complex system of hydraulic jacking gear to be assembled for the purpose.

Cables should be prestretched in accordance with the cable supplier's recommendations, but at minimum to the maximum design load for the application. The cable anchors at the facade boundary should be designed to accommodate the hydraulic gear used to apply the prestress load. The cables are typically overtensioned by as much as 5% to compensate for the cable relaxation that occurs shortly after tensioning even when prestretched cables are used. A properly calibrated and accurate tension-measuring device is used to verify the applied prestress loads (Figure 5.11). Tensioning methods usually prescribe that the system be allowed to stretch for a period of time, then rechecked and adjusted as required. Several cycles of tensioning and adjustment are sometimes required, with longer times between each cycle until the system is stabilized. The glass should not be installed until the system has stabilized.

Laser survey equipment and techniques can be used to map the position of each node. The resulting survey data are digitally compared to the theoretical net to identify "soft spots" or "hard spots" in the net, which can result from deviation of the actual boundary stiffness from the theoretical design stiffness (or from incorrect clamp positions or cable lengths). Compensating adjustments in the tensioning of the net can then be computed and implemented. Assuming that node positions and cable lengths are correct, simply moving individual node locations in an attempt to correct the problem may be ineffective, as moving one part of the net can affect the surrounding net geometry in an unpredictable manner. Thus, adjustments to the net are best made systemically rather than locally. The key to success in the installation of a cable net facade is to get the glass fixings located within tolerance without exception. If the vertices of the net are located accurately, glass installation can be remarkably efficient. If not, installation efficiency can be dramatically compromised by the adjustments to the net and clamp locations.

Dead load deflections are an important constructability consideration for any suspended systems and all cable systems. The overhead supporting structure will deflect under the added dead load of the glass. This deflection needs to be anticipated in system design and installation planning. A lobby facade renovation on a downtown Los Angeles building involved a cable-suspended horizontal mullion system. The point-fixed glass was hung from the structure starting at the top. The overhead beam deflected as the glass installation

FIGURE 5.11 A tension meter is being used here to measure the prestress levels in a cable.

progressed, throwing the joints between the glass out of alignment. A second and finally a third installation subcontractor were brought in to solve the problem, which ultimately required removal of all of the glass and a new start. The solution is as simple as anticipating the amount of deflection and adjusting for it in the initial positioning of the glass, such that by the time all the glass is installed, all glass panels are in the proper alignment. Another strategy is to calculate the expected amount of deflection and build camber into the supporting structure to compensate. Highly prestressed cable structures may be only minimally affected by the additional glass dead load.

The glazing system to be supported by the net dictates the tolerance requirements for the installation of the net. The glass system must be capable of accommodating some level of field tolerances in the structure, as well as any variances in the glass panels themselves. The more tolerance the glass system is able to accommodate, the lower the tolerance can be in the positioning of the net, reducing the difficulty of installation. Cable nets supporting bolted point-fixed glass can be exceptionally demanding with respect to the installed positioning of the net. The glass panels are delivered to the field as prefabricated panels, sized and with drilled holes at the corners. The holes accommodate a special countersunk bolt that fixes the panel to mating components located at the net's vertices. These fixings can range in design from simple steel plates to sophisticated cast stainless steel spider fittings that grab four adjacent corners of glass and, in turn, secure them to the vertex clamp of the net. If the clamp is not located within a very tight tolerance, mating the holes in the glass with the fixing component can present an unwelcome challenge.

The glazing systems most often used on cable nets are point-fixed, both drilled and clamped systems, as discussed in Chapter 2. Beyond aesthetics, the primary considerations for these alternatives are price and installation tolerance. The vertex clamping strategy is the most efficient, most economical, and most widely used with cable systems. Panelized or unitized systems have also been used, providing greater flexibility, generally lower cost, and more choices in glass supply, but at the expense of relative transparency and more visible sight lines than with the point-fixed systems.

A frequent question with respect to cable structure applications is whether it is necessary to adjust cable tensions periodically to compensate for cable stretch over time. This issue is best addressed by the cable system engineer on a case-by-case basis, but the determination of appropriate design prestress, the prestretching of all cables in the factory, the following of an appropriate installation method statement, and the verification that design prestress has in fact been achieved in the field should mitigate or eliminate this requirement. Some facade consultants recommend checking cable tensions after a year of service.

Method Statement

A method statement is particularly important on a complex cable net project with demanding installation requirements. An appropriate method statement for cable net structures will address the following considerations at minimum:

- Cable prestretch, packing, shipping, and site storage
- Component packing, shipping, and site storage
- Site preparation
- Survey requirements
- Tools and hydraulic equipment requirements
- Calibrated tension meters
- Part identification
- Assembly and installation plans
- Survey verification of anchor locations
- Assembly sequence of the cable net
- Pretension specifications for each cable
- Pretensioning procedure
- Post-pretensioning measurement of prestress values

- Validation requirements for the cable net before commencing glass installation (often requires a series of pretensioning measurements and adjustments separated by specified time intervals)
- Glass installation procedure
- Sequence of glass installation
- Weather seal procedure
- Inspection requirements and procedures
- Required approvals

Economy

Cable systems represent new technology from which cutting-edge applications will be forthcoming for years to come. However, the fundamental technology of cable structures is maturing rapidly, and with each new application, building owners, developers, architects, and contractors become more receptive to and interested in having such technology incorporated into their building projects. As recently emergent technology, and in spite of their obvious material efficiency, cable structures dominate the high end of the cost scale for SGFs and building enclosures. Much of this cost premium is due to the development costs associated with research, prototypes, mockups, testing, and installation methods and technology, all of which have necessarily been absorbed by these early projects. As a rough approximation, for a given application, a cable net is likely to cost two to two and a half times as much as a steel truss system. As the know-how and technology associated with cable structures are gradually disseminated into the broader marketplace so that more architectural firms and local glazing contractors become familiar and comfortable with them, the application costs should drop significantly, leading to more widespread use. At the same time, cable systems are the current wellspring of innovation in SGF development, and more high-profile, costly, and complex designs intent on pushing the building envelope are certain to come.

Chapter 6

Glass as a Structural Material

Glass is being used increasingly as a structural material (Figure 6.1). Even before the discovery of heat-treating glass to enhance its strength, the nineteenth-century conservatory designers and builders were using glass as a stressed skin to stabilize the iron structures supporting it. Glass is an exceptionally strong material, but its extreme brittleness presents distinct challenges in structural applications.

There are many aspects to the use of glass as a structural material, as well as books dealing exclusively with the subject.[1] In using glass as a structural material, it is necessary to understand the processes and techniques used to enhance the performance of glass as a load-bearing material. These are the fundamentals from which sound structural applications derive. Once the structural

FIGURE 6.1 Apple Store, Fifth Avenue, New York City, 2006, Bohlin Cywinski Jackson architect with Eckersley O'Callaghan as the glass engineer. The Apple Cube broke new ground in glass structure design.

components of glass have been devised, the next challenge becomes connecting them to each other and to other structural elements. The recently completed TKTS project at Times Square in New York City (see Chapter 17) affords an opportunity to see how the connections were handled in a heavily loaded glass structure.

Heat-treating

Heat-treating refers to the postprocessing of float glass to improve its strength and/or to alter its breakage behavior. Glass is annealed as part of the float glass process, and annealing itself is a form of heat treatment.

Heat-treating, or *toughening* as it is referred to in Europe, is a process developed by the French in 1928. It provided the material properties necessary for the structural glass systems to follow decades later. Point-fixed glass systems utilize heat-treated glass. There are two kinds of heat treatment, heat-strengthened and fully tempered (partially toughened and fully toughened). Fabrication requirements, tolerances, and testing procedures for heat-treated glass are defined in ASTM Standard C1048.

Annealed Glass

Annealing is a process of controlled heating and cooling of a material to remove internal stresses. With glass, the term *annealing* refers to the controlled cooling of float glass for the same general purpose. Internal stresses caused by uneven cooling of the material can significantly compromise its strength, causing it to fail under much lower stresses than material in which these internal stresses have been relieved. Annealing is required to facilitate the workability of glass, such as the easy and uniform cutting of the material. The float glass process has a built-in annealing procedure as a final step in the production of flat glass, and the raw glass resulting from this process is referred to as *annealed glass*. Subsequent secondary heating, such as in the production of bent glass, may require that the glass be annealed again as a final step in these processes.

Tempering

Tempering and *toughening* are terms used interchangeably in the glass industry in reference to the heat treatment of glass to produce a material with improved strength and altered breaking behavior. Tempering is a secondary process whereby annealed glass is subject to a cycle of carefully controlled heating and subsequent rapid cooling. After all cutting and machining work have been completed on a piece of annealed glass, it is run over horizontal ceramic rollers approximately 5 in. (127 mm) in diameter through a tempering oven, which heats it to approximately 620°C (1150°F).Tempering ovens are custom-built long enough to bring the glass to the required temperature in a precise amount of time. The process is tuned to the glass size and thickness. Some modern ovens employ a so-called shake-and-bake technique, whereby the glass cycles back and forth to reduce the necessary length of the oven. On reaching the required temperature, the glass exits the furnace and is rapidly cooled by airflow over both surfaces simultaneously. The glass first cools and solidifies at the surface. As the interior glass slowly cools and contracts, it gradually pulls the outer surface into compression. The end result is a sheet of glass with a core tension resisted by a surface compression. Glass is an exceedingly strong material in compression, but its brittleness leaves it vulnerable to the propagation of surface cracks under tensile loads. The compression of the glass surface significantly reduces this vulnerability.

Improved strength and resistance to thermal stress result from the tempering process. Fully tempered glass is four to five times stronger than annealed glass. Tempered glass also possesses a unique behavior when broken; the glass shatters into rounded kernel-size pieces without sharp edges. Because of this attribute, tempered glass is sometimes referred to as *safety glass*, and building codes require its use in and around doors and adjacent to other public circulation areas. Tempered glass cannot be cut or machined; all such working must be completed prior to tempering.

Modern glass produced by the float process is a remarkably flat material of high surface quality. The tempering process involves moving these flat glass panels through a specially designed oven. These ovens are custom in design and can vary substantially in width among fabricators. The tempering oven can be the limiting factor in the maximum glass dimension and must be considered during facade design, especially if the intent is to use very large pieces of glass. Included in this consideration should be the orientation of the glass in the oven in relation to its orientation on the building, as discussed in a following section on roller-wave distortion.

Fully Tempered (FT) Glass

FT glass has been heat-treated to have either a minimum surface compression of 10,000 psi (69 MPa) or an edge compression not less than 9700 psi (67 MPa) in accordance with the requirements of the American Society for Testing Materials (ASTM) Standard C1048, or to meet the requirements of the American National Standards Institute (ANSI) Z97.1 or the federal Consumer Products Safety Commission (CPSC) 16 CFR 1201 safety glazing standards. Glass with fully tempered surfaces is typically four times stronger than annealed glass and two times as strong as heat-strengthened glass of the same thickness, size, and type. If fully tempered glass is broken, it will break into small pieces, reducing the chance for causing injury. However, when the glass breaks, the small pieces make it more likely that the glass will become separated from the opening. Tempered glass complies with the safety glazing requirements outlined by ANSI Z97.1 and CPSC 16 CFR 1201.

Heat Strengthening (HS)

Partially tempered, partially toughened, and *heat strengthened* are equivalent terms for the heat treatment of glass yielding a material with strength properties between those of annealed and fully tempered glass. Heat-strengthened glass is two to three times stronger than annealed glass, whereas tempered glass is four to five times stronger. Heat-strengthened glass has a surface compression between 3500 and 7500 psi (24 and 52 MPa), as again defined by specification ASTM C1048, Kind HS. Heat-strengthened glass has improved resistance to thermal stress and is often specified for this attribute, especially as the outboard pane of insulating glass units (IGUs) in high-rise buildings with deep mullions where thermal stresses can result from high temperature variations in the glass between shaded and exposed areas. With a break behavior closer to that of annealed glass, heat-strengthened glass is not classified as a safety material and cannot be used in safety glass applications. Heat strengthening does not meet the requirements of ANSI Z97.1 or CPSC 16 CFR 1201.

Roller-wave

Raw float glass is a remarkably flat material with excellent optical properties and is largely free of distortion. This is most easily seen in the reflected light from a glass surface and is a visual consideration with architectural glass. Heat-treating can compromise the flatness of the glass, resulting in visual distortion. During the tempering process, the glass panel lies horizontally on a bed of ceramic rollers as it moves through the oven. As the glass is heated and approaches its plastic state, it is subject to slumping between the supporting rollers, resulting in a periodic wave-like surface distortion called *roller-wave*. Glass is seen largely through the reflections it produces, and excessive roller-wave can be perceived in the distorted reflections produced by the wavy glass surface. The higher the reflective properties of the glass are, the more visible will be the distortion.

Common wisdom is that the direction of the waves should be parallel to the horizontal direction, meaning that the horizontal dimension of the glass should be parallel to the rollers during tempering. This may not be possible if the glass module has a landscape as opposed to a portrait orientation with a large horizontal dimension. The horizontal orientation tends to minimize or eliminate a vertical rippling effect of reflected light as the viewer moves parallel to the facade, as in an automobile. However, the horizontal orientation will reveal roller-wave distortion in the reflected image of strong vertical elements such as building edges and utility poles. It is thus important to consider the site context when determining the orientation of heat-treated glass. In any case, care should be taken that the direction of the roller-wave is consistent throughout the facade. Laminated glass may exhibit increased distortion if the roller-wave of each piece is coincident, producing a lens effect. (Excessive roller-wave in laminated glass can also cause delamination.) All tempered glass will exhibit some level of roller-wave, but the magnitude can vary widely among manufacturers.

In high-quality frameless glass systems, roller-wave is an important consideration, and an appropriate tolerance should be determined and specified. Roller-wave is easily measured using specialized devices designed for this purpose. Unfortunately, in the United States, the industry standard for heat-treated glass, ASTM C1048 2004 Standard Specification for Heat-Treated Flat Glass—Kind HS, Kind FT Coated and Uncoated Glass, discusses distortion but defines no tolerance or minimum standard. If no specific roller-wave criteria are defined in a project's specifications, there will effectively be no control over this important attribute. Roller-wave tolerances can be specified within certain limits, although not all manufacturers will be able to meet a more demanding specification. In spite of highly sophisticated and automated tempering ovens, the process remains to a significant extent a craft. New tools, such as in-line optical equipment, are now able to provide virtually instant and ongoing feedback to the line operator. However, a combination of top-quality equipment and an experienced and knowledgeable operator is required to ensure optimal flatness in a tempered product.

Bow and edge lift are other possible forms of distortion resulting from the heat-treating process, and can be equally apparent and undesirable in application. Pilkington has set the industry standard with respect to such distortion in the production of their heat-treated architectural glass, significantly bettering regulatory standards where they exist.

Table 6.1 shows data compiled from the Web sites of Viracon and Pilkington regarding distortion resulting from heat.[2,3]

TABLE 6.1 Distortion Resulting from Heat Treatment

Type of Distortion	**Published Tolerance**		
	Viracon	**Pilkington**	**Standards***
Overall bow (in./linear ft)	0.031	0.024	0.062
Overall bow (mm/305 mm)	0.787	0.61	1.575
Roller wave			
Peak to trough (in.)	0.003	0.0008	No standard
Peak to trough (mm)	0.076	0.02	
Edge lift (in.)†	0.008	0.009	
Edge lift (mm)†	0.20	0.229	

*ASTM C1048 Standard for Heat-treated Flat Glass.

†Within 10.5 in. (267 mm) of leading and trailing edges.

Surface Flatness and Optical Distortion

A point-fixed screen wall is part of a complex facade system for the Clinton Library in Little Rock, Arkansas, a LEED Platinum certified building and winner of a National American Institute of Architects (AIA) Honor Award for Architecture in 2006. Polshek Partnership Architects specified the use of a laminated panel comprised of a tempered inner ply and an annealed outer ply to reduce optical distortion in the glass surface of the screen wall. The flatter surface of the non-heat-treated annealed glass minimizes the distortion of reflected light. While the laminated construction combining a tempered back ply with an annealed front ply will likely exhibit greater optical distortion than a simple annealed monolithic panel, visual mockups provided to the architect clearly demonstrated better optical properties than those of laminated panels where both plies were heat-treated. A tempered inner ply was required to accommodate the point-fixing system of the glass to the supporting structure.

Nickel Sulfide Inclusions and Spontaneous Breakage

Nickel sulfide is a contaminant, a small stone or crystal that can be present in float glass. In annealed glass it presents no problem, but in tempered glass it has been identified as the source for rare occurrences of spontaneous breakage, whereby the glass shatters for no apparent reason. Low-quality glass production may result in a higher occurrence of the contaminant. While these events are rare, they have produced considerable concern in the building community, with corresponding measures to reduce their likelihood.

Most structural glass facades (SGFs) built in North America and Europe have utilized fully tempered glass because of its higher strength and resistance to bending loads in the vicinity of the point fixing. Interestingly, in Asia and other developing areas of the world where the local glass supply may be of lesser quality, some SGF designers are moving away from the use of tempered glass, regarding the spontaneous breakage problem as simply too risky to tolerate. Instead, they are using heat-strengthened laminated glass panels. In fact, perhaps owing largely to liability concerns, glass fabricators in North America are cautioning against the use of tempered glass unless it is required for reasons of safety or strength. Viracon's Web site includes the following statement:

"Although the incidence of tempered glass breakage due to these inclusions is rare, greater publicity of their occurrence has resulted in an increased awareness of this phenomenon. In fact, limiting the use of tempered glass in commercial building applications has become the recommendation of a number of glass suppliers, including Viracon."[4]

Heat-strengthened glass, which is less strong than tempered glass, requires the use of a thicker pane or a laminated panel. The laminated panel is a better choice because of redundancy; if one ply were to break, the other ply would likely hold the panel in place until it could be replaced. This strategy is discussed further in Chapter 8.

Heat Soaking

Heat soaking is a process devised in response to the nickel sulfide and spontaneous breakage phenomenon. In this process, tempered glass is reheated to a specified temperature, usually about 290°C (554°F), held there for a specified time, usually several hours, and occasionally even subjected to several cycles of this heating and cooling. The effectiveness of this practice is somewhat controversial and it adds to the cost of a tempered glass product, but it has become standard practice for many structural glass producers and users.

One specification for heat soaking is the European Din standard requiring a minimum 12-hour cycle at a temperature of 290°C (554°F).

Chemical Tempering

Glass can also be tempered chemically as an alternative to a heat-treatment process. These processes are relatively new and are effective only in glass thinner than that typically used in buildings. Chemical tempering combines very high tensile strength with a breakage pattern of large shards, providing improved postbreakage behavior, but at a significantly higher cost. However, it may emerge as an effective future process that could eliminate the distortion caused by the heat-treatment process and provide for easier tempering of bent glass.

Laminating

Multi-ply glass lamination is the foundation technique for the use of a glass assembly as a component of structure. Modern techniques of glass lamination are highly effective in enhancing the load-bearing capacity of glass, as well as the safety of its use. Laminated glass has significantly increased usage where safety, security, sound attenuation, and strength are predominant design considerations.

The gluing or laminating of sheets of glass in layers evolved as a strategy for strengthening a glass panel and for providing additional safety by eliminating the risk of injury from glass shards resulting from the breaking of monolithic glass. Structurally, laminating increases the composite strength of a component, adds redundancy by reducing the risk of catastrophic failure if a single ply breaks, and improves the postbreak behavior of the material. The process was invented and developed by the French scientist Edouard Benedictus, who patented his new safety glass under the name "Triplex" in 1910. DuPont, a provider of interlayer material for glass lamination, has sponsored an architectural design competition that recognizes innovative work with laminated glass called the Benedictus Awards.

Lamination emerged early on as a strategy for improving the strength of glass in structural applications. As early glass fin facade applications grew in span, the fins were laminated to increase their strength and add redundancy to the structural member; if one of the glass layers broke, the other(s) would work to prevent failure. Multiple laminations, three-ply and more, were soon experimented with, further enabling the use of glass in structural applications. Glass treads and landings comprised of multiple laminations began to appear.

The most commonly used interlayer material is a plastic/vinyl called *polyvinyl butyral* (PVB). It is available in rolled sheet form in various thicknesses. The interlayer materials are supplied in rolls of varied length, width, and thickness. The width of the interlayer material can be a limiting factor in the maximum size of a laminated glass panel. The most common thicknesses are 0.03 and 0.06 in. (0.76 and 1.52 mm). A minimum interlayer thickness of 0.03 in. (0.76 mm) meets the requirements of ANSI Z97.1 and CPSC 16 CFR 1201 safety glazing standards.

The thickness of the interlayer used in a laminated panel is usually a function of the thickness of the glass ply. With the glass grids used in SGFs requiring a pane thickness generally in the 0.25 in. (6 mm) to 0.50 in. (12 mm) range, 0.06 in. (1.5 mm) thick PVB is most often used. The overall thickness of the fabricated two-ply panel would then be 9⁄16 in. (13.5 mm). The process involves heating and compressing the glass/PVB/glass sandwich and is accomplished in an autoclave. The translucent PVB becomes a clear, tough material adhering to the glass surfaces and binding the two pieces of glass firmly together. If one piece of glass breaks, the glass will remain stuck to the interlayer and will not fall from the panel. Even if both pieces of glass break, the shards will not separate from the panel, although the panel can deform and potentially separate from its support. This phenomenon is sometimes referred to as *dropout* and can be a consideration if the laminated panel is large and heavy, especially if the glass is used in a sloped application. Dropout can occur if the laminate is overstressed and tears as the panel deflects, allowing the panel to fall from its supporting frame in a single piece or multiple large pieces. Dropout is obviously more of a consideration with point-fixed glass than with fully perimeter-supported glass. Laminated glass is required by building codes in overhead applications and in sloped glazing angled 15 degrees or more off vertical.

Laminated glass is finding increased use in security applications. Multiple laminations, and laminations including a combination of polycarbonate and glass, have been shown to provide resistance to bullet and blast loads. Multilaminates of 4 in. (100 mm) and more have been produced. Impact loads such as those resulting from airborne debris caused by major wind events such as hurricanes are another security concern. The South Florida Building Code stipulates requirements for impact loads, and glass and window systems used there must be tested to show conformance. Laminated glass plays the primary role in meeting these performance criteria. Solutia and DuPont both manufacture interlayer products specifically designed for improved performance under extreme loading conditions. SentryGlas®, Saflex HP®, and Vanceva Storm® are trade names for a few of the available materials with enhanced properties.

Acoustics is another reason for the use of laminated glass. The interlayer has sound-diffusing properties that result in improved acoustic performance. The lamination material and thickness, and the sizes of the laminated glass pieces, all have an impact on the acoustic properties.

As a strengthening strategy, laminating has some advantages over heat-treating, although the two methods are often combined in structural glass systems. Laminated annealed glass can be worked after lamination. The glass is also free of the distortions that can occur from the heat-treating process. Some point-fixed facades have used a laminated glass panel design combining a tempered back ply to provide optimum strength with an annealed outer ply to reduce distortion in reflected images.

Most laminated glass is simply comprised of the interlayer material between two glass sheets: a two-ply panel. Multi-ply laminates have become common over the past two decades, however, in structural glass and security applications, as mentioned previously. Glass stair treads and landings are typically comprised of three or more plies. Beam and column elements integrated into the design of SGFs, as well as other forms of all-glass structures, are often comprised of multi-ply laminations.

Some interlayer materials maintain translucency after lamination, producing an effect similar to that of sandblasted glass without the problem of keeping it clean (the sandblasted surface picks up smudges and fingerprints very easily). The laminate material can also provide a decorative effect. A range of tinted and patterned laminates have become available, with more choices appearing daily as the industry competes for the attention of designers. Customized photographic images can even be printed on the laminate. Other laminating materials are available with properties that improve thermal performance, fire safety, and security.

A less often used laminating process involves a liquid resin instead of the sheet interlayer material. The glass lites are separated with spacers, and the edges are taped. The cavity is then filled with the resin and cured with ultraviolet light. This technique can be useful in laminating bent glass with small deviations between the bent surfaces.

PVB used as an interlayer in laminated glass has had an unfortunate tendency to wick moisture, discolor, and age poorly in the vicinity of the edges if the edges are left exposed to the elements, moisture, or incompatible materials. The weather seal in most SGFs and in all point-fixed glass systems is provided by a field-applied wet silicone joint between adjacent panes of glass, with the silicone adhering to the glass panel edges. With laminated glass, the silicone material is in contact with the exposed laminate at the glass pane edges. Problems can result if the interlayer is not compatible with silicone. Some laminated glass installations, as described here, have experienced a clouding of the interlayer emanating from the edge of the glass and spreading inward as much as approximately 1 in. (25 mm). A similar problem can occur with laminated panels whose edges are left exposed to the elements, and the application of an edge sealant may be required. Newer interlayer materials are available that manufacturers claim are compatible with silicone material. Such compatibility should be a clear specification requirement, or measures should be taken to treat the edge to isolate the silicone from the interlayer laminate. Coatings are available for this purpose, and the manufacturer of the interlayer should be asked to provide it. The designer should also confirm with the interlayer supplier that a selected material is suited to the application.

The industry has been developing new interlayer materials with improved performance intended to address some of these deficiencies. SentryGlas by DuPont is one such product, mentioned above, that has seen increasing use in SGF applications, including the work of such glass structure designers as James Carpenter and Tim Macfarlane. The case studies of TKTS (Chapter 17), the Broad Center (Chapter 13), Alice Tully Hall (Chapter 16), and others make use of this material because of its advanced properties. In addition to having increased resistance to edge degradation from either weathering or sealant incompatibility, SentryGlas is more structurally stable and stiffer than PVB.

According to DuPont, the material is 5 times tougher and up to 100 times more rigid than traditional PVB interlayer materials. This provides for longer spans in frameless glass lites without the need for intermediate support. The overall thickness of the laminated lite often can be less than with conventional interlayers. Deflections are reduced, and the glass lites tend to be flatter in application. DuPont claims improved postbreakage performance over conventional PVB laminates and enhanced resistance to dropout, the tendency of the glass panel to separate and fall from the supporting structure when all plies of glass have broken and only the interlayer is holding the panel in place. This is an important consideration in point-fixed applications, especially with overhead glass. SentryGlas is also finding extensive use in security applications where blast and impact resistance are paramount concerns.

DuPont publishes the physical properties listed in Table 6.2 for SentryGlas based on ASTM testing.[5]

TABLE 6.2 Physical Properties of SentryGlas

Property	Units, English (Metric)
Young's modulus	43.5 kpsi (300 MPa)
Tensile strength	5.0 kpsi (34.5 MPa)
Elongation	400%
Density	0.0343 lb/in.^{3} (0.95 g/cm^3)
Flex modulus 23°C (78°F)	50 kpsi (345 MPa)
Heat deflection temperature at 67 psi (0.46 MPa)	43°C (110°F)
Melting point	94°C (201°F)
Coefficient of thermal expansion	–20° to 32°C (–4° to 90°F) 0.10–0.15 mil/in.°C (10–15 10^{-5} cm/cm °C)

Some fabricators have reported problems in using the SentryGlas interlayer, and some issues are documented in Chapter 17. Pilkington has been using the material extensively for years, apparently with success, at least in a two-ply laminate. The multi-ply laminates may be more of a problem. It may also be that the material is different enough that it requires a level of adaptation by the fabricators in their production processes that will only happen gradually. SentryGlas is a rigid sheet material instead of a roll, and large sheets can be particularly difficult to handle. Whatever the issues, the material seems to be growing in use, and appears to be emerging as a significant material advance for facade designers seeking expansive daylight and heightened transparency in the building envelope. Future developments in interlayer material science can be expected.

Laminated glass is a valuable tool for the facade designer. SGFs using point-fixed glazing systems are making increased use of heat-strengthened laminated glass panels as an alternative to monolithic tempered glass, which can break spontaneously. New interlayer materials are emerging with wide-ranging properties. The architect on the TKTS project (Chapter 17) used various interlayer materials in response to a combination of structural and aesthetic considerations. Laminated glass strategies can address multiple considerations including appearance, thermal and acoustical performance, security, and safety.

Glass Fin Systems

If the notion of Foster's Willis Faber & Dumas facade as a starting point for SGF technology has any validity, then glass fin systems could be considered the oldest SGF system type. Certainly this structural form has been more widely applied than any other, perhaps because it has been transformed by companies like Pilkington into packaged product systems, available from a single source, with an extended warranty. Today, however, it is easy to piece together a glass fin system by buying glass locally or regionally and ordering hardware from a catalog. There are more facade engineers than ever before, with more software tools and analytical techniques, to assist with the design and calculations.

Glass fin facades are topologically equivalent to a mullion system. In fact, some members of the industry use the term *glass mullion systems* instead of the more familiar glass fin reference. The glass typically acts as a vertical mullion on the vertical glass grid, resisting lateral loads. The systems are most often suspended but can also be base-loaded. The glass cladding is typically suspended, with the dead load carried by overhead building structure.

The long, narrow fins are difficult to temper, and the maximum fin length varies among suppliers. If the spans exceed this length, then fin sections must be spliced together. A metal splice with multiple bolts is usually developed for this purpose that efficiently transfers the load between fin sections. Fins can be monolithic or laminated. The monolithic systems offer optimum transparency. Laminated systems can develop higher strength capacity and provide redundancy to the system. Glass fin facades have been constructed with spans in excess of 100 ft (30 m).

All-glass structures are one thing, but the use of glass as a structural component does not end there. The glass fin facades established the glass fin as a structural member. It has now been employed in a number of applications as a component of a hierarchical structural system. A secondary or tertiary steel component that spans between higher-order components to pick up, for example, a spider fitting that is on the glazing grid but off the primary structure grid can sometimes be replaced with a glass fin. This is a strategy used by facade designers when attempting to dematerialize a structural system.

Bolting and clamping systems are both available as off-the-shelf items, although the bolting systems are more common. The projects described in Chapters 7 to 17 evidence both types. The bolts are usually designed for countersunk holes, resulting in no projection beyond the glass surface. Pilkington has a system with the glass connector embedded within a two-ply laminate, leaving the exterior glass surface unbroken. The connection systems are designed to achieve an effective load transfer from the glass to the fin without concentrated point loads or significant bending loads. These considerations are discussed in greater detail in the following sections.

Connections[6]

Nick Leahy, lead architect for Perkins Eastman on the TKTS glass structure, comments that when working with glass as structure, “there are a few guiding principles: absolute certainty in the load paths, redundancy, and tolerances.” He speaks simply and directly to the core challenges of designing with glass as a structural material, but each of these issues is surrounded by a cloud of subtlety resulting from the many variables involved, ranging from material and process considerations to the structure's intended end use. One aspect of structural glass design that encompasses all three of these considerations is the connection between components. The connection must provide predictable and efficient load transfer to accommodate the load path. The connection is typically designed to surpass the strength of the members it connects, but in the case of a member failure the loads will be redirected; the remaining structure must be evaluated for this condition and a scheme developed so that the structural members and connections are not overstressed to failure, leading to catastrophic failure. This is the consideration of redundancy. Finally, every connection must be considered with respect to tolerances. Glass is not drilled-to-fit on the building site. The materials are prefabricated in the factory, and each structural glass component possesses dimensional variances accumulating from the tolerances of raw material manufacture and postfabrication processing. The designer must identify the range of dimensional variance, and procedures must be established to ensure that the materials fall within the specified range. The connection is then designed to fit up and function within this range of dimensional variation.

The TKTS project (Chapter 17) presents a unique opportunity to examine the connections between structural glass members. The project is essentially a ramp-shaped freestanding glass enclosure, the roof of which is a series of glass risers and treads that climb from the base of the ramp to the top. The risers and treads are supported by 30 ft (9 m) glass stringer beams, a six-ply pinned composite built up of three layers of two-ply laminated glass blades. An upper and a lower beam type span the full run of the steps and are end supported at three locations, each representing a different condition: a base connection, a midwall connection, and an end wall connection at the top of the stepped roof. The midwall and end wall are laminated multi-ply load-bearing glass walls. All three connections are unique.

Base Connection

The base is a pinned connection near the bottom end of the beam (Figures 6.2 and 6.3). The pin is perpendicular to the beam axis, allowing unrestrained in-plane rotation, thus preventing any bending loads at the connection. The pin is part of a stainless steel anchor component fixed to a concrete footing. A stainless steel connection bracket is factory assembled to the beam end that terminates in a bent plate, which mates with the pin. The beam is set down atop the pin in the anchor bracket, and two bolts inserted through the bent plate under the pin secure the beam end from uplift.

Midwall Connection

Both the upper and lower beam types have a beam end supported at the midwall, also a pinned connection. Here the anchor bracket is mounted to the top edge of the multi-ply load-bearing glass midwall (Figures 6.4 and 6.5). The bracket incorporates the pin and also ties to a metal redundancy beam that runs through the structure, providing support in case of a failure to the midwall glass. Stainless steel plates with a hooked end are attached to each side of the beam end. The hooks are set over the pin; the hooked beam bracket of the lower beam nests with that of the upper beam. The installation of a lower bracket on each plate serves to secure the beam end to the midwall bracket.

End Wall Connection

The top end of the upper beam connects to the top of a load-bearing glass wall built of large four-ply laminated glass panels as indicated in Figure 6.6. A rotule connection is used here that provides 360-degree rotation from a point within the plane of the supporting glass wall, accommodating load transfer without creating any bending moments. A stainless steel bracket is pinned to the end of the upper beam and attaches to the rotule pin, which transfers the beam load to the rotule bearing plate and into the glass (Figure 6.7).

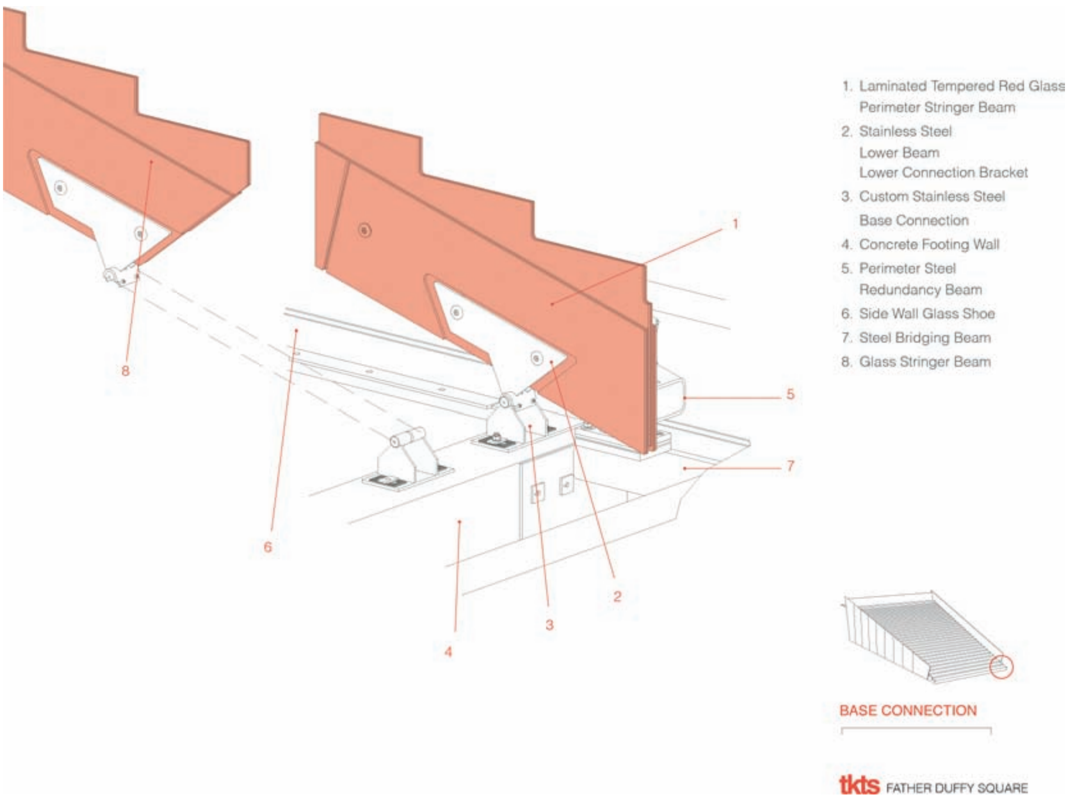


FIGURE 6.2 TKTS booth, Times Square, New York City, 2008, Perkins Eastman architect with Dewhurst Macfarlane and Partners as glass engineer. Note the footing connection detail at the base of the lower stringer beam (see Chapter 17).

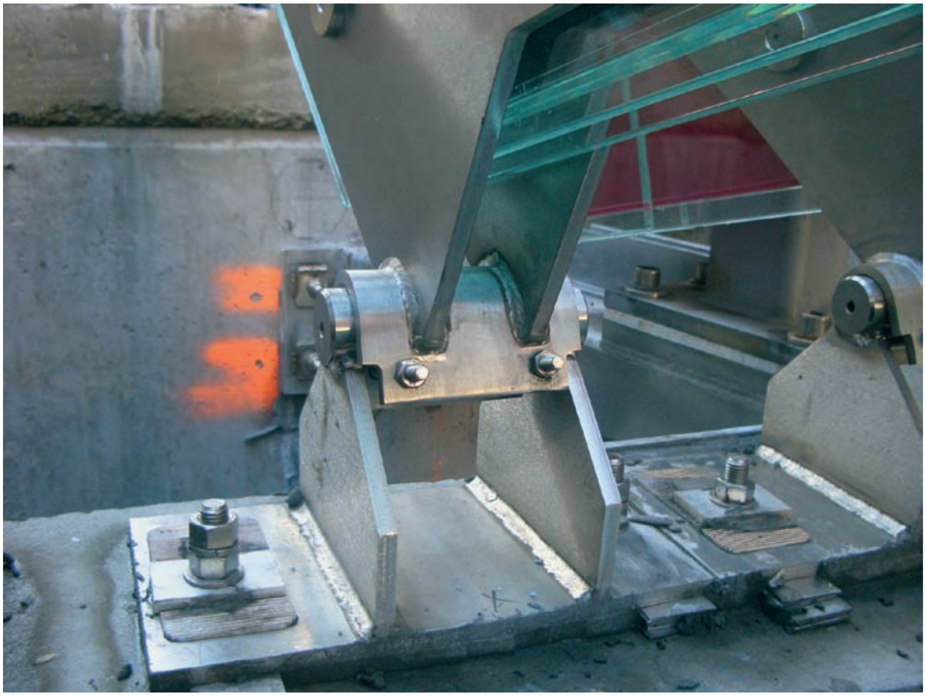


FIGURE 6.3 Footing connection detail during construction.

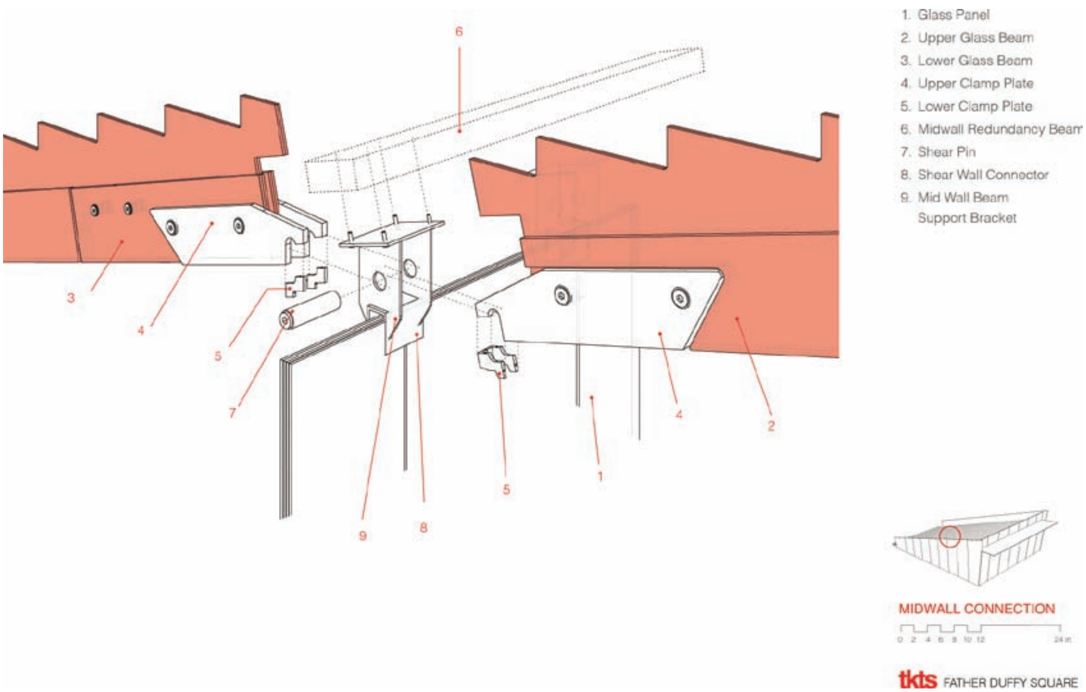


FIGURE 6.4 Midwall connection detail. A load-bearing four-ply glass wall supports the upper and lower beam ends.

Beam Assembly: The Pins

Again, the challenge is in the subtleties. Before the load transfer mechanism can function as intended, the loads must transfer from the laminated glass blades of the beams and into the stainless steel connection brackets at either end. It is not possible to simply drill a hole in the glass and bolt it together with a conventional bolt and nut, as with metal plates. The torque would bring undesirable stress to the vulnerable glass surface. The surface, particularly the edges, of glass is fragile and the source of most glass breakage. Microscopic cracks in the surface and edges can propagate when stressed, resulting in fracture. This is particularly true with tempered glass, where the heat-treating process that has given the material its additional strength also produces internal stresses that can be released with nearly explosive force if the edge or surface integrity of the material is breached. It can take remarkably little to cause this. A section of tempered glass can support surprising loads, and even withstand repeated and intense impacts, but even light contact with a hardened sharp metallic edge can cause tempered glass to shatter in its characteristic fashion, producing small kernel-sized pieces. This is the reason that the edges of glass used in structural application are usually polished to remove as many of the microscopic cracks as possible. Exposed edges in vulnerable locations are often capped or otherwise protected, as with the treads on the TKTS structure.

Concentrated point loads are thus problematic in glass. The special bolted connections developed

FIGURE 6.5 Finished photograph of the midwall connection.

for point-fixed glass are designed to address this problem by facilitating full bearing contact between the bolt assembly and the hole in the glass, using a hole that is large enough to produce the bearing area necessary to facilitate load transfer. This is typically accomplished through the use of a non-metallic transitional material, such as a Delrin® bushing, that develops full bearing with the entire inner surface of the glass hole. This mitigates any concentrated point loads to the glass. The problem was significantly greater with the stringer beams for the TKTS project, first because of the magnitude of the loads and second because of the multi-ply, composite construct of the beams.

The technique developed to pin the two-ply laminated beam elements together for the stringer beams employed a $1\frac{3}{4}$ in. (44 mm) Nylatron® bushing. The individual glass pieces were first fabricated, including shaping, hole cutting, and edge treatment, all of which must be completed prior to tempering. The materials were then tempered and, finally, laminated into the two-ply blades from which the beams were built. Glass lamination is not an exacting process. Even with the best fabricators, the range of dimensional variation in edge alignment is relatively large. The materials tend to move under the heat and pressure induced in the autoclave. Aligning multiple holes is particularly challenging. In addition, there is a necessary tolerance in the size of the glass holes. The original intent was to cut bushings at the thickness of the two-ply laminate, about $1\frac{1}{16}$ in. (27 mm) thick and $1\frac{3}{4}$ in. (44 mm) in diameter, but when the disc was sized to accommodate the smallest diameter resulting from the dimensional variations, the bushing became too small for the larger range produced by the dimensional variation. The decision was to cut a separate bushing for each piece of glass, two for each laminate's blade. This meant that the dimensional variations resulting from the laminating process could be ignored.

If the bushings are cut to a plus tolerance equaling the minus tolerance of the glass hole, there is

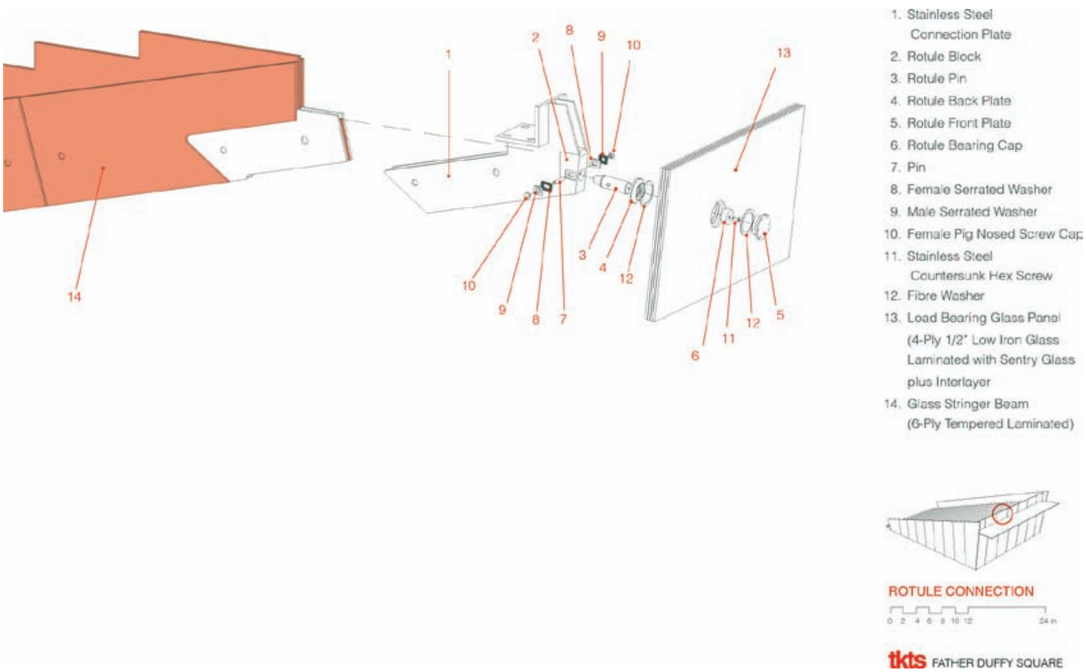


FIGURE 6.6 Rotule detail at the top of the upper stringer beam. The beams are supported from the top of four-ply glass panes nearly 17 ft (5.2 m) tall.

a defined maximum gap between the bushing and the hole. For example, if a 1.00 in. (25.40 mm) hole is cut to a ±0.01 in. (0.25 mm) tolerance, the smallest conforming hole size will be 0.99 in. (25.15 mm). If the bushing also has a ± 0.01 in. (.025 mm) tolerance, the nominal diameter for the bushing will be 0.99 – 0.01 = 0.98 in. (25.15 – 0.025 = 25.13 mm). The smallest bushing diameter is 0.97 in. (24.64 mm) and the largest hole is 1.01 in. (25.65 mm), leaving a maximum differential of 0.04 in. (1.01 mm). This is a ridiculously trivial math exercise, but it is amazing how often this analysis is ignored, resulting in parts that will not fit up. It gets more complex as system tolerances stack across many materials and components.

The bushings were to be secured within the holes with an epoxy glue (Figure 6.8). Soon after the fabricator began this process, they started

FIGURE 6.7 Construction detail at the rotule connection.

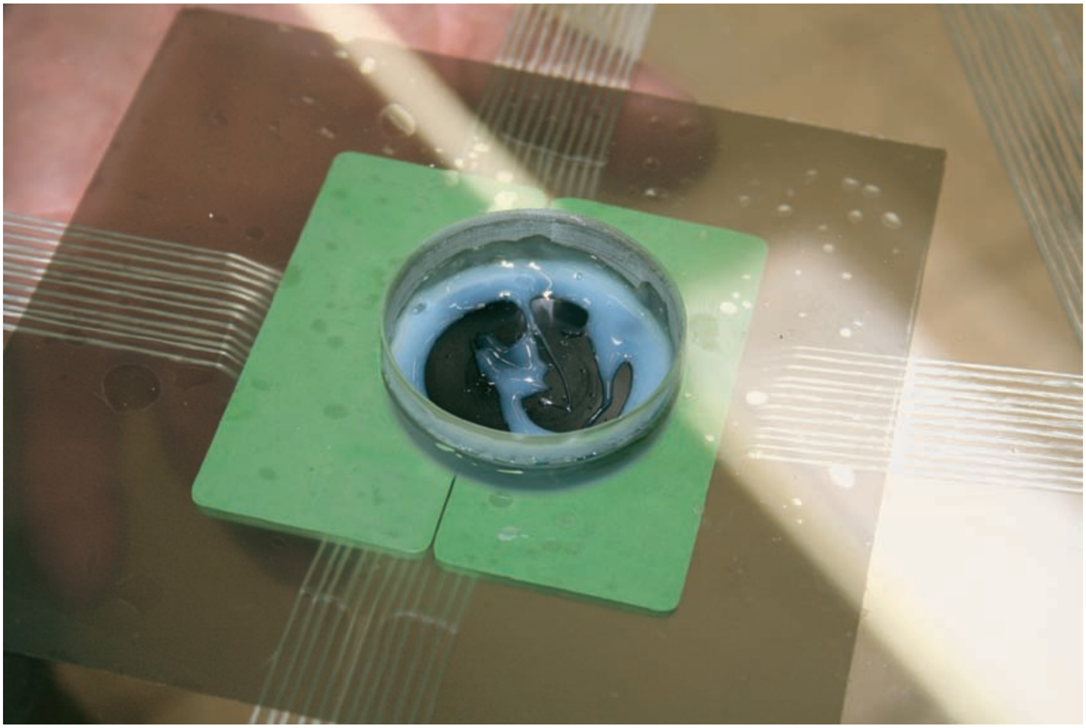


FIGURE 6.8 A Nylatron disk has been epoxy glued to the bottom ply of a stringer beam two-ply laminated component. Separate disks had to be used for each side because of imperfect hole alignment and varying hole tolerances. The tolerance between the disk and the hole diameter had to be very tight or the epoxy process would break the glass.

experiencing delamination of the glass around the holes, and in some instances the glass broke when handled. It was ultimately determined that if the epoxy between the edge of the bushing and the edge of the glass was too thick, the heat generated by the epoxy cure or a stress induced by the shrinkage of the epoxy material trying to pull the bushing and glass edge together (or perhaps both factors combined) caused the glass to break. If the bushing was held to a very tight tolerance with the hole, there was no problem. The holes needed to be fabricated to a much tighter tolerance, but they were already complete and could not be modified once the glass was tempered. There was no choice but to essentially fabricate custom shims for every hole, significantly complicating production.

The assembly of the beams required pinning three of the two-ply laminates together in overlapping positions; each blade was pinned in two locations. This involved jigging the glass blades together in the proper position, securing them, mounting a magnetic drill press, and drilling through the bushing material of all three blades simultaneously. This produced a perfect hole without any of the tolerance issues presented by the laminating process (Figures 6.9 and 6.10). A stainless steel pin machined to very high tolerances was then inserted into the hole, providing a snug fit and highly efficient load transfer between the laminated blades.

Beam Assembly: End Brackets

A similar issue caused by the inherent inaccuracy of the laminating process shaped the design of the stainless steel end brackets on the beams. The beam ends sit in the brackets like a foot in a shoe, with load transfer through the bottom end of the glass beam and into the bracket, where it is transferred to the supporting structure. The six individual pieces of glass that comprise the beam section are fixed in position with each other by the pins, but

FIGURE 6.9 Three two-ply laminates are aligned at the pin locations, and a jig and a magnetic drill are used to core a high-tolerance hole through all six layers of disk material.

FIGURE 6.10 The pin mates perfectly with the hole through the disk material, providing an optimum bearing surface and load transfer between the pin and beam, thus compensating for the inevitable misalignment between the glass plies of the laminated beam.

FIGURE 6.11 A construction detail at the midwall connection shortly after the application of grout, which ensures uniform bearing of the beams on the four-ply glass wall.

with some variation in their alignment perpendicular to the beam axis. If the bottom edge of the glass were to sit on the flat metal of the shoe, only the single lowest-positioned glass piece would bear on the shoe surface, resulting in a concentrated load that would nullify the benefit of the multi-ply composite construction.

The solution developed by the TKTS team utilizes a special grout material produced by Hilti. A gap was designed between the bottom of the glass laminates and the base of the bracket. The grout was applied to fill this space, ensuring full bearing of the bottom of each glass edge with the shoe surface, regardless of any differences in alignment between the six glass plies. This was a common concern throughout the load path of the structure and was similarly addressed using the grout. It was applied along the entire base of the load-bearing walls to ensure full and uniform bearing from the glass panels to the supporting structure. The grout was used at the midwall connection from the bracket that supports the beam ends and transfers the loads into the glass wall (Figure 6.11). It was also used at the rotule connection to ensure full bearing between the rotule assembly and the edges of glass within the hole, where, once again, offsets in the holes between the four plies of glass comprising the wall panels would have compromised the bearing surface. The grout material is extremely resistant to compressive forces and cures quickly, setting up in approximately 10 minutes and fully hardening in 24 hours.

The application of the grout on the rotule connection was a particular challenge, with

FIGURE 6.12 The rotule fitting is suspended in the glass hole as grout is applied through injection holes in the rotule cap plate. The design allowed for visual confirmation that the material was applied free of voids.

significant influence on the method of installation. A novel jig was designed and fabricated that hooked over the top of the load-bearing wall, straddling the hole in the glass panels for the rotule connection and supporting the top end of the upper beam, clamping it in place. The beams were thus suspended but not connected. The rotule assembly was installed and propped up within the hole, using very small clear setting blocks. The glass was countersunk so that the front plate of the rotule would sit essentially flush with the outer glass surface. The gap between the outer plate and the glass was blocked with a clear tape, and the grout was injected through small holes in the outer plate. This allowed the installer to visually confirm uniform coverage of the grout material (Figure 6.12).

The TKTS project is a small gold mine of information for anyone interested in designing and/or building glass structures or implementing innovative building technology of any sort. Like the global economy, the project constituents are bundled together; everything is interlinked. There can be no separation between design and fabrication or between initial concept development and installation of the final pin (or rotule) completing the installation. Facade specialist and consultant Franz Safford, who was deeply involved in the TKTS project, compared the structure to a Formula One race car: "Just keeping the wheels on the road takes an entire choreographed team effort. We were pushing the materials and processes on so many fronts that the design, fabrication, and build teams had to stay in lockstep at all times, or glass started breaking." See Chapter 17.

Chapter 7

LA Live Tower

Podium Facades
Los Angeles, California

FIGURE 7.1 The podium facades are located at the base of the 56-story tower in the heart of the LA Live complex, with Staples Arena to the left.

General Information	
Year completed	2010
Building size, sq ft (sq m)	2 million (185,806); 56 stories
Building type	Mixed use: hospitality, residence, entertainment
Building cost, USD	Approx. 1 billion
Project Credits	
Owner	AEG Worldwide
Architect	Gensler (Los Angeles)
Facade consultant	JA Weir Associates
Building engineer	Nabih Youssef Associates
General contractor	Webcor Builders
Design-assist, design-build facade specialist	Enclos Corp with ASI Advanced Structures Inc.[1]
Facade steel fabricator	TrussWorks International (TWI) Kumar Inc.
Glass-fixing component supply	Kinzi (Thailand) Co. Ltd.
Glass supplier	Cristacurva, GlasPro
Facade System	
Structure type	North wall: mullion system South wall: truss system
Facade system cost, USD/sq ft (sq m) installed	North wall: 233 (2508) South wall: 312 (3358)
Total facade area, sq ft (sq m)	North wall: 2575 (239) South wall: 12,199 (1133)
Glass grid module orientation	Horizontal
Grid dimension height × width ft-in. (mm)	4 × 7 (1219 × 2134)
Glass type Imperial units specified, metric units approximated.*	North facade 13⁄16 in. (19.52 mm) laminated starting outboard: ½ in. (12 mm) fully tempered (FT) low-iron 0.06 in. (1.52 mm) polyvinyl butyral (PVB) ¼ in. (6 mm) FT clear Pilkington Advantage with pyrolytic low-e coating no. 4 surface South facade ⅞ in. (21.04 mm) laminated starting outboard: ½ in. (12 mm) FT low-iron 0.03 in. (0.76 mm) PVB solar control film: Southwall XIR® (see description below) 0.03 in. (0.76 mm) PVB ¼ in. (6 mm) FT clear
Glass system type	Point-fixed clamped and bolted
Maximum span, ft (m)	52 ft (15.8 m)
Deflection criteria	L/175 simple spans 2L/175 cantilevers
Project delivery	Design-assist services followed by design-build, with Enclos performing everything but material fabrication

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The LA Live tower houses a JW Marriott Hotel and the Ritz-Carlton Hotel and Residences, with an adjoining convention center, and is the centerpiece of the new 4 million sq ft (371,612 sqm), $2.5 billion LA Live development (Figure 7.1). The mixed-use complex includes the Nokia Theater, a Regal Cinema, and numerous restaurants and nightclubs. LA Live is immediately adjacent to the Staples Center and the Los Angeles Convention Center, forming a mega sports and entertainment complex in downtown Los Angeles intended by the developer to be the "Times Square of the West."

The tower is 56 stories high, with a distinctive tapering profile and an all-glass unitized curtain wall skin, incorporating 34 different types of glass in what architect Gensler refers to as a "variegated facade." The focus of this case study is the structural glass facades (SGFs) at the podium level of the tower. The podium level consists of three separate elevations, up to 52 ft (15.8 m) in height, of point-fixed (edge-clamped), tempered laminated glass.

Building Structural System

The novel design and an aggressive construction schedule drove decision making on the project's construction. The project's structural engineer, Nabih Youssef Associates, designed a steel frame structure using steel plate for the shear walls rather than conventional concrete. The design is credited with conserving space, resulting in additional marketable floor area, minimizing the construction schedule, and significantly decreasing construction costs. The anchor steel required for the podium-level SGF was easily integrated into the design of the building structure.

Facade Program

There are two facades enclosing the lobby of the JW Marriott Hotel at the podium level. The north facade includes the main entry portal into the lobby, with sidewalk access and a valet station just off Olympic Boulevard. The facade has a vertical span of 25 ft (7.6 m) and is about 114 ft (34.7 m) in length, with a 14 ft (4.3 m) step near one end.

The south facade provides egress to the hotel lobby from the LA Live pedestrian promenade. This facade is more complex than the north facade and is comprised of three walls: the east, north-south (middle), and west walls. The east and north-south walls span 52 ft (15.8 m) vertically, and the west wall spans 24 ft (7.3 m). A 104 ft (31.7 m) length of the east wall encloses the lobby and adjacent lounge, and incorporates an entry portal with a glass awning cable-supported from the facade structure. This facade abuts the north-south wall, which encloses a restaurant within the hotel lobby (Figure 7.2). Three bays of the north-south wall structure extend into the lobby interior, partitioning the restaurant entrance from the lobby proper. At the other end of the north-south wall, the shorter 50 ft (15.2 m) long west wall encloses the other side of the restaurant. A single bay skylight runs continuously along the top of the north-south wall.

FIGURE 7.2 Plate trusses spanning 52 ft (15.8 m) define the south facade.

Facade Structure

North Facade

The north facade is supported by a mullion system. A structural vertical mullion spanning 25 ft (7.6 m) is spaced at 7 ft (2.1 m) along the length of the wall (Figure 7.3). The rectangular steel tube mullions are 12 in. (305 mm) deep and 4 in. (102 mm) wide, and taper at the head and foot to a simple pin connection to a concealed anchor plate. The outer face of the mullions includes an incremental connection plate welded parallel to the mullion length on 4 ft (1.2 m) centers. The glass fixings bolt to these plates. A 14 ft (4.3 m) beam spanning between two mullions is used to create the entry portals, with the intermediary mullion supported off the beam.

South Facade

The south facade uses a built-up plate truss as the primary structural component (Figures 7.4 and 7.6). The 52 ft (15.8 m) trusses taper at the foot to a simple pin connection in the same vocabulary as the north wall mullions. At the top of the north-south wall the trusses step back at a right angle to form a single bay of skylight glass, which also acts as a parapet to an intermediate-level outdoor roof garden (Figure 7.5). The slender, lightweight trusses are laterally braced every 12 ft (3.7 m) against lateral torsional buckling by a pair of prestressed horizontal cables; an inner cable penetrates through a cutout in the truss web, and a parallel outer cable runs across the back of the trusses. The cables are fixed at each truss by cast stainless steel clamping assemblies. Pretension requirements for the horizontal cables range from 2.5 to 5.5 kips (11 to 25 kN).

FIGURE 7.3 The north facade structure is a mullion system with a 25 ft (7.6 m) steel mullion tapering to a pin connection at the head and foot.

FIGURE 7.4 The plate trusses are fabricated to Architecturally Exposed Structural Steel (AESS) standards and include a bracket at the front face to attach the glass-fixing components.

FIGURE 7.5 The trusses step back at their tops to create a 7 ft (2.1 m) skylight that also acts as a perimeter partition to an upper-level entertainment area.

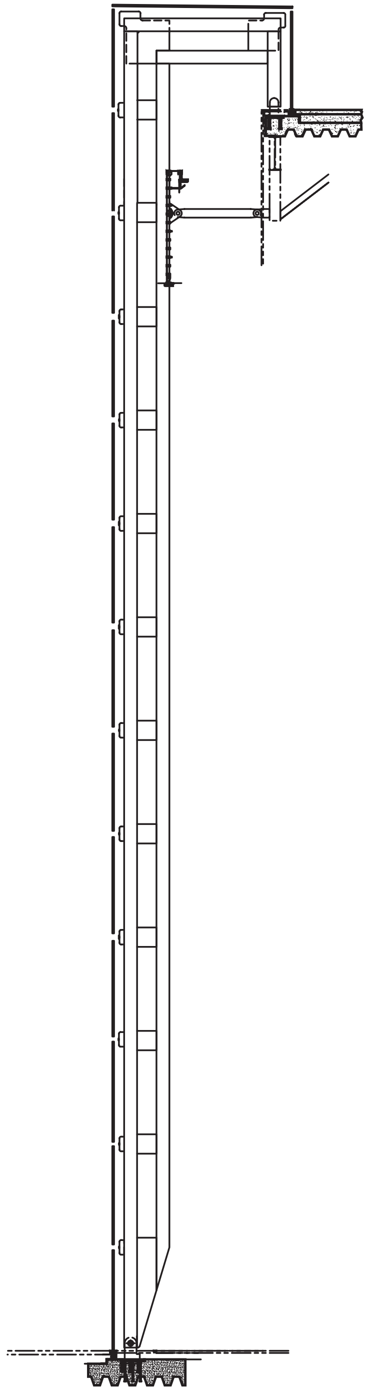


FIGURE 7.6 Typical south facade section showing the truss configuration.

Each wall contains a single end bay condition that acts as an integrated ladder truss to provide in-plane stability to the wall structure (Figure 7.7 and 7.10). Horizontal compression ties align with the horizontal cable runs to form a module that is stiffened by diagonally crossing cable pairs. Pretension requirements for these diagonal cables range from 5 to 13 kips (22 to 58 kN). A unique condition occurs at the corner between the north-south wall and the west wall. The truss here bisects the 90-degree angle between the walls. Compression ties between this truss and those immediately adjacent on each side form modules similar to the ladder trusses, which are similarly stabilized by crossing cable pairs (Figure 7.8).

Another interesting feature of the south facade is the pop-out section that occurs on the east wall. Here the glass steps out from the primary glazing plane over a large rectangular area of the facade, framing one of the large light-emitting diode (LED) displays. The glass is stepped away from the face of the trusses by laminated glass fins.

A 20 ft (6.1 m) canopy is integrated into the structural system over the entry portal of the east wall (Figure 7.9). The facade glass is notched to allow the steel plate beams supporting the canopy glass to attach directly to the wall trusses. Diagonal cables also tie the outer end of the beams back to the trusses.

All steel fabrication was done to Architecturally Exposed Structural Steel (AESS) standards and coated with a factory-applied, high-performance, three-part aliphatic urethane with metallic silver topcoat.

FIGURE 7.7 Each south wall facade includes a braced end bay to provide in-plane stability.

FIGURE 7.8 This corner truss is a unique condition at the interface of two perpendicular wall segments that comprise part of the south facade enclosure.

Glass System

Logically, the glass on the podium facades differs for the north and south facades. The north facade uses a 13⁄16 in. (21 mm) laminate with a PVB interlayer. The south facade uses 7⁄8 in. (22 mm) glass with a solar control film sandwiched between two PVB interlayers. The film is XIR® by Southwall Technologies, a transparent, spectrally selective metallic coating that reflects solar heat while transmitting visible light. The glass is on a uniform horizontal grid for all the facades, which are 4 ft tall by 7 ft wide (1.2 m by 2.1 m) (Figure 7.11).

FIGURE 7.9 A 20 ft (6.1 m) canopy is supported by the south facade truss system, with cable tiebacks penetrating through slots in the glass membrane.

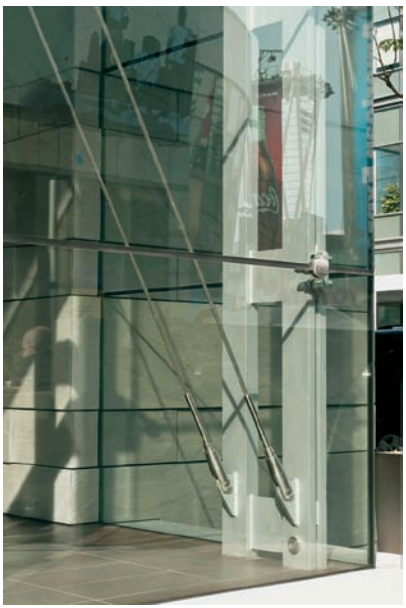


FIGURE 7.10 In-plane bracing at an end module of the south facade. Note the different foot design of the end truss.

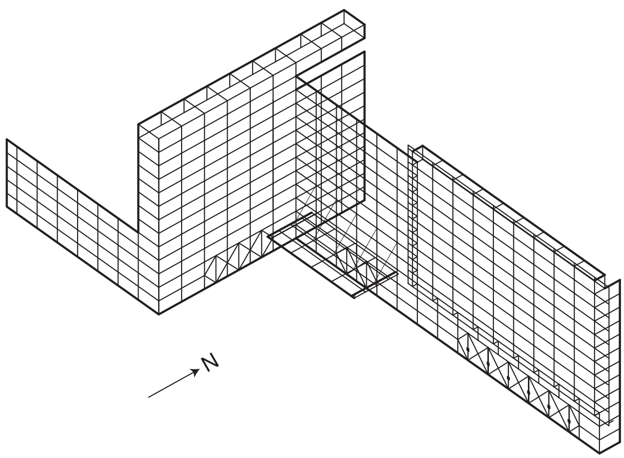


FIGURE 7.11 South facade glass grid diagram.

An interesting problem occurred on the north facade glass that ultimately resulted in its replacement. The problem was not noticed until after installation. Distortion was observed in an approximate 4 in. (102 mm) band around the perimeter of every glass panel. The rest of the panel surface appeared generally flat and without significant noticeable distortion. The glass makeup was ½ in. FT by 0.06 PVB by ¼ in. FT (12 mm FT by 1.52 PVB by 6 mm FT). To improve thermal performance, a low-e coating was specified for the no. 3 surface. Extensive research involving the production of many glass samples to study the problem was undertaken. While the results of the investigation were not conclusive, the project team believes that the problem was caused by the heat-treating of the pyrolytic coated glass. Soft low-e coatings must be applied after heat treatment of the glass. The more robust pyrolytic coatings, or hard coats, are applied during the float process and can be subsequently heat-treated. It appears, however, that the presence of the coating reflects heat in the tempering oven, altering the heating and cooling behavior of the glass and making it more susceptible to distortion at the edges of the panel.

The problem was not observed in the glass samples provided by the fabricators, although subsequent review revealed that it was present in the samples. It is noteworthy that the initial glass did not violate any specification requirements; thus, there were no grounds to reject the glass. In fact, the original fabricator offered to replace the glass but could not promise that the replacement glass would be any better. U.S. standards do not address optical distortion in any meaningful way, including the more common problems of roller-wave distortion and edge curl resulting from heat-treatment processing. The facade designer is left to create specific requirements in the project specifications or to use European standards. The best course of action is to discuss the expectations of the developer and design team, with respect to optical distortion, with qualified glass processors in order to develop an appropriate glass specification.

When the decision was made to replace the glass, samples were solicited from alternative suppliers, and Cristacurva,[2] a specialty glass fabricator, was selected to provide the replacement glass on that basis. It appeared that the glass panel's makeup tended to contribute a "lens effect" that exaggerated the optical distortion. The samples showed that moving the low-e coating to the no. 4 surface helped to reduce the effect. While the replacement glass is a noticeable improvement, distortion at the edge is still apparent, but it is limited to a narrow band around the perimeter.

Some designers prefer bolted point fixings, while others prefer the clamping strategy. Both are used in the podium at LA Live, but the predominant strategy is a clamped fixing (Figures 7.12 and 7.13).

FIGURE 7.12 Typical glass system connection detail using a clamp-type component, requiring no perforation in the glass.

FIGURE 7.13 Glass system connection detail: corner condition.

Bolted fixings were used in conditions where there was no base support for the glass, so it was hung from a bolted perforation. The brackets and clamps were custom designed for this project and manufactured of cast stainless steel in Thailand.

Facade Concept Development

Enclos was involved with the architect very early in the design process, providing extensive design-assist services to support the concept development process. The services included design, detailing, and engineering analysis, as well as ongoing budgeting to provide a context for decision making for the design team. The design work continued seamlessly after the award of a design-build contract by the general contractor. Budget constraints emerged as the facades moved closer to construction, and the Enclos team was well positioned to provide value engineering services that reduced costs while minimizing the aesthetic impact on the design.

Testing

There were no formal testing requirements for the podium facades. Enclos conducted their own testing of the system at Smith-Emery.

Straying momentarily from the focus on the podium, an extensive mockup was prepared and tested for the tower curtain wall system. However, another, more unusual mockup was constructed: a visual mockup. Glass selection is among the most difficult tasks falling to the facade designer. Given the various types of glass, laminates, and coatings, there are literally thousands of combinations to choose from, each presenting a unique visual appearance.

FIGURE 7.14 It is always a challenge to anticipate what the many variations of glass will look like in place. Enclos constructed a gimbaled rack for the simultaneous evaluation of large glass mockups under varying light conditions.

Moreover, the visual appearance of any glass type is a function of its properties of reflectance, absorption, and transmittance in combination with ambient light conditions, which change constantly throughout the day as the sun moves through the sky and throughout the year as the earth's axial orientation to the sun cycles through a complete orbit. The facade designer is often in the position of attempting to envision what a certain glass type will look like on a high-rise tower while looking at a 1 sq ft (0.1 sqm) sample. This can lead to unpleasant surprises for the design team when the specified skin is installed. The problem is all the more challenging when there are multiple glass types comprising the facade. LA Live may be rather extreme, with 34 different glass types, but most projects include multiple variations as part of the facade program.

To facilitate the glass selection process, Enclos built a large gimbaled steel rack. The rack accommodated the mounting of large samples: small units with the same combinations of glass types and aluminum as the full-scale units would hold. The units could be mounted side by side for comparison, and the entire rack could be rotated to simulate different lighting conditions (Figure 7.14).

Project Delivery

Enclos delivered the facade program under a design-build contract issued by the general contractor. Enclos performed every aspect of the facade work except fabrication. Design and engineering were done by an in-house team. AESS steel fabrication was provided locally by two fabricators: Kumar Inc. and TrussWorks International, a steel fabricator specializing in AESS. Cast component fabrication was provided by a Thai company specializing in stainless steel. An attempt was made to procure glass locally, but ultimately, most of the podium glass was provided by Cristacurva and shipped to Los Angeles from Mexico. All materials were shipped directly to the job site for installation by Enclos field operations crews.

Installation Strategy

The structure and glass systems were designed for ease of installation. The structural mullions and plate trusses required only two pins each to be secured in place, one each at the head and foot. The trusses were lifted directly from flatbed trailers and set in place, thereby eliminating the need for on-site storage and minimizing the potential for damage to the prefinished components. The small number of horizontal compression ties were bolted to the trusses through predrilled holes, and the bracing cable systems were installed by pinning shackle end terminations to lugs welded to the trusses and then were pretensioned. The glazing plates welded to the front chord of the mullions and trusses were then surveyed for accurate positioning and adjusted as required. The glass fixings were next bolted to the structure, and the glass was clamped into position. Finally, the wet silicone was applied to the glass joints and tooled smooth. Installation tolerances are summarized in Table 7.1.

TABLE 7.1 Tolerances for Installation of Podium Facade Structure

Vertical tolerance for fabrication and installation from theoretical	1 in. (25 mm) maximum upward or downward
Lateral tolerance for fabrication and installation	1 in. (25 mm) in any horizontal direction from theoretical
Concrete	½ in. (13 mm) in any direction
Tolerances of podium facades	
Survey and layout connections	± ⅛ in. (3 mm)
Vertical member plumbness	± ⅛ in. (3 mm)
Vertical trusses and framing	± ⅜ in. (10 mm) in plane of wall ± ¼ in. (6 mm) perpendicular to the wall
Horizontal framing	± ⅜ in. (10 mm) vertically ± ¼ in. (6 mm) maximum between horizontal framing members on either side of a vertical member

Strategies for Sustainability

The south facade has far greater solar exposure, and a different glass makeup was called for as a strategy for controlling solar heat gain (Figure 7.15). One of the better-performing materials available for this purpose is the XIR film mentioned previously. When used with clear glass, it provides 72%

light transmission while reflecting about half of the infrared heat energy, and it has a solar heat gain coefficient (SHGC) of 0.41, lower with tinted glass. The material is sandwiched between two layers of PVB in the laminated unit. The heat-rejecting film produces low surface reflectance that is uniform over both flat and curved surfaces.[3] The application of the material is a specialty, and not all glass fabricators are qualified in its use. Cristacurva includes the use of XIR among its many specialties.

Summary

Decisions made by the developer and the build team can, on occasion, be frustrating to the architect and a puzzle to onlookers. Elegant, highly transparent, and beautifully detailed facades were built at the podium level, only to have huge, brutish sign structures built immediately in front of them. From the interior of the restaurant, the view through the highly transparent facade past the painstakingly crafted steelwork of the trusses is largely blocked by the crude, incongruous support structure of the digital sign, creating a bona fide head-scratching moment.

Nonetheless, the LA Live complex has provided downtown Los Angeles with a world-class pedestrian environment, and the glass-enclosed lobby of the JW Marriott Hotel is the highlight of the development. The unique structural systems combine craftsmanship, transparency, and economy in an uncompromisingly elegant solution for the podium facades (Figure 7.16).

FIGURE 7.15 The south facade experiences considerable solar exposure despite the presence of nearby buildings. A solar control glazing was used to provide an improved SHGC.

FIGURE 7.16 Rather than pursue maximum transparency, the designers chose to express the trusses as strong visual elements in the facade.

Chapter 8

Suvarnabhumi Bangkok International Airport (SBIA)

Main Terminal Building (MTB) Facade
Bangkok, Thailand

FIGURE 8.1 The MTB showing deep roof overhangs over a glass-enclosed interior.

General Information	
Year completed	2006
Building size, sq ft (sq m)	Over 6 million (563,000)
Building type	Airport
Building cost, USD	Approx. 1.3 billion[1]
Project Credits	
Owner	Airports of Thailand (AOT)
Architect	Murphy/Jahn Architects
Building engineer	Werner Sobek Ingenieure
Terminal facade design	Werner Sobek Ingenieure Murphy/Jahn Carl D'Silva, Sanford Gorshow
Mechanical, electrical, plumbing (M/E/P) engineer	Flack + Kurtz Consulting Engineers
Climate consultant	Transsolar
Construction manager	MJTA; a joint venture of Murphy/Jahn Architects (U.S.), TAMS (project management, U.S.), and ACT Engineering Consultant (Thailand)
General contractor	ITO Joint Venture (Italian-Thai, Takanaka, Obayashi)
Terminal facade contractor	KAMA JV with ASI Asiatic (Thailand)
Engineering consultant to facade contractor	Connell Wagner (nka Aurecon) Richard Green, John Perry, Tim Phillips
Installation subcontractor	Alfasi Steel Constructions (Australia)
Cast and machined fittings fabricator	Kinzi (Thailand)
Stainless cable	Arcus Australia
Galvanized cable	Brugg (Switzerland)
Glass manufacturer	Asahi Glass
Glass fabricator	Thai German Specialty Glass Co., Ltd.
Facade System	
Structure type	Truss system with primary mast trusses (vertical) and secondary cable trusses (horizontal)
Facade system cost/sq ft, USD (installed)	Approx. 83 (893)[2]
Total facade area, sq ft (sq m)	Approx. 361,000 (33,537)
Glass grid module orientation	Square
Grid dimension height × width ft-in. (mm)	7 ft 5 in. (2260 mm) square
Glass type Metric units specified, imperial units approximated.*	13⁄16 in. (21.52 mm) laminated 3⁄8 in. (10 mm) heat-strengthened (HS) 0.06 in (1.52 mm) polyvinyl butyral (PVB) 3⁄8 in. (10 mm) HS) Butacite® interlayer by DuPont with neutral gray tint
Glass system type	Point-fixed, through-bolted with cast stainless steel spider
Maximum span, ft (m)	Approx. 100 (30)
Deflection criterion	L/180
Project delivery	Design-build by local facade contractor, subcontracting everything but installation

*The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The SBIA is among the busiest airports in Asia. It features a glass-box Main Terminal Building (MTB) enclosing over 6 million sq ft (563,000 sq m) (Figure 8.1). The MTB was widely reported to be the largest single-building enclosure at the time of its completion.[3] The complex includes 51 contact gates, 69 remote gates, and 5 gates that accommodate the Airbus 380. The new airport has the capacity for 76 flights per hour, serves 45 million passengers per year, and handles 3 million tons of cargo per year. The SBIA is anticipated to establish Bangkok as the dominant transport hub in Southeast Asia.

The project was some 45 years in the making, delayed by everything from regime change to lack of funding. A design competition held in 1994 was won by Murphy/Jahn Architects, only to have the Thai currency collapse in 1997, initiating the collapse of the entire Asian economy. Construction was finally able to commence in 2002.

Building Structural System

At 1870 by 690 ft (570 by 210 m), the main terminal roof structure is the largest of its kind, comprised of eight supertrusses sitting on eight pairs of columns (Figure 8.2). The trusses clear span 413 ft (126 m) with cantilevers of 138 ft (42 m) at each end. The supertrusses are spaced at 266 ft (81 m) intervals, which, engineer Sobek remarks, "compares to a bridge of noteworthy span."[4] All trusses are designed to be as light as possible. Columns and trusses were built on site from high-strength welded steel plate. The primary trusses have horizontal upper chords and a "hunched" lower chord, with geometry approximating the moment curve of a single-span girder with a cantilever. The trusses were built on the ground, jacked to the level of the column capitals, and slid to the side until they were aligned with the column capitals. The three-chord primary trusses are connected by secondary trusses supporting sun protection elements that comprise the roof, which ultimately creates very large overhangs to the terminal facades[5] (Figures 8.3 and 8.4). The length of the MTB required two expansion joints, essentially forming a series of three independent structures.

Facade Program

The vertical glass facade that encloses the MTB is about 100 ft (30 m) high and runs for a total of 3610 linear ft (1100 m) in defining the perimeter enclosure; it was claimed to be the largest point-fixed glass application on completion. The facade is supported by a complex structural system comprised of guyed

FIGURE 8.2 Eight supertrusses and column pairs provide the primary structure for the MTB, one of the largest single-building enclosures in the world.

masts reaching nearly the full height of the facade, with prestressed horizontal cable trusses spanning between them (Figure 8.5). According to Richard Green, the project designer for facade engineer Connell Wagner, "the project introduced advances in technology for stainless steel casting, tension cable usage, erection methods and glass design."[6]

Facade Structure

Mast trusses 82 ft (25 m) tall spaced at 30 ft (9 m) intervals comprise the facade's primary structural support.[7] They are pinned at the base and restrained by the roof structure against lateral load (Figures 8.6 and 8.7). Roof deflections and the connection detailing at the top of the facade were carefully considered to prevent the facade structure from being subject to any roof loads (Figure 8.8). Horizontal cable trusses span between the masts and define the horizontal glass gridlines. The spreader struts of the cable trusses reach out to pick up a cast spider fitting, which fixes the glass. A horizontal framing element spans between the

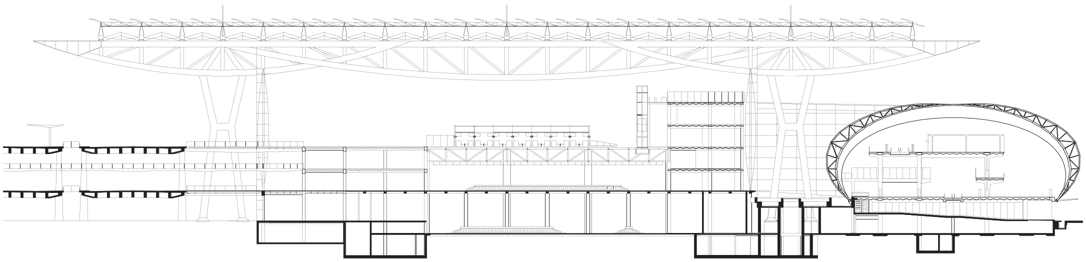


FIGURE 8.3 MTB elevation showing the inset location of the terminal facades.

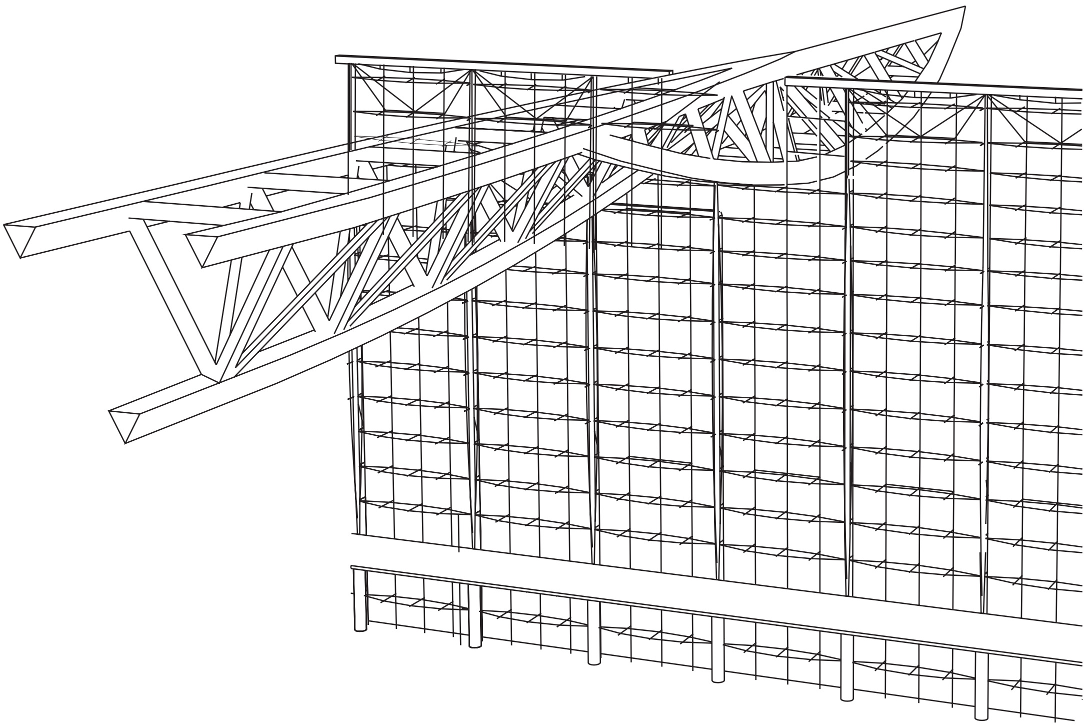


FIGURE 8.4 Interface of a supertruss with the terminal facade.

FIGURE 8.5 The view up a primary mast truss reveals bracing elements perpendicular to the glass plane and connections to horizontal cable trusses, which support the glass.

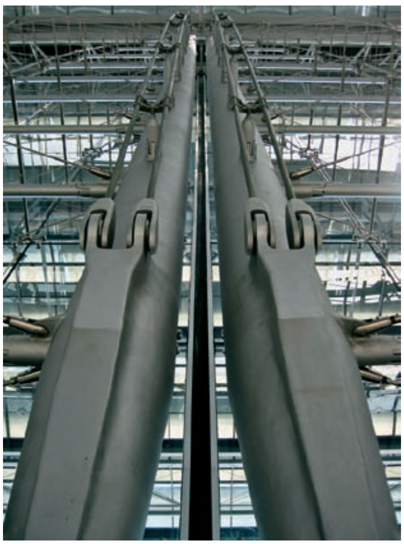


FIGURE 8.6 Cast cable ties at base of mast trusses at expansion joint.

FIGURE 8.7 The masthead and footing are large castings. The footing tapers to a pin connection.

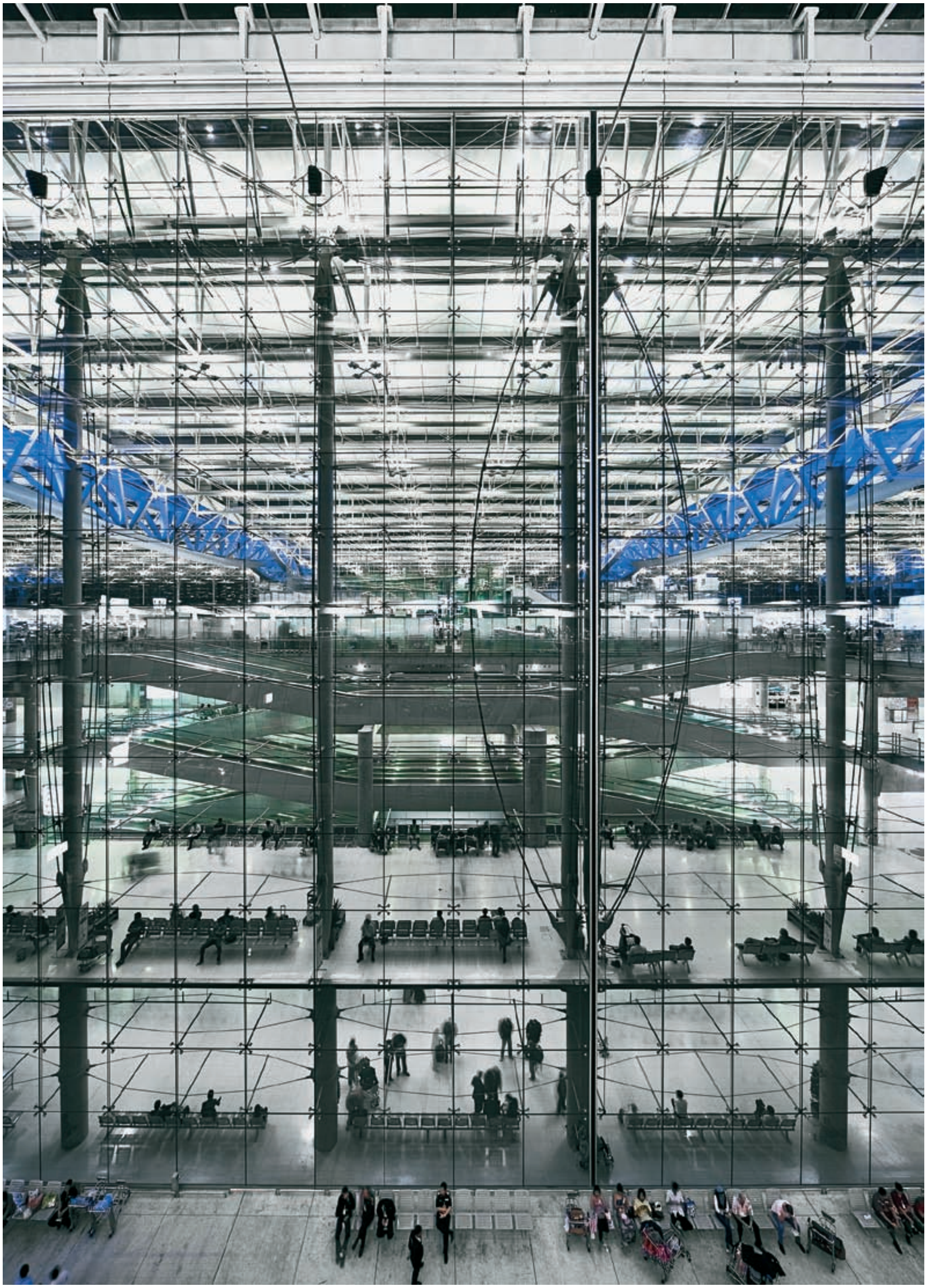


FIGURE 8.8 The full elevation of the facade system reveals remarkable transparency. The top band of the facade structure is designed to accommodate large design load movement and deflections of the roof structure.

mast tops to resist the forces of the horizontal cable trusses. At section ends and corners of the enclosure where the facade structure terminates, deep in-plane cable trusses brace the facades against in-plane prestress forces and live loads, what Green calls a “compensation truss.”[8] The glass weight is supported from dead load rods hung from the top horizontal framing member. High-tension Dyform® wire was used for the cable trusses.

The mast trusses were fabricated just outside of Bangkok and consisted of 22 in. (560 mm) diameter pipe, together with large tapered castings at either end, which were manufactured in South Korea. Two cable braces are located on the mast trusses perpendicular to the facade plane. Green was able to value engineer the cables down from approximately $1\frac{15}{16}$ to $1\frac{9}{16}$ in. (50 to 40 mm), reportedly saving $2 million USD on this refinement alone.[9] It was ultimately determined that the masts could have been designed at a smaller diameter with a heavier wall thickness, but because of long lead times, the material had already been ordered and was not returnable.

Glass System

The glass system is point-fixed, utilizing a straightforward cast stainless steel spider component that was custom designed for the project and produced by Kinzi. The glass is perforated and countersunk at each corner with through-bolts securing the glass to the spider fittings (Figure 8.9). The weather seal is provided by a field-applied butt-glazed silicone joint between the glass panels. While the structure was complex, the glass requirements for the terminal were simple in their uniformity: 7 ft 5 in. (2.25 m) square, $\frac{13}{16}$ in. (22 mm) laminated glass throughout. In fact, laminated glass is used throughout the airport, involving over 2.2 million sq ft (200,000 sq m), presumed by many to be the largest laminated glass installation on a single project. The terminal roof glass incorporates a low-e coating and ceramic frit. Approximately 366,000 sq ft (34,000 sq m) of laminated glass are used in the terminal facades, which Sobek calls “one of the largest glazed areas found today.”[10]

The original glass specification for the terminal facades was tempered monolithic with a pyrolytic low-e coating on the no. 2 surface. There were several rounds of changes to the glass specification as the project progressed. The low-e coating was ultimately value-engineered out. Insulated glass was considered, but given a stratified thermal comfort strategy in which only the lower 8% of the terminal air volume is cooled, the increased cost of the insulating glass unit (IGU) was ultimately deemed unjustifiable.

The use of laminated heat-strengthened glass instead of tempered glass is an alternative solution developed by Green for the airport project to mitigate the potential for spontaneous breakage due to nickel sulfide contamination.[11] It is typical, when using glass in point-fixed applications, to temper the glass to provide maximum strength to resist the bending moments that can occur around the holes as the glass is subject to dynamic loading. Heat strengthening is a lower-temperature heat treatment process resulting in reduced strengthening of the material; tempered glass is roughly four times stronger than annealed glass, while heat-strengthened glass is twice as strong. The possibility of nickel sulfide–induced spontaneous breakage, a concern with tempered glass, is effectively eliminated with heat-strengthened glass.[12] As the glass is less strong, either a thicker glass or a laminated panel would have to be used when substituting

FIGURE 8.9 Cast stainless steel spider fitting.

heat-strengthened for tempered glass. Laminated panels also provide the benefit of panel retention if a single ply breaks, and under some conditions, even both plies break. Laminated heat-strengthened panels thus became the system of choice. The use of this glass makeup in a point-fixed application had not been previously documented, requiring the design team to undertake a program of research, analysis, and testing to proof the design.

In daylight conditions, the glass can appear completely opaque because of the light that it reflects. Heat treatment can deform the surface flatness of the glass, resulting in obvious and generally undesirable distortion to these reflections. At night, under artificial light, the glass virtually disappears (Figures 8.10 and 8.11).

According to a DuPont newsletter,[13] laminated glass using Butacite provided other benefits, including reductions in solar heat gain and aircraft noise. Bruce Wymond of Meinhardt Facade Technology, facade consultant to the owner, is quoted as saying, "Butacite® PVB interlayer was used to enhance acoustic performance and provide safe resistance to fallout in the event of glass breakage. Laminated glass with Butacite® also provides safe breakage characteristics in the event of a bomb blast."

Facade Concept Development

Werner Sobek with Helmut Jahn provided the concept development for the terminal facade, as well as for the concourses, as part of an international design competition. Sobek comments on the terminal facade, "The search for simplicity, a minimized amount of material to be installed, and rigorous consequence in all of the decisions a structural engineer has to make were the driving forces while we were designing this facade."[14] The facade design is reminiscent of prior work by Jahn for the Cologne-Bonn Airport Terminal 2.

FIGURE 8.10 A solar-control interlayer makes the glass reflective from the exterior. Reflections reveal optical distortion resulting from heat treatment of the glass.

The project was besieged by budget problems, and the planned construction was left in doubt for several years. Rounds of value engineering followed, including the detailing of the facade structure using flat steel bar stock as a tensile element in place of cable. The facade contractor and their consultant again reconceived the facade at the detail level during the construction phase of the project.

Design Development and Analysis Tools

ASI Asiatic modeled the structural system in three dimensions, using MicroStation and AutoCAD, and performed analysis with Strand7. Connell Wagner modeled facade structure component designs, castings, and spreaders, utilizing the AutoCAD three-dimensional modeler to develop the shapes and CADian for renderings and visualizations. Strand7 was used for finite element analysis (FEA), and Solidworks was used for mold design for the castings. Cast element designs were completed in 3 months, with materials on site within 5 months (Figure 8.12). Green comments, "The use of integrated digital design techniques minimized lead times and allowed sophisticated design requirements to be implemented within demanding program requirements."[15]

Testing

Kinzi was intensively involved in the design development of the cast components, as discussed below, and in the development and execution of a program of proof testing for the customized components. The testing program included components, assemblies, and a full-scale performance mockup of the facade system (Figure 8.13).

FIGURE 8.11 The large roof overhangs are intended to shade the facades from the tropical sun. The facades comprise a minimal membrane between inside and outside environments.

FIGURE 8.12 A butterfly cable guide, one of the cast fittings developed for the MTB facade structural system.

FIGURE 8.13 Extensive testing was carried out on this large facade mockup.

Project Delivery

There was furious international competition for this job for a long period of time. As the budgets were squeezed down, most of the international competitors dropped out. The majority of materials and fabrication for the airport came from Southeast Asia and China. Ultimately, the MTB facade contract was awarded to a local Thai facade contractor working with a specialty U.S. design firm experienced with advanced facade technology. The MBT facades were supplied at a remarkably low cost; this resulted in part from economies of scale, but low labor rates, especially for site labor, are the biggest factor.

When the Murphy/Jahn design was handed off to the build team, there was much confusion and disagreement about the intended contracting strategy to execute the design. Some believed that the facade systems were intended to be delivered and installed by a facade contractor using a design-build strategy. The terminal facade design was well represented in the project documents but was not complete, as is usually the case with a design-build performance set of construction documents. Others were of the opinion that the job at hand was to build what was on the drawings and leave it at that. In the highly charged political environment of contractors from a mix of nations and with dissimilar contracting experience, a dispute soon arose over the project delivery strategy and the meaning of design-build. Needed design and specification development became extremely difficult as subcontractors were ordered to "build what is on the drawings," even when inadequate or conflicting information was present. Ultimately, the design with the flat bar stock tensile elements in place of cables was deemed unworkable (or otherwise undesirable), and the door was opened to a design-build methodology. Facade consultant Connell Wagner was brought into the project late in the schedule by the facade contractor in an effort to resolve the impasse. Collaborating with local fabricator Kinzi, Connell Wagner undertook what was essentially a value engineering effort that, despite the resulting net cost increase, was ultimately successful in instituting key material and process upgrades and the completion of unresolved system detailing.

Installation Strategy

Issues of constructability were a primary consideration from the beginning of the design process. The schedule was extremely tight, and there was no time for delay in fabrication or erection. Every design consideration was made within this context. There was a 3-month window between beginning the component design and procurement. A detailed method statement from the facade contractor was required by the general contractor and was reviewed by all relevant parties. Mast bracing cables were made for the project, and were designed and ordered within the first 2 months of Connell Wagner's involvement. Hydraulic pretensioning of the mast cable braces was required; the connections were detailed so that all tensioning could be done at the mastheads. All four cables were tensioned simultaneously from a single pump to ensure equal prestress loads in all cables. Provision was made so that prestress could be checked and adjusted as required (Figure 8.14).

Alfasi Steel Constructions from Australia was an erection subcontractor to the facade contractor, erecting the mast trusses. A less expensive Chinese erection subcontractor was brought in to provide the rest of the facade installation (Figure 8.15).

Strategies for Sustainability

To ensure sustainability, a good place to start is a lightweight and material-efficient structural system. With the terminal facade, Green contends, "the use of advanced design techniques and precision

FIGURE 8.14 A worker prepares to connect a cable high up on one of the mast trusses.

casting minimized the material usage, energy to fabricate and finish the parts as well as the visual sight lines. This minimizes environmental impact, both in terms of materials and the environment created within the building."[16]

A number of energy-efficiency strategies were investigated by the design team led by Transsolar, and some were adopted. Passive strategies include a roof design that creates large overhangs over the terminal facades. A trellis roof design puts shading louvers outside the weather envelope, significantly reducing heat gain to the building's interior. The overhangs are also covered with an open louvered system to encourage ventilation to the large areas below.

The glazing strategy was crucial to the envelope's performance and thus to the success of the project. The application of a ceramic frit was used as the primary vehicle to control solar gain. No frit was used on the terminal facade glass because the overhangs effectively prevented direct solar penetration in these areas. Elsewhere, different fritting densities (75, 65, 55, 37, 20, and 0%) were used to achieve different transmission values. Optimizing the building envelope is reported to have reduced the cooling demand by 35%, and the radiant floor-cooling system reduced the energy demand by an additional 30%. A thermal stratification strategy was used to thermally condition the large enclosures, with an air-conditioned zone extending to just over 8 ft (2.5 m) above floor level; the cool air was supplied at ground level through a radiant cooling system in the floor and a low-volume air supply, while the unoccupied upper areas of the enclosures are much warmer. The building is designed so that no artificial lighting is needed during daylight hours even on an

FIGURE 8.15 A caulking crew applies the silicone material that provides the weather seal.

overcast day. The limited use of artificial lighting was an important factor in reducing cooling loads.[17]

The analysis provided by Transsolar included stationary and transient fluid dynamic simulations.[18]

Summary

The structural glass facade (SGF) of the MTB is part of an integrated energy concept for the new SBIA. The system achieves a high level of openness, transparency, and natural light, which were all part of the design. The use of heat-strengthened laminated glass is a notable deviation from standard practice. The component development and detailing of the terminal facade structure by Connell Wagner demonstrates a balance of engineering capability and aesthetic sensibility that is vital given the exposed structural systems used in SGFs (Figure 8.16). Richard Green substantiates the value of involving key suppliers early and intimately in the design process when implementing innovative building technology. Another key component of the success of the project was the intensive consideration of constructability issues early in the design process and throughout design development.

The application of a highly glazed structure in a tropical environment runs contrary to conventional practice; time will tell the success of this bold approach. Facade performance may have been improved with the use of IGU and a strategically located low-e coating, but the cost/benefit metrics are not favorable for the use of the more expensive glazing in this region, and the stratified thermal comfort strategy in the terminal building made them even less so. Whether there will be any monitoring and evaluation of energy performance is unknown; it would be interesting to determine how various aspects of the building perform. The integration of passive solar design principles and the abundance of natural light to reduce energy consumption and cooling loads are laudable design features.

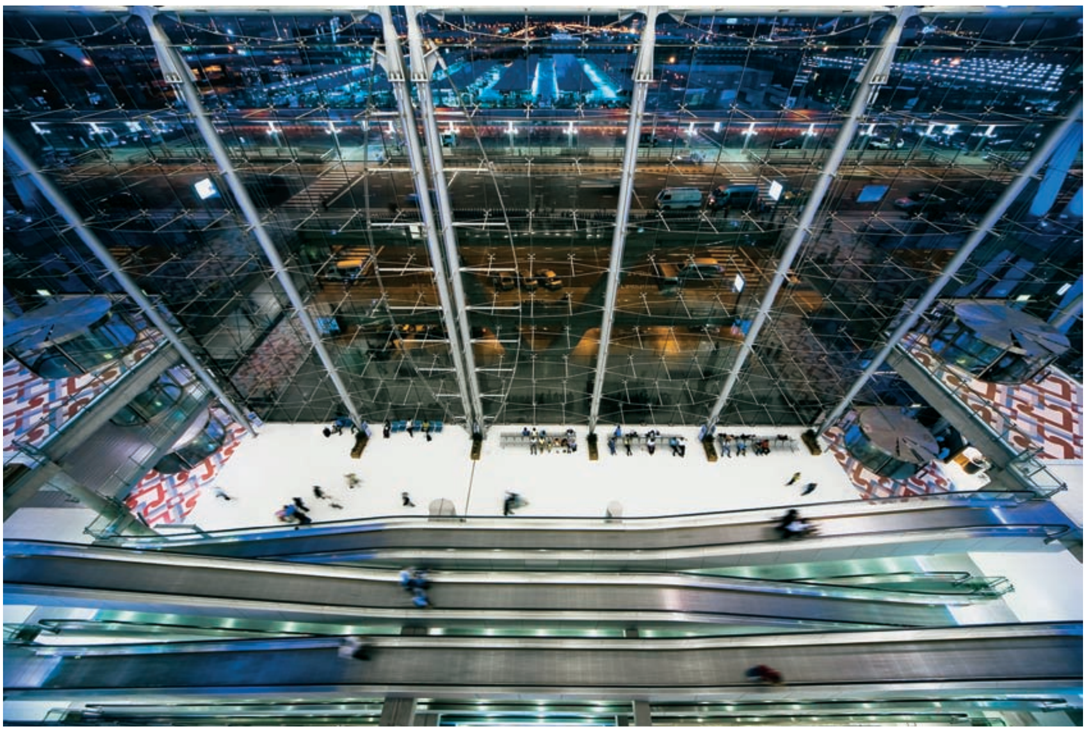


FIGURE 8.16 The in-plane bracing trusses are clearly visible in this view.

Chapter 9

Eli and Edythe Broad Stage

Santa Monica, California

FIGURE 9.1 Diffuse daylighting is provided to the interior through the clerestory.

General Information	
Year completed	2008
Building size sq ft (sq m)	32,000 (2973)
Building type	Cultural
Building cost, USD	Approx. 34 million
Project Credits	
Owner	Santa Monica College Performing Arts Center
Architect	Renzo Zecchetto Architects
Building engineer	Nabih Youssef & Associates
Acoustic consultant	Jaffe Holden Acoustics, Inc.
Sound isolation and noise control consultant	Newson Brown Acoustics, LLC
Construction manager	Michael Stebbins
General contractor	FTR International, Inc.
Facade design-builder	Corona Aluminum Co.
Facade engineer	W&W Glass, LLC
Glass manufacturer and fabricator	Pilkington
Glass system manufacturer	Pilkington
Mast truss system designer and supplier	TriPyramid Structures
Perimeter metal	GlasWal Systems Limited
Facade System	
Structure type	Mast truss system
Facade system cost per sq ft (sq m)	Approx. 205 (2207)
Total facade area, sq ft (sq m)	4213 (391)
Glass grid module orientation	Vertical
Grid dimension height × width ft-in. (mm)	5-4 × 7-11 (1626 × 2413)
Glass type Metric units specified, imperial units approximated.*	11/16 in. (17.52 mm) laminated glass with embedded connector starting outboard: 1/4 in. (6 mm) fully tempered (FT) low-iron 0.06 in. (1.52 mm) SentryGlas (SG) 3/8 in. (10 mm) FT low-iron
Glass system type	Point-fixed bolted
Maximum span, ft (m)	Approx. 34 (10)
Deflection criterion	L/175
Project delivery	Design-build

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The Broad Stage is located at 11th Street and Santa Monica Boulevard in Santa Monica, California, and anchors a performing arts complex at the Santa Monica College Madison Campus. Funded entirely by private donors, the new performing arts facility cost $34 million and boasts a 499-seat performance stage, a newly renovated theater, and rehearsal and classroom spaces. The intent of the College and architect Renzo Zecchetto was to create a world-class performing arts space where theater, dance, and musical performances could be accessed by the community and students alike. The facility incorporates a state-of-the-art acoustical design and promises to deliver a world-class entertainment experience.

Surrounded by a residential neighborhood on three sides, busy Santa Monica Boulevard borders the site to the south, presenting a significant acoustical challenge for the large glass facade enclosing the spacious lobby. The axis of the rectangular site parallels the dominant city street grid in the northwest–southeast direction. The location of the main parking lot to the south provides a visual and acoustical buffer to the facility from the busy roadway. The main entrance is set back from 11th Street. The main lobby is accessed from an elevated platform through the glass facade. The highly transparent glass facade floods the interior lobby with light during daylight hours while acting as a lighted beacon after dark[1] (Figure 9.1).

Building Structural System

A poured-in-place concrete frame supports a roof of concealed steel trusses as the primary building structure. The frame is clad on the exterior in wood,

FIGURE 9.2 The basic facade structural system consists of alternating cable trusses and suspended horizontal outriggers.

stone, and glass. The structural glass façade (SGF), with its exposed steel structure, is the prominent architectural feature of the facility.

Facade Program

The glass facade is a vertical clerestory rising over the stone-clad south facade and the wood canopy over the east entrance, allowing natural light to penetrate into the lobby area. Point-fixed glass is supported by a mast truss structural system, which transfers design loads at the top to the roof structure and at the base to the reinforced concrete building structure. The facade provides an expansive, airy, light-filled space, while the entry-level structure below provides support to the facade as well as to the dramatic cantilevered canopy and accommodates the entry portals.

Facade Structure

The mast truss system has trusses spaced 11 ft (3.4 m) on center (Figures 9.2 and 9.3). The trusses are suspended from the building structure using a

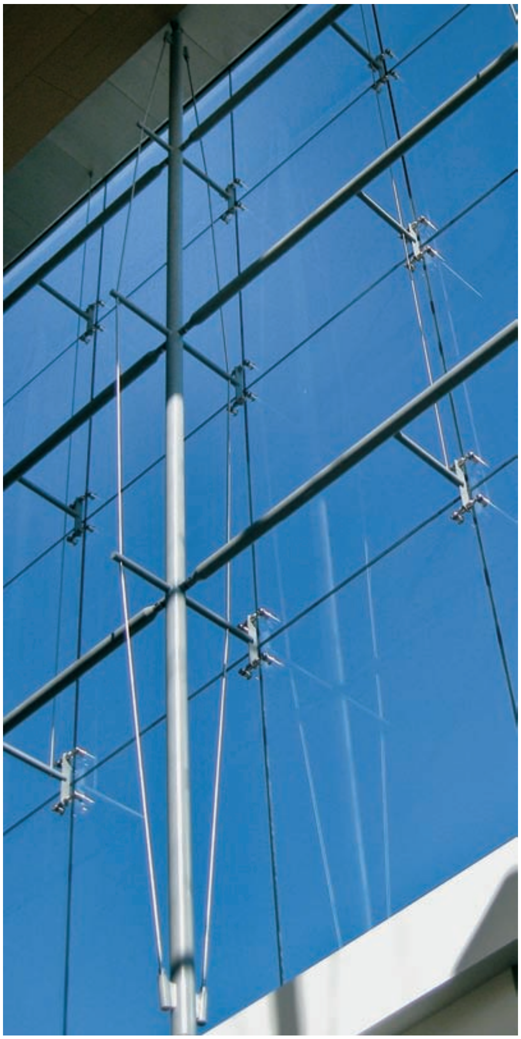


FIGURE 9.3 The basic mast truss form.

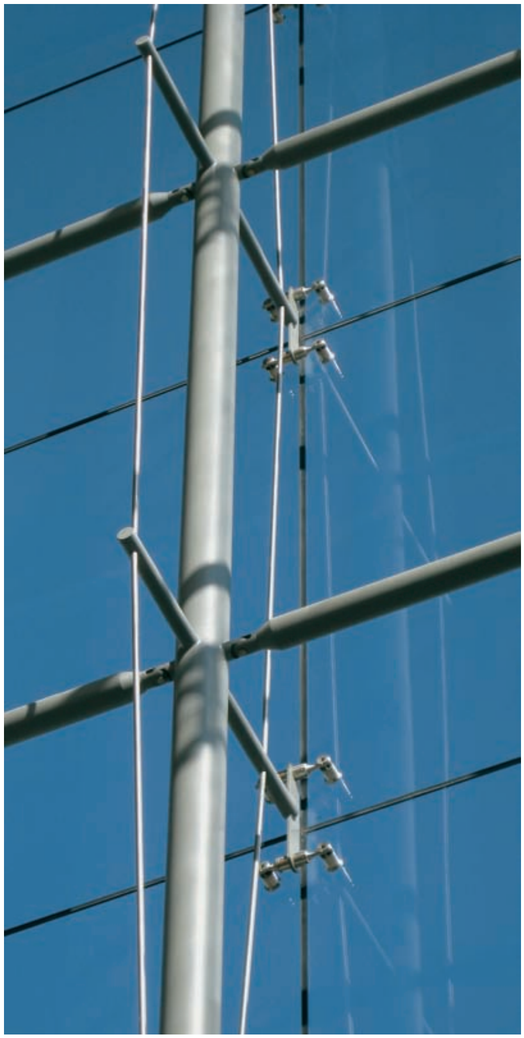


FIGURE 9.4 Bracing struts welded to the mast extend to the glass plane. A vertical plate welded to the strut end provides for the attachment of the glass fixings.

ridged connection to the steel frame of the roof and a slip connection to the concrete at the bottom of the facade. Steel tube spreaders extend from the trusses with a welded vertical steel blade paralleling the glass joint. The trusses are fabricated to Architecturally Exposed Structural Steel (AESS) standards and painted with a three-part aliphatic urethane coating. American Society of Testing Materials (ASTM) A316 stainless steel rods brace the central mast element of the trusses against lateral wind loads (Figure 9.4). The rods are continuous, passing through holes in the spreader ends from truss top to bottom, eliminating the need for costly interstitial fittings. The rods are cold headed at either end, and a threaded coupler secures them to an anchor bracket mounted on the truss assembly at either end.

The glass grid module is half of the truss spacing, meaning that a truss exits only at every other vertical division of the glass grid. A horizontal spar spanning between the trusses supports the intersections on the glass grid falling between the trusses. A welded outrigger at the midspan of this member extends out to the glazing plane with a connection assembly identical to that at the trusses. A dead load cable hung from above supports the self-weight of the glazing system at the ends of the outriggers. The facade corner conditions are similarly treated, with an adaptation of the horizontal member, leaving the corners open with minimal structural support (Figures 9.5 and 9.6).

While of related morphology, note the dramatic difference in scale and complexity between this

FIGURE 9.5 The corner condition is treated as an extended outrigger, simplifying the structure and heightening the facade's transparency.

FIGURE 9.6 This exterior view of the corner condition reveals the minimal structure.

truss system and that described in the Bangkok Airport case study presented in Chapter 8.

Glass System

The glass is 11⁄16 in. (17.52 mm) laminated low-iron Pilkington Optiwhite. Pilkington Integral 905 fittings are supported from the steel blade at the end of the spreaders and outriggers (Figure 9.7). These are attached to the embedded fastener to fix the glass to the structure. This results in no penetration through the glass to the outside. A 5⁄8 in. (16 mm) joint between the glass panes is filled with field-applied silicone to provide the weather seal. The glass edges at the boundary interface are set into aluminum channels on setting blocks (bottom) and sealed with silicone.

Facade Concept Development

The architect conceived of a highly transparent clerestory glass facade but left the system type and detailing undefined, developing instead a broad, undefined, performance-based specification for permitting purposes. This strategy was possible because of a *deferred approval* process adopted by the State of California, as discussed below. The architect envisioned two primary states for the glass facade, depending upon natural lighting conditions. During daylight hours, the clerestory would flood the lobby hall with diffuse light. After nightfall, an artificial lighting scheme would highlight the wood shell of the hall, creating a welcoming lantern effect as the clerestory, dominated by reflections throughout the day dematerialized, revealing the rich warmth of the interior finishes. A facade design-builder was later selected that brought a team of designers, fabricators, and material suppliers together, and the facade system detail design was developed between them in collaboration with the architect.

The design-build team provided informal presale services gratis to the architect as required to support the development of a basic concept and performance specification that could be included in project contract documents.

Project Delivery

The Broad Stage was a State of California project under the jurisdiction of the Division of the State Architect (DSA). The facade system went through a deferred approval process provided by the state

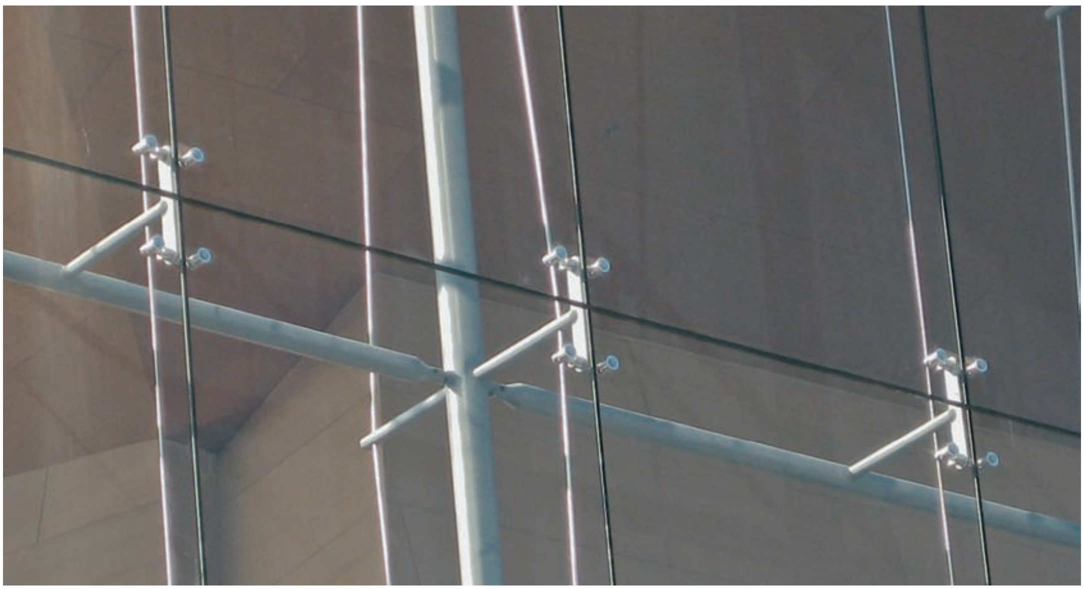


FIGURE 9.7 Exterior point fixings; note the minimal site line of the silicone joint possible with laminated or monolithic glazing.

to accommodate systems that cannot be efficiently designed without the input of a specialty supplier. Design elements that may be deferred are limited to such things as sprinkler systems, access floors, elevator guide rails, exterior wall systems, skylights, window wall systems, stage rigging, and others, as must be agreed to in advance by the DSA. Without this process, the architect would be required to provide a complete design of the facade system at the time of permitting, effectively precluding any significant involvement from material suppliers, fabricators, and specialty contractors. As it is, the architect is required to provide detailed performance specifications and loading criteria for the facade in the project plans and specifications. The architect also assumes responsibility for coordinating the work, ensuring that the facade is properly designed by licensed professionals, designing all interface requirements, and verifying that deflections, drifts, and vertical and lateral loads are adequately addressed.[2]

This allows the architect to include an innovative facade design in a project by simply defining the area of the work, an indication of design intent if desired, and a comprehensive performance specification. Once the project is permitted and enters the build phase, a specialty contractor can be selected to provide design-build services for the facade system. The contractor works with the architect to develop the system, submitting engineering drawings and calculations through a shop drawing submittal process, with the design-builder acting as the engineer of record for the facade system.

In this case, the facade design-builder provided presale concept development support to the architect at no cost in exchange for certain related products being specified in the project's contract documents, thereby providing a reasonable expectation that the upfront costs absorbed at risk could be recouped in an eventual design-build contract, as indeed occurred. Pilkington products were specified in the contract documents, and the design-build contractor was selected through a negotiated bidding process.

Installation Strategy

Anchor assemblies were first installed at the boundary of the facade, at the top steel frame and bottom concrete curb. The assembled trusses were then hoisted and set in place by securing the pinned connections at the top and bottom. The dead load cables were next hung between the trusses, providing for the assembly of the horizontal components, the ends of which were simply pinned to the trusses, with the outriggers clamping to the dead load cables to stabilize the assembly. The stainless steel barrels and glass fittings were then installed on the vertical blades at the glass plane and carefully set to a tolerance of 0.08 in. (2 mm). The glass attachment points were then surveyed and the entire structural system adjusted as necessary to ensure the necessary tolerances. The structural system was then ready to receive the glass. Individual panes were hoisted into place using a vacuum glass lifter attached to a crane. The panes were installed row by row, working from the top down, to avoid having to work over the installed glass. The glass was sized to provide a gap between panes approximately ⅝ in. (16 mm) thick. Structural silicone was then applied to the joints to provide the weather seal. The glass surfaces adjacent to the joints were taped, the joint surfaces cleaned, and the silicone applied. Finally, the silicone material was tooled to provide a smooth and aesthetically pleasing joint. After the initial curing of the silicone, which required approximately 24 hours, the tape was removed.

Strategies for Sustainability

In addition to acting as an acoustic buffer between the hall and Santa Monica Boulevard, the facade system is part of the lobby's natural ventilation scheme, with the tall spaces between the facade and the auditorium shell providing a thermal chimney effect. Cool ocean air from the nearby Pacific Ocean is drawn in from the lower west through automatic motorized operable windows, and the warm air is exhausted at the top on the east side.

Summary

The mast truss system developed as a custom solution for this project is a simple, elegant, efficient, and well-executed response to the project's needs. The structure is expressive while providing a minimalist aesthetic to the relatively short span of the clerestory (Figure 9.8). The detailing also is simple and refined and the craftsmanship excellent, adding to the overall polished air of the performing arts complex. The detailing is cleverly executed to minimize or eliminate the use of expensive castings and machined fittings, optimizing the system's economy.

The facade design is nicely integrated into the building architecture, both visually and functionally. The play of daylight within the space is the predominant feature of the lobby hall, replaced as the facade dematerializes under artificial lighting by a lantern glow defining the facility at night. Functionally, the use of laminated glass with sound-dampening properties enables the facade to provide an acoustical buffer between the busy roadway of Santa Monica Boulevard and the interior spaces. The enclosure provided by the facade also acts as part of the natural ventilation system, minimizing cooling requirements for the heating, ventilation, and air conditioning (HVAC) system.

As with many structural glass facade (SGF) applications, the success of this project can be attributed to a productive collaboration between the architect and a competent design-build team.

FIGURE 9.8 This simple system design presents a minimal profile.

Chapter 10

300 New Jersey Avenue (51 Louisiana Avenue)[1]

Atrium Enclosure
Washington, D.C.

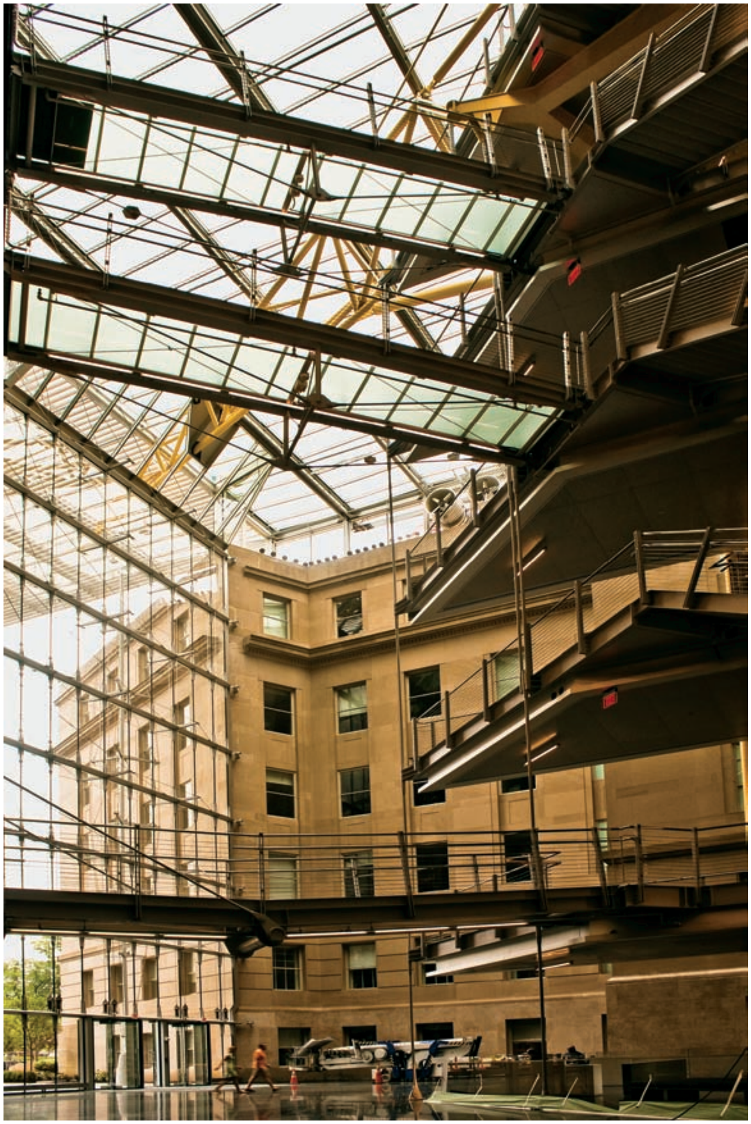


FIGURE 10.1 The atrium enclosure is a 10-story glass wall and skylight roof.

General Information	
Year completed	2009
Building size, sq ft (sq m)	275,000 (25,548), 10-story
Building type	Corporate office
Building cost, USD	Approx. 71 million
Project Credits	
Owner	JBG Companies
Architect	Rogers Stirk Harbour + Partners Dennis Austin, Mike Fairbrass, Ivan Harbour, Annie Miller, Nick Mitchell, Richard Rogers, Andrei Saltykov, Patricia Sendin, Paul Thompson[2] With HKS Architects
Building engineer	SK&A Associates (U.S.) Expedition Engineering (U.K.)
General contractor	Clark Construction
Design-assist design-build facade specialist	Enclos Corp with ASI Advanced Structures Inc.[3]
Rod supplier	Deacon (U.S.)
Steel fabricator	Metfab Steelworks (Orange, New Jersey)
Glass supplier	Viracon
Facade System	
Structure type	Cable truss wall and custom skylight
Facade system cost, USD/sq ft (sq m) installed	Approx. 250 (2673)
Total facade area, sq ft (sq m)	Approx. 12,500 (1161) skylight 4000 (372) wall
Glass grid module orientation	Vertical
Grid dimension height × width ft-in. (mm)	Wall: approx. 11 × 4 (3353 × 1219) Roof: approx, 8-3 × 4 (2515 × 1219)
Glass type Imperial units specified, metric units approximated.*	Wall and sloped glass 1⅜ in. (33.52 mm) laminated IGU starting outboard: ¼ in. (6 mm) fully tempered (FT) low-iron ½ in. (12 mm) airspace (AS) ¼ in. (6 mm) FT low-iron 0.060 (1.52 mm) polyvinyl butyral (PVB) 5/16 in. (8 mm) FT low-iron VE15-2M low-e no. 2 surface with edge deletion Roof glass 1 5/16 in. (31.52) laminated IGU starting outboard: ¼ in. (6 mm) FT ½ in. (12 mm) AS ¼ in. (6 mm) FT 0.06 (1.52 mm) PVB ¼ in. (6 mm) FT

Facade System (cont.)	
Glass type (cont.)	High-opacity white frit no. 2 surface Viracon VE15-2M low-e on no. 2 surface with edge deletion
Glass system type	Wall: point-fixed clamped
Rod material	Macalloy 460
Maximum span, ft (m)	Approx. 42 (12.8) wall
Deflection criteria	L/240 + ¼ in. (6 mm) L/140 glass insulating glass unit (IGU) edges
Project delivery	Design-assist, design-build

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

This office complex in Washington, D.C., by Pritzker Prize–winning architect Richard Rogers includes a new glass-clad 10-story office building and a novel glass atrium enclosure (Figure 10.1). The new building is an expansion of two historical stone-clad buildings. The central atrium joins the three facilities together at multiple levels with 16 glass sky-bridges. The 10-story atrium enclosure is largely comprised of a full-height glazed entry wall and a skylight roof. In addition to a unique aesthetic of exposed structure, the system designs respond to the challenging constructability issues of a highly constrained urban site, as well as an aggressive construction schedule. The existing buildings remained operational during construction, creating the necessity for minimal site disruption throughout the process.

FIGURE 10.2 The atrium ties three buildings together at multiple levels using 16 glass bridges spanning to a central elevator/utility core.

Atrium Structural System

A centrally located tree-like steel-framed structure provides the primary structural system for the atrium, supporting a trapezoidal glass roof. The structure also acts as the atrium's core, supporting various building system components including exposed heating, ventilation, and air conditioning (HVAC) equipment (Figure 10.2). The exposed structure is painted bright yellow, a signature design element of Rogers.

Facade Program

The atrium enclosure required the design of the vertical glass entry wall and roof as part of an integrated assembly. Accordingly, all elements of the enclosure are discussed here: the entrance wall, the sloped transition, and the skylight roof (Figure 10.3).

Facade Structure

Entrance Wall

The 102 ft (31.1 m) tall by 42 ft (12.8 m) wide entry wall combines transparency with an expressive structural design (Figure 10.4). An overriding design consideration was to minimize loads on the existing buildings. The dead load of the entire wall is suspended from the new building structure, and wind loads on the wall are resisted by tensile bracing elements that tie back to the new building .

A series of seven suspended horizontal trusses and a portal beam provide the wall structure. The trusses are fitted with 2 ft (61 cm) vertical armatures to point-fix laminated insulating glass units (IGUs). Whether owing to the bilateral symmetry or the profile, Rogers refers to the design as a "kipper truss." These trusses are built up from augmented steel W-sections, plate armatures, and tension rods. Out-of-plane bracing rods at the truss end adjacent to the new building provide lateral stability. Spring mechanisms at the opposite end absorb deflections and differential building movement without inducing high compressive stresses into the structural components.

Vertical loads are accumulated at the top of the wall, transmitted through interior and exterior out-of-plane diagonal rods, and delivered to the adjacent new building structure at one side of the wall. In essence, the entrance wall is hung from the new building structure, which was designed to accommodate these loads, thereby minimizing loads to the existing building along the opposite edge of the wall. The kipper trusses are hung sequentially, one from the next, from stainless steel rods on both the interior and exterior of the wall (Figures 10.6 and 10.7). The rods terminate at the portal beam

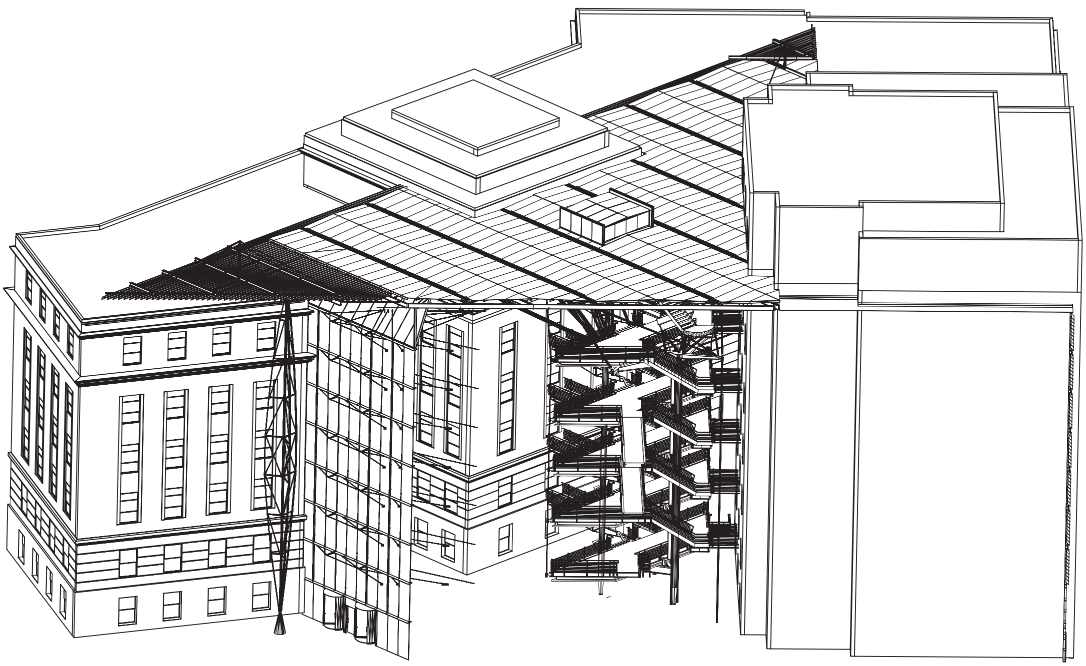


FIGURE 10.3 Three-dimensional model of the two existing structures and the central atrium's specialty glazing (new office building omitted for clarity).

FIGURE 10.4 The glass entry wall is suspended from an overhead beam that is cantilevered from the new building structure on the left, so that it applies only minimal loads to the older building on the right.

in a series of spring connections (Figure 10.5). The spring is slightly compressed and installed at the bottom terminus of the rods. Deflection of the glass facade further compresses the spring. In returning to its predeflection shape, the spring stabilizes the system.

Skylight

The glass roof is a low ridge and furrow design covering 12,500 sq ft (1,161 sqm) of plan area. Generally triangular in plan, the skylight measures approximately 180 ft (54.9 m) along the north and west edges and approximately 260 ft (79.2 m) along the hypotenuse. The skylight structure is comprised of prefabricated steel ladder frames built of channel and pipe. The ladder frames are supported by the walls of the buildings at the perimeter of the skylight, as well as by the steel tree in the center of the atrium (Figure 10.8). The southwest and northeast corners of the skylight extend beyond the atrium to support overhead aluminum louvers. In the southwest corner, the extension is achieved by cantilevering the skylight framing. In the northeast corner, it is achieved with a mast truss outside the wall and diagonal hanger braces (Figure 10.9). There is a sloped transition between the wall and roof that is described below.

Building Movement

The skylight roof, sloped wall transition, and entrance wall make up the composite atrium enclosure. The glass enclosure ties together three separate buildings of dissimilar construction and built during different time periods when building practices and code requirements varied. The result is considerably different behavior among them with respect to movement induced by various loading conditions. Even identical buildings will not move in

FIGURE 10.5 The wall is hung from tension rods that terminate in a spring connection at the door header, allowing the wall to deflect under lateral loads but returning it to its original position as the loads decrease and accommodating any vertical deflections while keeping the rods always in tension.

phase when subject to identical loading conditions. The engineering team built a three-dimensional digital model of the glass enclosure and surrounding buildings as a tool for studying the relative building movements. The intent was to develop a design for the roof and wall that could fully accommodate these movements with an efficient and minimal structure. Drift conditions are accommodated by providing suitable movement joints between the skylight and the adjacent building structures. At the skylight level, the new building can move up to 2 in. (51 mm) in any horizontal direction relative to the existing buildings.

Glass System

The entry wall laminated IGUs are 11 ft tall by 4 ft wide (3.4 by 1.2 m), low-iron, low-e coated and tempered. Stainless steel clamp fittings penetrate the glass joint and point-fix the glass to the trusses at the end of 2 ft. (61 cm) armatures extending above and below the trusses. The weather seal is provided by a field-applied butt-glazed silicone joint.

The skylight glass is laminated IGUs with a ceramic frit and a low-e coating, measuring nearly 8 ft 3 in. by 4 ft (2.5 by 1.2 m), fully perimeter supported on aluminum frames. The glass is factory preglazed onto the aluminum frames, with the resulting panels acting as a cassette-type glazing system. The aluminum frames span lengthwise between the steel ladder frames. The connection between the aluminum frames and steel ladder frames is achieved with a paddle arm and pin connection (Figures 10.10 and 10.11).

The transition between the vertical entrance wall and the glass roof is a single-story skylight 14 ft (4.3 m) long and sloped at an angle of 49 degrees. The full-size laminated and tempered IGUs are perimeter supported on aluminum frames. The sloped portion is shaded by overhead aluminum louvers, which continue the skylight geometry

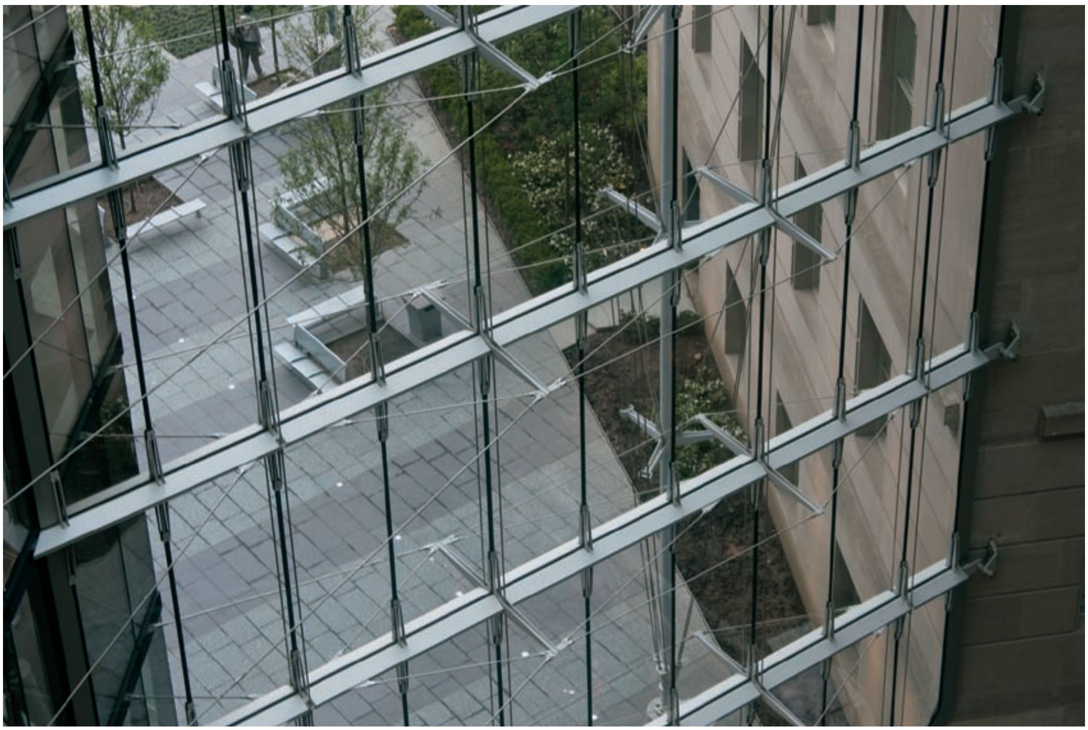


FIGURE 10.6 The kipper truss design is apparent here.

beyond the entrance wall. A metal panel is placed within the sloped wall at the point of truss penetration and is designed to accommodate the structural movements without imposing loads on the sloped wall (Figure 10.12).

Facade Concept Development

A design-assist contracting strategy provided for the early participation of a specialty facade contractor as part of the design team, who worked closely with the architect through concept and design development. This proved key to the successful implementation of the challenging facade program. The custom glazing systems developed for the atrium wall and roof are unique minimalist solutions developed in response to the architect's aesthetic intent and the constructability challenges presented by the building program. The ability to

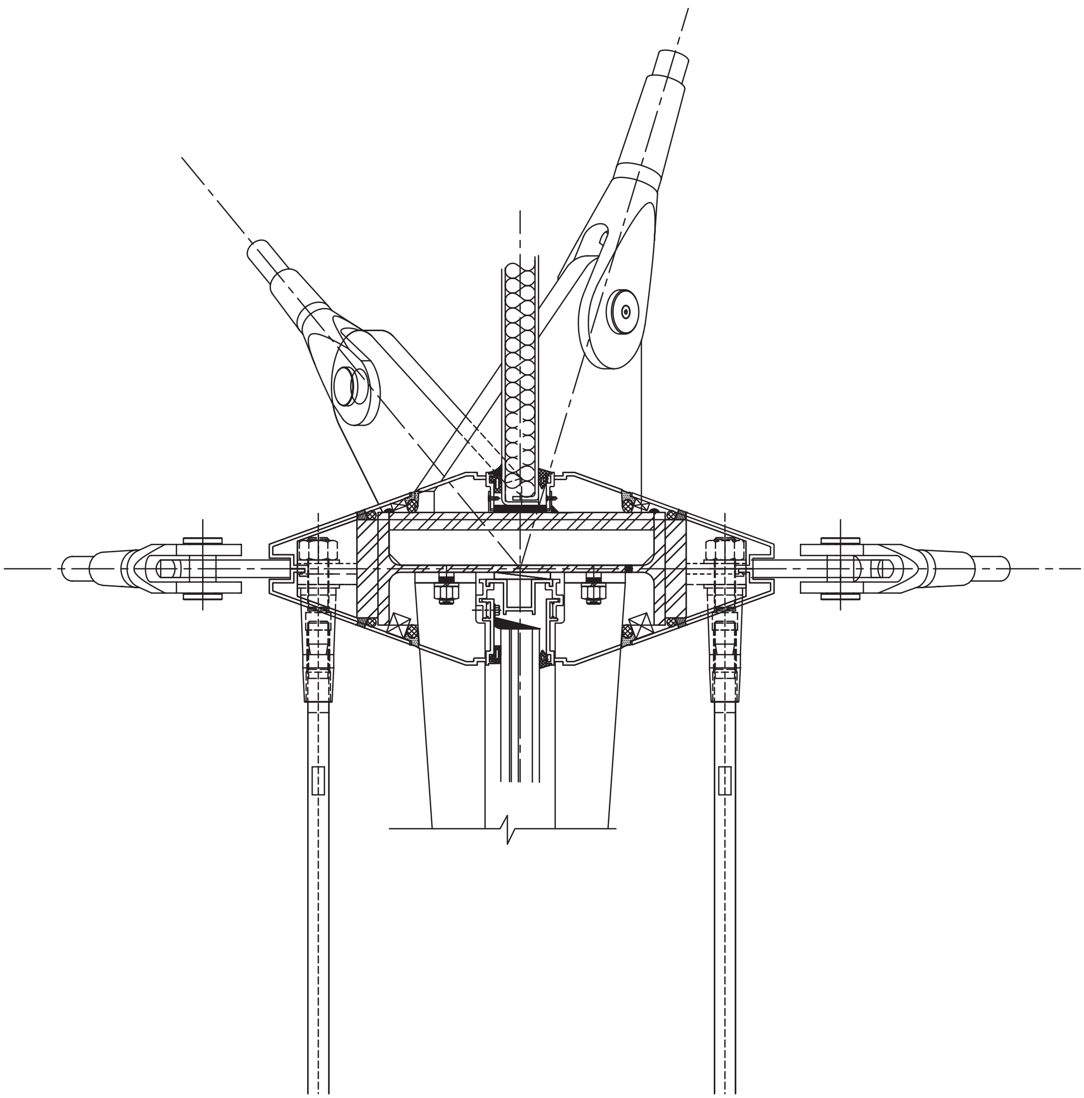


FIGURE 10.7 Top of the suspended wall detail.

anticipate and address constructability issues early in the design process contributed much to the ultimate success of this project.

A comment from the architect's Web site emphasizes this point:

> *As part of the design stage work for the 12,500 square foot (1,161 sqm) atrium's glass roof, and integral to RRP's design process, the client agreed to engage a specialist engineer/fabricator of bespoke glazing systems. Advanced Structures Inc (ASI) was brought on board to work directly with RRP and the engineer of record in designing the atrium's glass roof and walls. The process allowed for an easy transition of early structural and glazing concepts from RRP and Expedition Engineering to the project's Washington-based team. Early exchanges between RRP and ASI typified the working collaboration between architect and engineer/fabricator that is habitual in RRP's work. The benefits to the project were manifold, including optimized off-site assembly via a glass roof system; ease of on-site erection via direct steel supplier input; visual clarity via custom extrusions studies; cost assurance; and—above all—client confidence in the process.*[4]

Testing

A full-scale mockup test was part of the facade program. The mockup included all three elements of the enclosure: wall, transition, and roof. The mockup met all specified requirements (Figures 10.13 and 10.14).

FIGURE 10.8 The skylight framing is supported by perimeter building structure and the dramatic yellow tree truss that houses the central circulation.

FIGURE 10.9 A mast truss supports skylight framing that extends over the entry area and contains shading louvers.

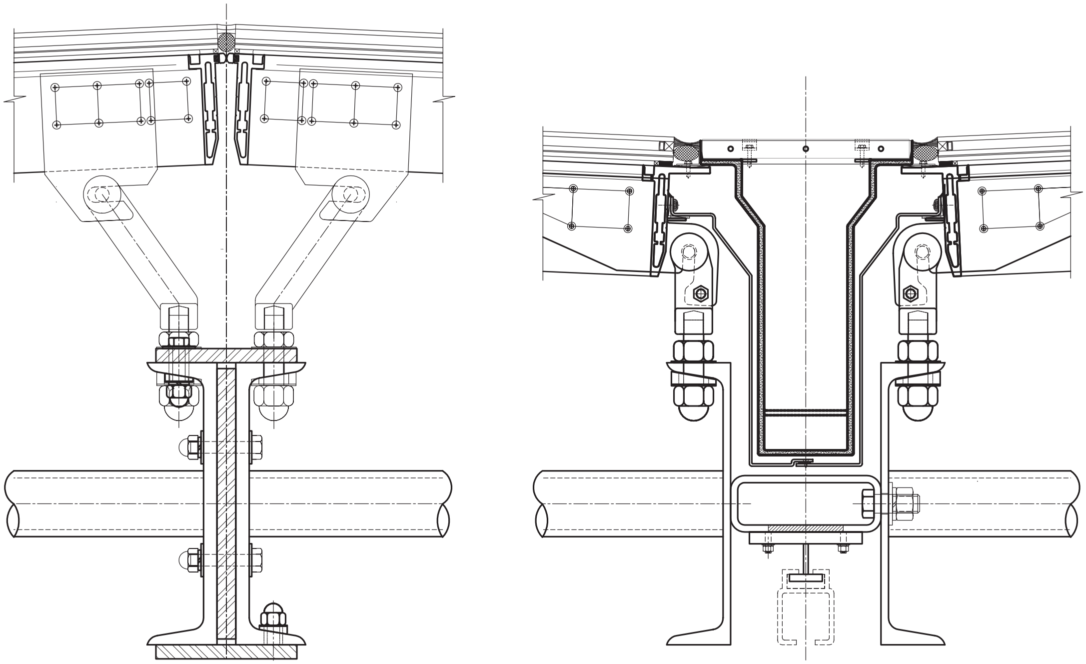


FIGURE 10.10 Skylight ladder frame at the high-point ridge (left) and the low-point valley with an integral gutter (right).

FIGURE 10.11 Glass roof detail showing the paddle arm and pin connection of the glass system to the ladder trusses. The primary structural member is actually split into two channels that are part of separate ladder trusses.

Project Delivery

The project started under a design-assist strategy with an agreement that if established budget targets were met, a design-build contract would be issued. This resulted in an uninterrupted process from concept design through construction. Primary material suppliers and fabricators were selected early in the design process because of the specialty nature of the work. Steel fabrication was a particular concern, with all of the systems being exposed. The project was the recipient of the Washington Building Congress–Craftsmanship Award for 2009.

Installation Strategy

Space was very limited on the dense urban site, and the office buildings immediately adjacent to the site remained operational throughout construction. In addition to the general contractor, over 40 subcontractors and an average of 200 site workers each day were involved in construction activities extending over a 3-year period. Such tight constraints required intensive site logistics, collaboration, management, and coordination among trades to ensure optimum workflow and minimal disruption to immediately adjacent building occupants.

Key to the success of the complex installation of the glass enclosure was a custom structural system for the glass wall and skylight that anticipated the requirements for installation in their respective design. The skylight roof system was prefabricated in fully glazed subassemblies off site. The supporting structure was also prefabricated and shipped to the site as assembled units. The skylight structural system was designed with a split-beam structural element running in the primary spanning direction. Ladder frames were assembled under factory-controlled conditions into 12 ft (3.7 m) wide subassemblies up to 48 ft (14.6 m) in length. The finished sections were stacked

FIGURE 10.12 The yellow roof support truss penetrates the sloped skylight transition through a metal panel.

FIGURE 10.13 A full-scale test mockup includes wall, transition, and roof sections.

on flatbed semitrailers and shipped to the site on a just-in-time basis to minimize site inventory and storage space. The sections were lifted from the trailer by an overhead crane and set directly into position, secured by a simple bolted connection. Crane setting positions were carefully mapped and their availability coordinated with the other trades (Figure 10.15).

Factory prefabrication concentrated assembly work in the factory, enhancing product quality and minimizing site labor. Detailed installation planning accelerated assembly and installation work, and minimized disruption to this challenging building site.

Strategies for Sustainability

The partially vented atrium structure is part of the building's energy strategy, intended to act as a thermal buffer to the south facade of the new building, maximizing daylight while mitigating the effect of solar gain. A number of other sustainability features were incorporated into the design of the new office building itself. The project attained a Leadership in Energy and Environmental Design (LEED) Gold rating from the U.S.Green Building Council.

FIGURE 10.14 A kipper truss forms part of the mockup.

Summary

This project transformed an existing site, including two older buildings, into a focused office community, with the addition of a new glass-clad mid-rise building and a connecting transparent atrium that acts as the main entry into the building complex (Figure 10.16). The development brings a contemporary modernist aesthetic to the traditional architecture of the nation's capital, nicely integrating public and private office space in a manner that encourages meaningful social interaction. Design was used to satisfy challenging building conditions, including advanced facade technology, a constrained building site, an aggressive construction schedule, and the need to minimize disruption to existing office buildings, which remained operational throughout construction. Offsite prefabrication was used as a predominant strategy to satisfy the program requirements, and the structure and cladding systems were designed to provide for ease of factory fabrication and assembly and to facilitate rapid site installation, all without compromise to the minimalist aesthetic of the atrium structure.

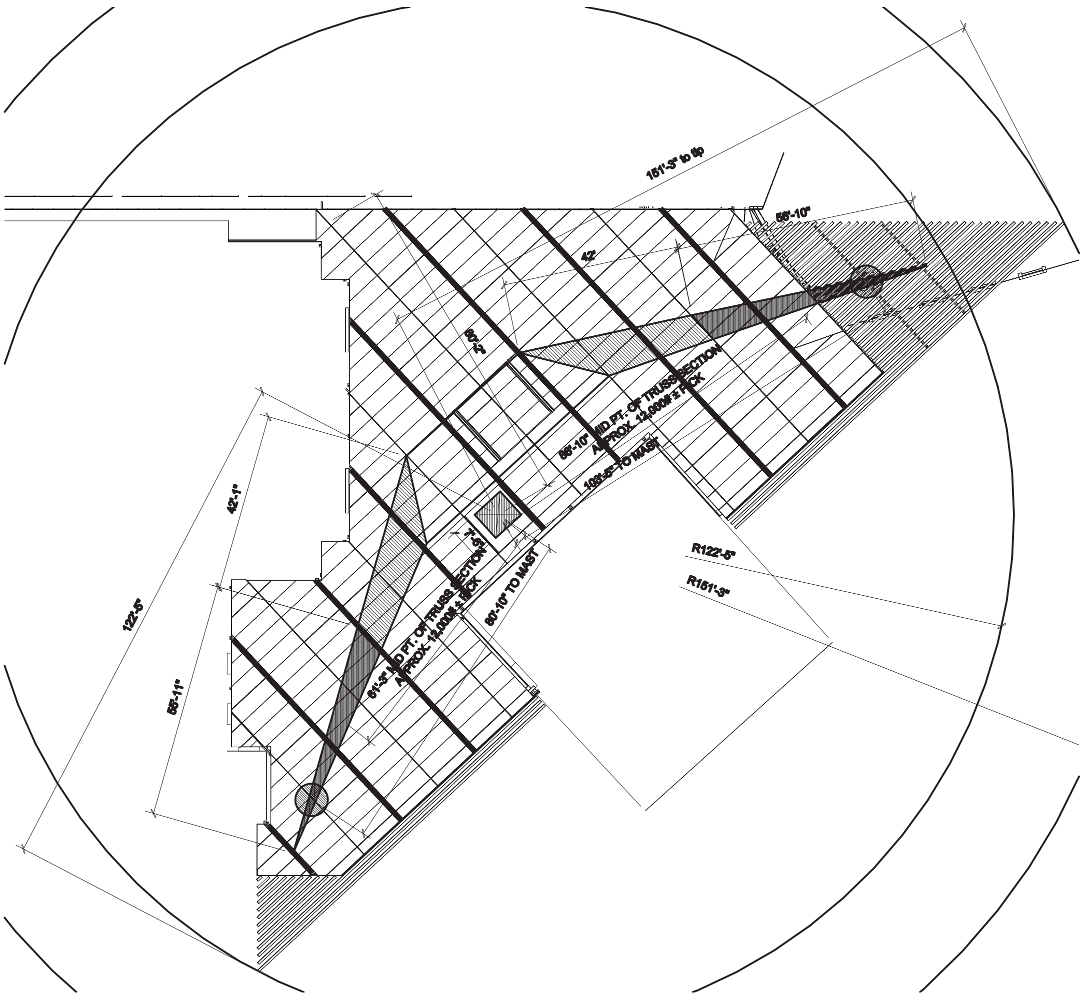


FIGURE 10.15 Crane picks were carefully choreographed, as represented in this line drawing.

FIGURE 10.16 The atrium entry wall as the new building (to right) nears completion.

Chapter 11

Vivian and Seymour Milstein Family Heart Center

New York Presbyterian Hospital
New York City

FIGURE 11.1 A transparent membrane introduces the facade aesthetic at the building entry.

General Information	
Year completed	2010
Building size, sq ft (sq m)	125,000 (11,613); eight-story
Building type	Health care (hospital)
Building cost, USD	Approx. 125 million
Project Credits	
Owner	New York Presbyterian Hospital
Lead architect	Pei Cobb Freed & Partners Ian Bader, Alan Gordon, Michael Lyon
Associate architect	Da Silva Architects
Facade consultant	Thornton-Tomasetti Group
Structural engineer	Thornton-Tomasetti Group
Mechanical, electrical, plumbing (M/E/P) engineer	Syska Hennessy Group
Climate consultant	Arup
Lighting consultant	BDP Lighting
Acoustical consultant	Sandy Brown
General contractor	FJ Sciame Construction D Haller, Inc.
Construction manager	Bovis Lend Lease
Facade design-builder	W&W Glass, LLC
Cable truss systems designer and fabricator	TriPyramid Systems
Glass supplier	Pilkington
Facade System	
Structure type	Vertical rod truss climate wall; horizontal rod truss lobby wall
Facade system cost, USD (installed)	14.5 million
Total facade area, sq ft (sq m)	33,000
Glass grid module orientation	Vertical
Grid dimension height × width, ft-in. (m)	Climate wall approx. 16 × 5 (4877 × 1524) Lobby wall approx. 7-7 × 5-8 (2311 × 1727)
Glass type Metric units specified, imperial units approximated.*	Climate Wall (double-skin) Outboard leaf 15/16 in. (24.52 mm) laminated starting outboard: 9/16 in. (15 mm) fully tempered (FT) 0.06 in. (1.52 mm) polyvinyl butyral (PVB) 5/16 in. (8mm) heat-strengthened (HS) Inboard leaf and return wall 1-3/4 in. (44.52 mm) laminated insulating glass unit (IGU) starting outboard: 9/16 in. (15 mm) FT in. (16 mm) airspace (AS) 1/4 in. (6 mm) FT 0.06 in. (1.52 mm) PVB 1/4 in. (6mm) FT

Facade System (cont.)	
Glass type (cont.)	Atrium Skylight glass 1 11/16 in. (41.52 mm) laminated IGU starting outboard: 1/2 in. (12 mm) FT 5/8 in. (16 mm) AS 1/4 in. (6 mm) FT 0.06 in. (1.52 mm) SentryGlas (SG) 1/4 in. (6 mm) FT (Silver spacer and gray silicone; 60% black dot ceramic frit coating on the no. 2 surface) Atrium Wall 1 13/16 in. (47.04 mm) double-laminated IGU starting outboard 1/4 in. (6 mm) FT 0.06 in. (1.52 mm) SG 3/8 in. (10 mm) FT 5/8 in. (16 mm) AS 1/4 in. (6 mm) FT 0.06 in. (1.52 mm) SG 1/4 in. (6 mm) FT (Tiers above the bottom tier have a 40% black dot ceramic frit coating on the no. 2 surface.) Exterior Soffit Glass 15/16 in. (24.52 mm) laminated starting outboard: 9/16 in. (15 mm) FT 0.06 (1.52 mm) SG 5/16 in. (8 mm) FT Pilkington Optiwhite low-iron throughout All tempered glass heat-soaked
Glass system type	Point-fixed bolted with integral fitting
Maximum span, ft (m)	Atrium 40 ft (12.2 m); climate wall 16 ft (4.9 m)
Deflection criterion	L/140
Project delivery	Design-build

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The Family Heart Center is sandwiched between two existing hospital blocks at the 168th Street campus of the Presbyterian Hospital. The curving four-story glass facade of the Center acts as a focal counterpoint to these existing masonry buildings, providing panoramic views of the Hudson River and the Palisades beyond. The new state-of-the-art facility seamlessly connects the added diagnostic, ambulatory surgery, critical care, and cardiac catheterization facilities to the existing buildings on multiple levels, providing continuity of medical function and circulation. Architects Pei Cobb Freed & Partners sought to maximize the therapeutic benefits of daylight by flooding the interior spaces with natural light. An aesthetic of refined transparency and exposed structure is apparent throughout the building (Figure 11.1). The project incorporates several novel facade elements important to the building architecture, but the signature element is the climate wall: a fully glazed curving double-skin facade. The curve is comprised of segmented flat glass units. In addition, a four-story atrium space reached through a sweeping corridor from the main entry features a 70 ft (21.3 m) tall glass wall and skylight roof. The atrium encloses suspended pedestrian glass-floored bridges, which tie the new facilities to the old ones at every level (Figure 11.2). The Center targeted LEED Gold certification.

Building Structure Interface

The building structural system is comprised of steel decks and reinforced concrete superstructure. The

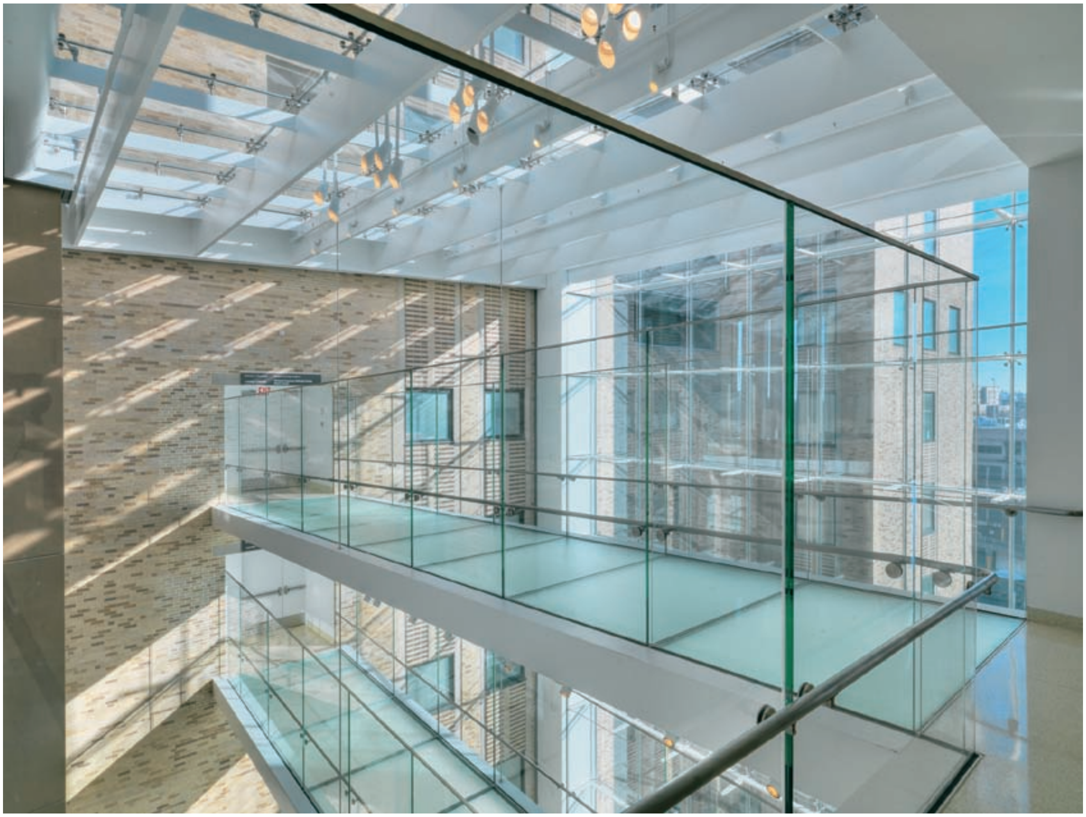


FIGURE 11.2 The atrium bridges the new building with the old, providing access at each level.

cable truss system cantilevers from the building structure to create the climate wall enclosure, with lateral restraint provided at each floor level. A steel frame of W24s on the first and fifth floors runs along the perimeter of the climate wall and is attached to existing buildings on either side, requiring expansion joints on both sides of the climate wall accommodating movement up to 5 in. (127 mm).

Facade Program

The facade program on this project incorporates three primary elements: a climate wall, an atrium, and entry structures. The refined entry systems provide an elegant introduction to the building and a striking first impression. The double-skin facade referred to as the *climate wall* is claimed to be the first of its kind in New York City. The faceted curving facade floods public areas of the building interior with natural light. A novel double-skin construction provides for both energy efficiency and visual transparency. A glass roof and a 70 ft (21.3 m) tall glass wall enclose the atrium space, through which cut pedestrian bridges tying together the facilities at each level.

FIGURE 11.3 The entry wall cable truss system establishes the vocabulary for the truss system used for the climate wall. Note the glass box vestibule in the middle ground.

Facade Structure

Cable trusses are the primary structural strategy for supporting the facade elements, but the structural systems take distinctly different forms in each of the facade areas.

Entry Structures

The gleaming stainless steel cable trusses supporting the point-fixed low-iron glass that encloses the building entries derive from the same vocabulary as the truss system used for the climate wall. Double trusses are used to accommodate an entry vestibule structural glass enclosure (Figure 11.3).

Climate Wall

Twenty-eight vertical cable trusses define the climate wall, located on 5 ft (2.5 m) centers at each vertical gridline of the glazing grid. Each truss runs the full four-story height of the climate wall, anchored at the top and bottom back to the building structure. The trusses are also tied back to the floor slabs at each level, providing lateral restraint to the system and minimizing spans to floor-to-floor dimensions, which vary slightly but are approximately 16 ft (4.9 m) (Figures 11.4 to 11.7).

The truss design is comprised of rod bracing elements between struts at each floor level; thus, there are four modules per truss. The spreader struts at the top and bottom of each module tie into a slotted connection at each floor slab on the inboard side, and support a grating system that provides maintenance access within the cavity while permitting unrestricted airflow. The strut assemblies define the cavity depth of the double-skin wall at approximately 30 in. (762 mm). A half strut is located at the midspan of each module, which clamps the rods at their intersection and reaches from there out to the glass plane to provide necessary midspan support to the full-height exterior glass panels. A suspended dead load rod runs vertically just behind the glass plane, tying to each of the strut ends, thus carrying the glass dead load to the supporting building structure at the top of the climate wall. The struts are fabricated from machined stainless steel, and A316 stainless steel rods are used in lieu of cables. The rods are prestressed in the field to a nominal 5 kips (22 kN).

Atrium

The atrium facade employs a different strategy for the supporting structure. The vertical wall of the atrium is approximately 70 ft tall by 40 ft wide (21.3 by 12.2 m) and is supported by eight horizontal cable trusses spaced at just over 8 ft (2.4 m) on center, suspended from vertical cables (Figure 11.8). The truss configuration is topologically similar to a Vierendeel truss, built up of welded steel plate, but with the inner chord consisting of a $\frac{7}{8}$ in. (22 mm) cable prestressed to 13 kips (58 kN). Three fabricators were used to provide the Architecturally Exposed Structural Steel (AESS) painted steel fabrication due to demanding scheduling requirements. The trusses are suspended along the outboard chord from overhead cables hung from a steel lattice structure that also supports the atrium roof glass (Figure 11.9). The roof structure is exposed 3 in. thick by 30 in. deep (76 by 762 mm) solid steel plate beams.

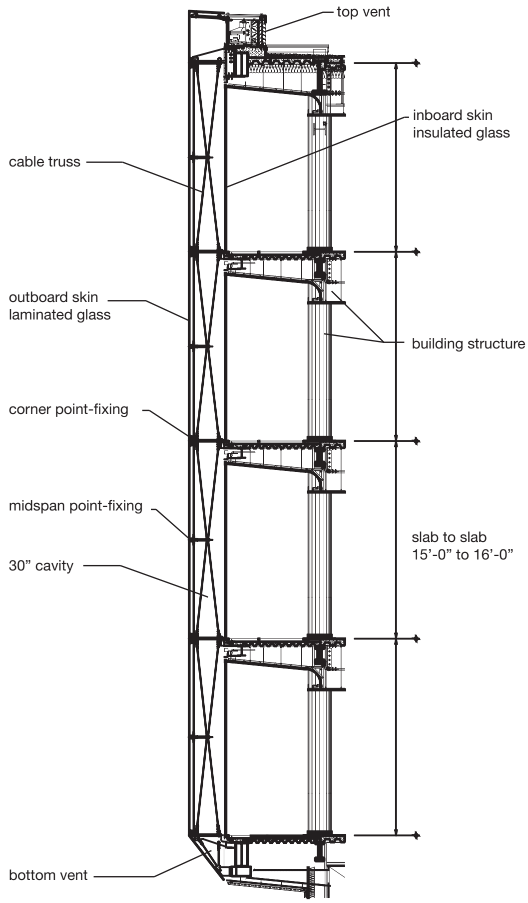


FIGURE 11.4 Section of the climate wall.

Glass Grid

The glass membrane of the climate wall is not actually curved but segmented; each glass panel is flat. The vertical glass grid module at the climate wall varies slightly from floor to floor but is approximately 16 ft (4.9 m). The horizontal module is uniform at 5 ft (2.5 m). The interior leaf of the climate wall is made up of full-height floor-to-ceiling glass panes, dead loaded to the floor slab. The exterior skin is suspended from above by a dead load cable and point-fixed to the cable truss system.

The atrium wall's 70 ft (21.3 m) vertical dimension is subdivided into nine horizontal modules of approximately 7 ft 7 in. (2.3 m). Eight horizontal trusses are located on the glass grid. The lowest glass tier is set into a reglet flush with the floor level. The vertical glass grid is defined by the eight $\frac{3}{4}$ in. (19 mm) vertical rods from which the horizontal trusses are suspended, which are spaced at 5 ft 8 in. (1.7 m).

Glass

The architects elected not to use any performance coatings on the high-transmittance, low-iron glass because of their desire for the purest natural light, yet they needed to mitigate the effects of poor thermal performance produced by the clear, uncoated material. The straightforward solution for the atrium wall glass was a 40% black dot frit pattern applied to the no. 2 surface of the $1\frac{7}{8}$ in. (47 mm) double-laminated IGU. The lowest tier of glass excluded the frit to provide unobstructed views at ground level.

A similar approach was adopted for the overhead glass, but with a denser frit pattern covering 60% of the glass surface. This relatively high-density frit is virtually imperceptible from the ground level, the skylight glass appearing transparent. The laminated panel of the IGU was inboard, as required by code for overhead glass.

A more complex double-skin strategy was developed as the thermal control strategy for the climate wall, easing the performance demands on the glass itself (Figure 11.10). The outer skin is $\frac{15}{16}$ in. (24.52 mm) laminated glass. The inner skin is the primary weather barrier, and uses $1\frac{3}{4}$ in. (44.52 mm) floor-to-ceiling laminated IGUs. All glass is low-iron Optiwhite by Pilkington.

Glass System

The spreader struts at the top and bottom of each cable-cross on the climate wall cable trusses support a four-pronged cast stainless steel spider fitting on their outboard end, providing a bolting point for four adjacent glass corners. The half strut located at the cable cross reaches out to the glass plane to fix a two-pronged cast stainless fitting that provides necessary midspan support to the approximately 16 ft (4.9 m) tall glass panels.

The glass on the atrium wall and roof is also point-fixed, with the spider fitting stepped off from the supporting structure, floating the glass membrane away from the structural system (Figures 11.11 and 11.12).

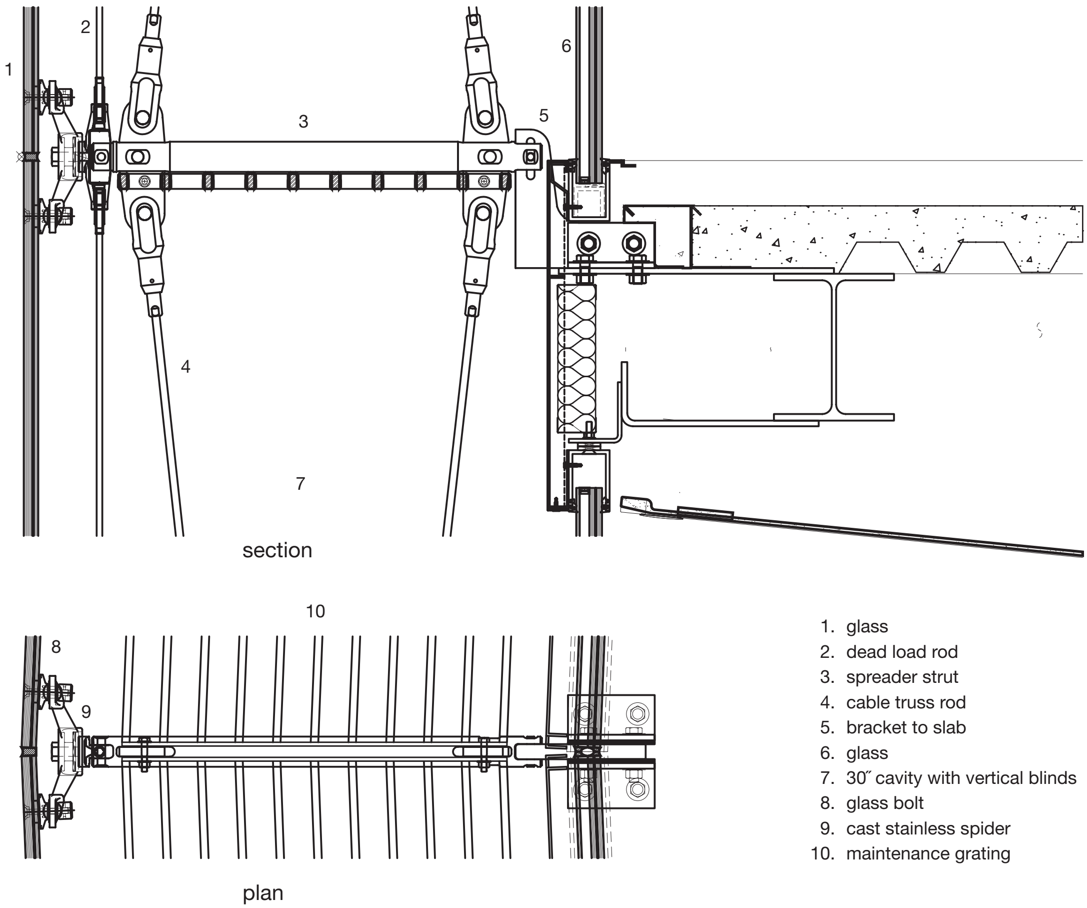


FIGURE 11.5 Strut detail of the climate wall.

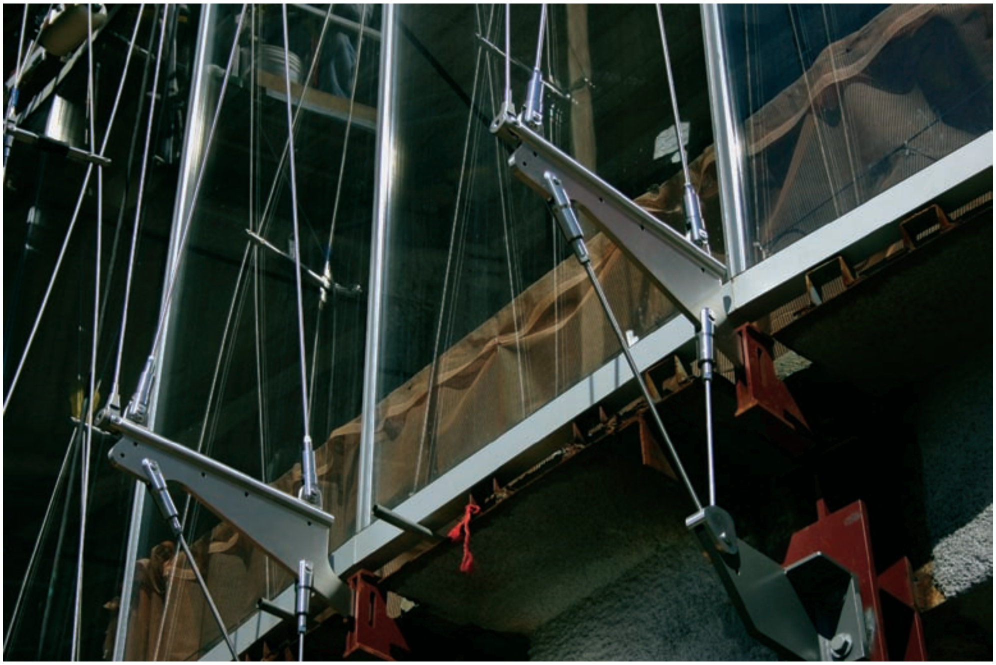


FIGURE 11.6 Kicker strut detail at the base of the climate wall.

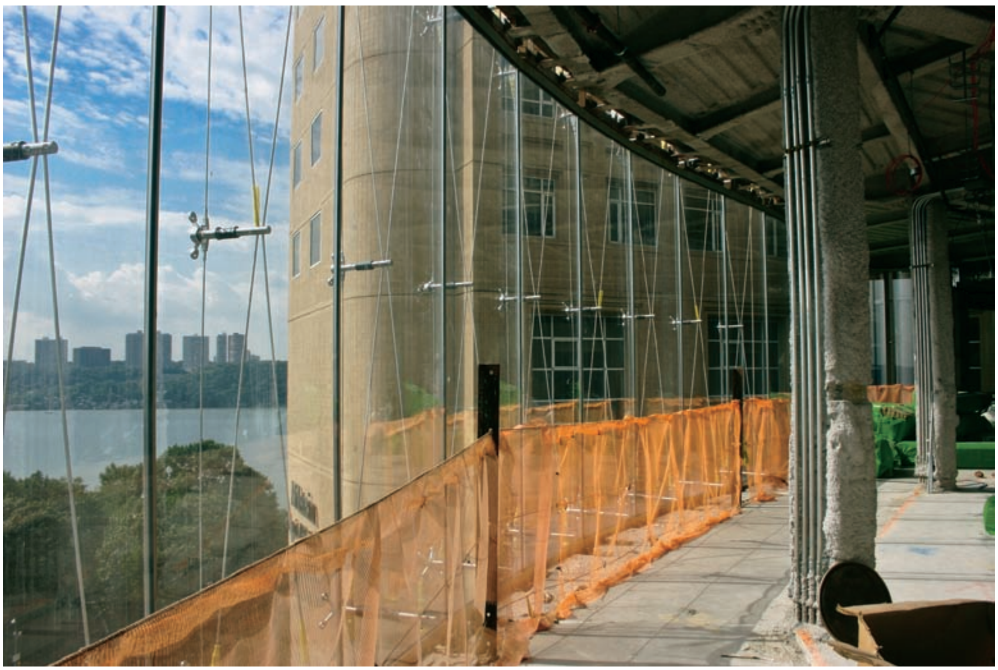


FIGURE 11.7 Climate wall under construction. The short strut provides midspan support for the floor-to-ceiling height glass panels.

FIGURE 11.8 The atrium wall is supported by horizontal cable trusses.

FIGURE 11.10 Inside the cavity of the climate wall during construction.

FIGURE 11.9 The atrium wall intersects with a glass skylight roof.

FIGURE 11.11 Detail of glass fixing on the atrium wall. Note the dead load rods.

Facade Concept Development

The initial facade concepts were developed by the architect and the facade consultant. The facade design-builder was also brought into the process early to work through the engineering and detailing of the systems, to address constructability issues, and to develop an installation plan. Arup provided climate design input during early concept development.

Testing

A mockup of the climate wall two bays high by two and a half modules wide was assembled to test the system, with an overall size of approximately 12 ft wide by 42 ft tall (3.7 by 12.8 m) (Figure 11.13). The mockup was subject to the following American Society for Testing Materials (ASTM) and American Architectural Manufacturers Association tests:

Air Infiltration: ASTM E 283-04 @ 6.24 psf (30.5 kgf/sq m)
Static Pressure Water Resistance: ASTM E 331-00 @ 10 psf (48.8 kgf/sq m)
Dynamic Pressure Water Resistance: AAMA 501.1-05 @ 10 psf (48.8 kgf/sq m)
Structural Performance: ASTM E 330-02 ± 45 psf (220 kgf/sq m)
Lateral Displacement/Interstory Drift Test (AAMA 501.4) 0.4 in. (10 mm) left/right and in/out

The mockup passed all of the required tests without issue.

FIGURE 11.12 Plate beams support the point-fixed roof glass.

FIGURE 11.13 Base detail from an exceptionally beautiful performance mockup.

Mockups Are Integral to Process of Innovation

It is not uncommon for a problem to surface during the implementation of a custom facade design despite the best efforts of all involved; in fact, it should be expected. The response to the problem and the way it is managed, however, are the keys to mitigating the risk to the project's success. It is far better to discover problems before they impact the building site. This is a function of the mockup. A problem emerged on the New York Presbyterian Hospital's climate wall structure during the mockup test. A glass fitting was rotating under load and deforming the glass bolt assembly. TriPyramid immediately investigated the problem and developed a solution, but the solution had to be proofed. A quick secondary mockup of the climate wall rod truss was assembled using a full-size strut and short rods (Figure 11.14). The truss rods were deliberately undertorqued to mimic a worst-case condition. A hydraulic cylinder was attached to the strut end so that system loading could be simulated (Figure 11.15).

FIGURE 11.14 Test setup to simulate the rotation problem identified during mockup testing.

The glass dead load was applied to this mockup, and the rotation was simulated as during the primary mockup. A shim strategy between the face of the strut and the spider fitting was developed and integrated into the system. The mockup was tested multiple times, simulating both dead and wind loads to verify the efficacy of the shim strategy. The test results were documented to illustrate that the proposed solution worked.[1]

FIGURE 11.15 A hydraulic cylinder at the strut end accommodates the simulation of dead and wind loads on the rod truss–glass system interface.

Project Delivery

The construction manager issued a design-build contract to the facade contractor. The design-build contractor provided comprehensive services, with installation services self-performed. The design and supply of the structural systems was subcontracted to TriPyramid Structures. The design detailing and craftsmanship evident in the structural components bring an extraordinary gem-like quality to the facades (Figure 11.16).

Installation Strategy

The immediately adjoining existing hospitals were required to remain open for the duration of construction activities, presenting the construction manager and site contractors with significant challenges in site logistics and sound control.

The inner skin floor-to-ceiling IGUs of the climate wall were installed first (Figure 11.17). Stainless steel cable truss components were made in Massachusetts and shipped to New York. The trusses were assembled in place at the building site, working from the top down (Figure 11.18). After all of the trusses were assembled and secured, they were pretensioned one at a time. Prestress loads were minimal at 5 kips (22 kN). The grating was installed at slab levels spanning from strut to strut, and all flashings and closures were installed. Spider fittings were installed to a tolerance of ±⅛ in. (3 mm) and surveyed for accuracy. Point fittings were preinstalled on the glass, and the lites were placed row by row, working from the bottom tier upward. A gasket was installed between panes on the inside of the outboard skin. The outer surface was taped in the vicinity of the gaps, and a wet silicone weather seal was applied from the outside.

FIGURE 11.16 The detailing and craftsmanship combine to provide a gem-like quality to the facade systems.

The horizontal trusses for the atrium wall were partially prefabricated and shipped to the site on flatbed trucks. The suspension rods were hung from the overhead truss support spanning across the top of the atrium wall. The trusses were then hung from the rods, working from the top truss down, with the attachment at either end of the truss chord and the cable brace to wall anchors. The truss cables were prestressed to 13 kips (58 kN) and verified with a tension meter. The cast spider fixings were bolted to the outer truss chord, and glass installation proceeded as with the climate wall.

Strategies for Sustainability

The Family Heart Center targeted and achieved a LEED Gold rating and is believed to be the first hospital to achieve this rating. The building program includes a number of green considerations, some of which involve the facade systems.

The climate wall is an integral part of the facility's energy system, with the 30 in. (762 mm) cavity acting as a thermal and acoustical buffer to the outdoor environment and, in combination with the glass, providing a 9.5 R-value (0.11 U-value), close to that of a simple 2x4 wall and well above that of even a triple-glazed IGU. In summer, a passive stack effect draws air from vents at the bottom of the wall and exhausts hot air at top vents. In winter the vents are closed, creating a warm air buffer to the interior.

FIGURE 11.17 Construction photo of the climate wall facade on the left (the rod truss system was not yet installed) and the atrium on right.

FIGURE 11.18 Glass installation in progress on the climate wall.

Automated motorized sunshades are an important part of the climate wall's performance, working to minimize direct solar penetration and glare. The broad vertical fabric louvers are programmed to track the movement of the sun, optimizing daylight to the interior, controlling direct solar penetration, and mitigating glare (Figure 11.19). The deep cavity presents an ideal location for the broad sunshade louvers, blocking solar penetration before it breaches the inner skin yet protected from the elements, thus minimizing maintenance requirements for the system. One hundred percent daylight has been provided to each of the climate wall stories, optimizing comfort and functionality in these largely public spaces and contributing LEED points. The system varies throughout the day, depending upon lighting conditions, from fully closed during certain midday periods of solar exposure to fully open in the evening and throughout the night.

Summary

The use of structural glass facade (SGF) technology in this project is extensive and masterful. The climate wall is indicative of the trend in applying the technology as a part of high-performance building skin solutions. View and the provision of abundant, unadulterated natural light were the primary design drivers here, rolled into a program including LEED certification and placing an emphasis on the energy performance of the building skin. The application of the cable truss on the climate wall is modest in span, but the configuration is well integrated into the climate wall design and is quite functional, defining the cavity and supporting the maintenance grating and outboard glass membrane. The detail design and craftsmanship embodied in the structural systems are exemplary (Figure 11.20).

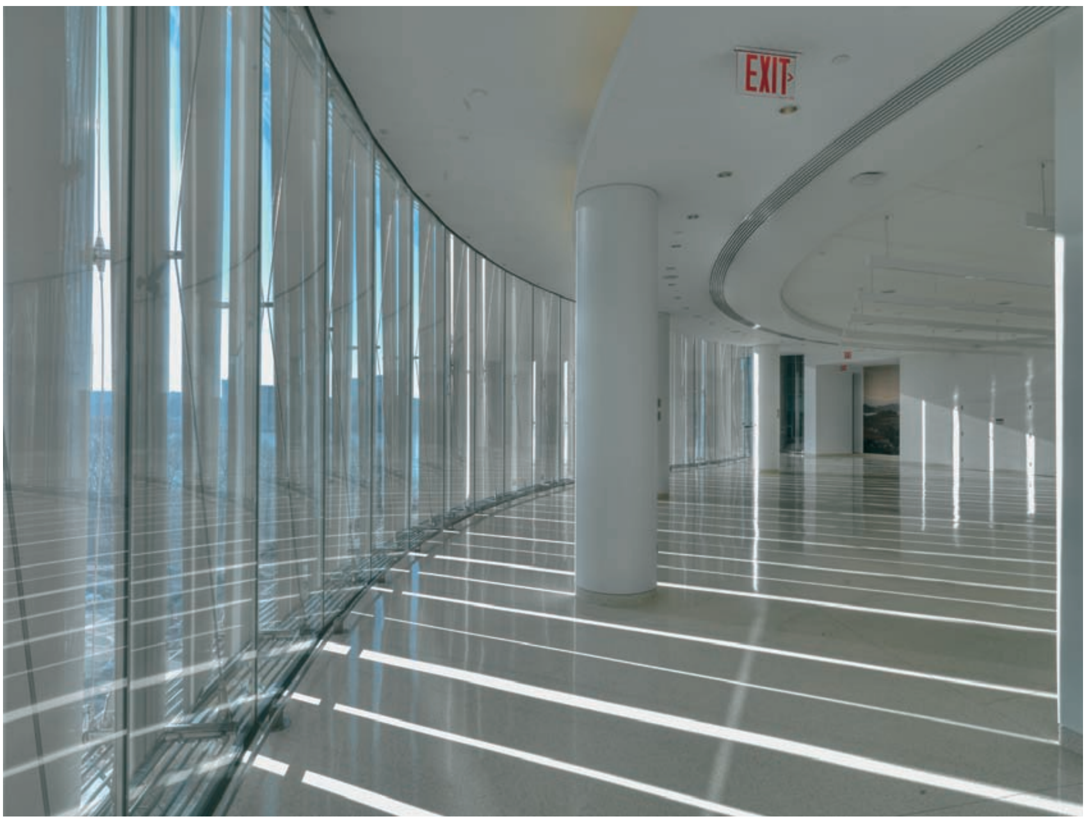


FIGURE 11.19 Automated fabric shades within the climate wall cavity close to prevent most direct solar penetration to the interior.

FIGURE 11.20 The entry vestibule combines glass, glass fins, and cable trusses.

Chapter 12

Strasbourg Railway Station Multimodal Hub

Strasbourg, France

FIGURE 12.1 The stone facade of the old station glows behind the transparent glass shell of the new entrance enclosure.

FIGURE 12.2 The new glass enclosure curves along the face of the old station, creating a climate-moderated public space that provides access to the various transport options.

General Information	
Year completed	2007
Building size, sq ft (sq m)	25,833 (2400)
Building type	Transportation hub, addition
Building cost, USD	Undisclosed
Project Credits	
Owner	Réseau Ferré de France Société Nationale des Chemins de Fer Français
Client	SNCF—Agence des Gares French National Railways
Architect	AREP (Amenagement Recherche Poles d`Echanges); Jean-Marie Duthilleul
Structure and facade engineer	RFR Ingénieurs
Climate consultant	Transsolar Energietechnik GmbH
Lighting and facade consultant	CSTB
General contractor	SNCF, AREP
Facade contractor	Seele GmbH & Co. KG
Glass fabricator	Seele GmbH & Co. KG
Facade System	
Structure type	Hierarchical system of cable-braced arches and cable trusses
Facade system cost, USD (installed)	Undisclosed
Total facade area, sq ft (sq m)	Approx. 64,583 (6000)
Glass grid module orientation Grid dimension height × width ft-in. (mm)	Vertical Approx. 16 × 5 (4877 × 1524)
Glass type Metric units specified, imperial units approximated.*	9⁄16 in. (13.52 mm) laminated cold-formed 1⁄4 in. (6 mm) fully tempered (FT) low-iron 0.03 (0.76 mm) solar control film (Southwall XIR 72/47) 0.03 (0.76 mm) 1⁄4 in. (6 mm) FT Ceramic frit no. 2 surface Low-e no. 4 surface
Glass system type	Vertical capture, horizontal butt-glazed
Maximum span, ft (m)	Undisclosed
Deflection criteria	Undisclosed
Project delivery	Specialty facade contractor Seele working with facade engineer RFR

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The new extension to the Strasbourg Station is a striking transparent glass enclosure, vaguely reminiscent of the Bicton Gardens glass house built in England in the early nineteenth century. This rail transportation hub is located in the urban center of Strasbourg, France, and acts as a gateway between northern France and Europe, serving 60,000 passengers a day. The old station dates back to 1878. The facility underwent a recent expansion to both modernize the station and increase the passenger capacity. The designers were faced with the formidable challenge of honoring the historical context of the site and protecting the aging stone facades of the existing architecture while accommodating the ambitious modernization program established by the governing authority. The solution was found in the construction of a large, clear bubble along the front of the existing station. This highly transparent glass enclosure has been constructed along the southern exposure of the old building, which permits a view of the original architecture from the forecourt and public garden (Figures 12.1 and 12.2). The new enclosure now covers and protects the fragile stone facade of the old station building. The 82 ft (25 m) wide entrance space running the length of the building accommodates passenger access to rail lines, buses, and trams in the old station and the descent to the underground S-Bahn lines.

Building Structural System

The new glass enclosure abuts the fragile stone facade of the old station architecture. It was necessary, then, and an important part of the design program, that the new structure apply no significant loads to the old building (Figure 12.3).

FIGURE 12.3 Steel arches frame the first two bays of the addition. Note that the new structure cantilevers out over the old building but does not touch it.

Facade Program

In the new station extension, the facade is the enclosure: a freestanding lightweight structure with an integrated, highly transparent, fully glazed skin. The enclosure is 492 ft (150 m) long and ranges from 23 to 82 ft (7 to 25 m) in width, and 56 to 72 ft (17 to 22 m) in height, and incorporates 64,583 sq ft (6000 sq m) of glazed surface area. The facade program included the complete structure and cladding system that comprises the enclosure.

Facade Structure

The geometry of the glass shell developed by RFR is derived from a toroidal form generated by the revolution of a curve about an axis inclined at 17 degrees from the vertical.[1] The structure for the new enclosure is a hierarchical organization of load-bearing components (see Figure 12.6).[2] As no significant loading could be applied to the old station structure, a series of slender tubular steel columns were constructed outboard of the existing facade to support the long edge of the glass enclosure at the interface with the existing building. These columns are spaced at 30 ft (9 m) and extend the full height of the old building facade. From them spring transverse arches, cable-braced and prestressed, that curve out and down to ground-level anchors, providing the enclosure its basic form (Figure 12.4). Rather than being uniformly circular, the unique arch forms consist of five tangent circle arcs of varying radii, ranging from roughly 36 ft (11 m) to 100 ft (30 m). The cable bracing radiates from the inside face of the arch and ties back to the base of the columns, providing transverse stability while minimizing the arch member profile (Figure 12.5).

FIGURE 12.4 Horizontal cable trusses space the 30 ft (9 m) bays, and cables brace the arches.

FIGURE 12.5 All elements of the structure can be seen in this view except the columns just outside the old facade.

The steel arches are fabricated to the equivalent of Architecturally Exposed Structural Steel (AESS) standards, and are built up from two curved tubes separated by a continuous steel plate web welded along the entire length of the tubes. The arch members taper at the head and foot, with the bottom flange of the arch tapering down to meet the column capital, then back up again to narrow as the arch tapers back to cantilever over the roof edge of the old station building.

The entire 460 ft (140 m) long enclosure is built of a continuous structure without expansion joints. Longitudinal cable trusses provide the secondary structure—what RFR refers to as “fink trusses”—spanning horizontally between the arches and tying them together along the entire length of the enclosure. There are eight of these trusses per bay, with approximately 14 ft (4.5 m) radial intervals between them. Finally, five transverse ribs that parallel the path of the arches and define the vertical component of the glazing grid provide the tertiary structure. The tertiary components are comprised of T-sections spaced at approximately 5 ft (1.5 m) intervals (varying transversely over the toroidal surface) and begin to define the enclosure envelope in anticipation of the glass cladding. A network of continuous cable bracing between the arches ensures full lateral load transfer through the structural system (Figure 12.8).

Glass System

Cold forming of glass is a relatively recent technique for bending glass whereby curvature is provided without the heating process associated with conventional glass-bending processes. Cold-formed glass benefits from the absence of optical distortion typical of heat-treated glass (Figure 12.7). Curved glass was preferred over segmented flat panels by the design team as a means of emphasizing the toroidal geometry of the envelope. The glass grid is comprised of tall, narrow quadrilaterals, approximately 16 by 5 ft (5 by 1.5 m), running up and over the enclosure, the extreme aspect ratio maximizing flexibility across the shorter bending axis (Figure 12.8).

The panels are a two-ply laminate of ¼ in. (6 mm) tempered glass, with a solar film sandwiched between two layers of 0.03 in. (0.76 mm) PVB interlayer. There are two general approaches to accomplishing the cold bending of the glass. If the bends are moderate, it is possible to laminate the glass as flat panels and apply the bending force in the field during installation, securing the panels in the bent form. Alternatively, the glass lites can be prebent and laminated while in the bent form. The latter technique has two advantages: it results in lower built-in stresses, and consequently can accommodate tighter bending radii, and the prebent panels are easier to install. Handling, shipping,

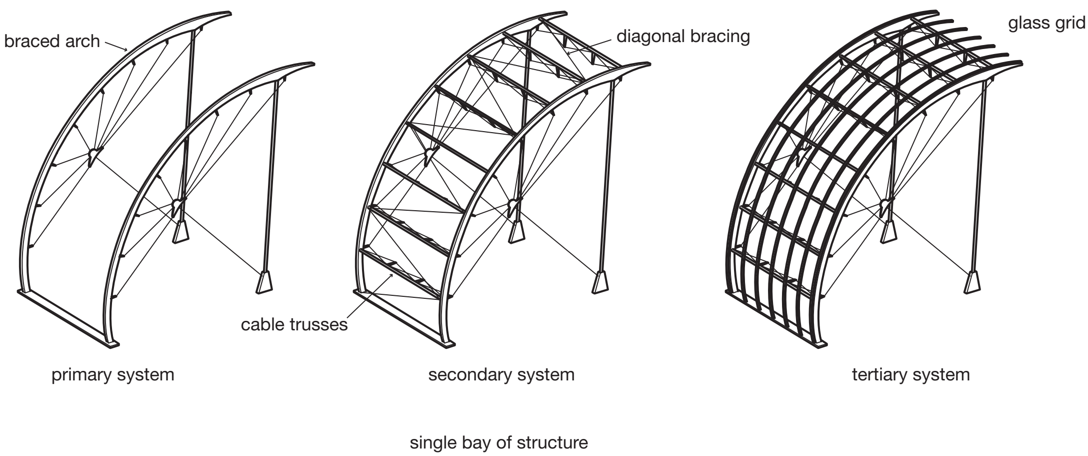


FIGURE 12.6 Simple diagram of the hierarchical structural system.

and certainly fabrication are more challenging, but these challenges have been confronted and mastered by Seele. Sedak, part of the Seele Group, is at the forefront of laminated glass technology, producing a remarkable range of products including partial-surface laminated structural panels, composite material laminates, and the largest laminated glass panel manufactured to date at nearly 44 ft (13.3 m) by just over 10 ft (3.1 m). The decision was made to prebend the glass.

The use of an appropriate interlayer is important to the cold-forming process. While adequate for this application, conventional polyvinyl butyrate (PVB) interlayers can be too ductile to fully restrain the built-in stresses that result from the process and have a tendency to creep over time. Adequate adhesion and stiffness properties of the interlayer are important to ensure the long-term performance of cold-formed laminates.

The glass panels are mechanically fixed with an extruded aluminum pressure gasket system to the transverse structural ribs, being continuously supported along all four edges.

Facade Concept Development

AREP designers originally conceived of a large, transparent glass enclosure to protect the fragile stone facade of the old station. RFR was brought into the project because of their extensive experience with glass facade technology, including the cold forming of glass, and their facility in developing complex geometrical form. They developed a novel,

FIGURE 12.7 The glass is cold-formed in the absence of the heat characteristic of the conventional glass-bending process. The glass module has a slender aspect ratio with the short axis perpendicular to the curvature of the glass, facilitating the cold-bending process. The optical quality of the glass resulting from the cold forming is apparent from the reflections.

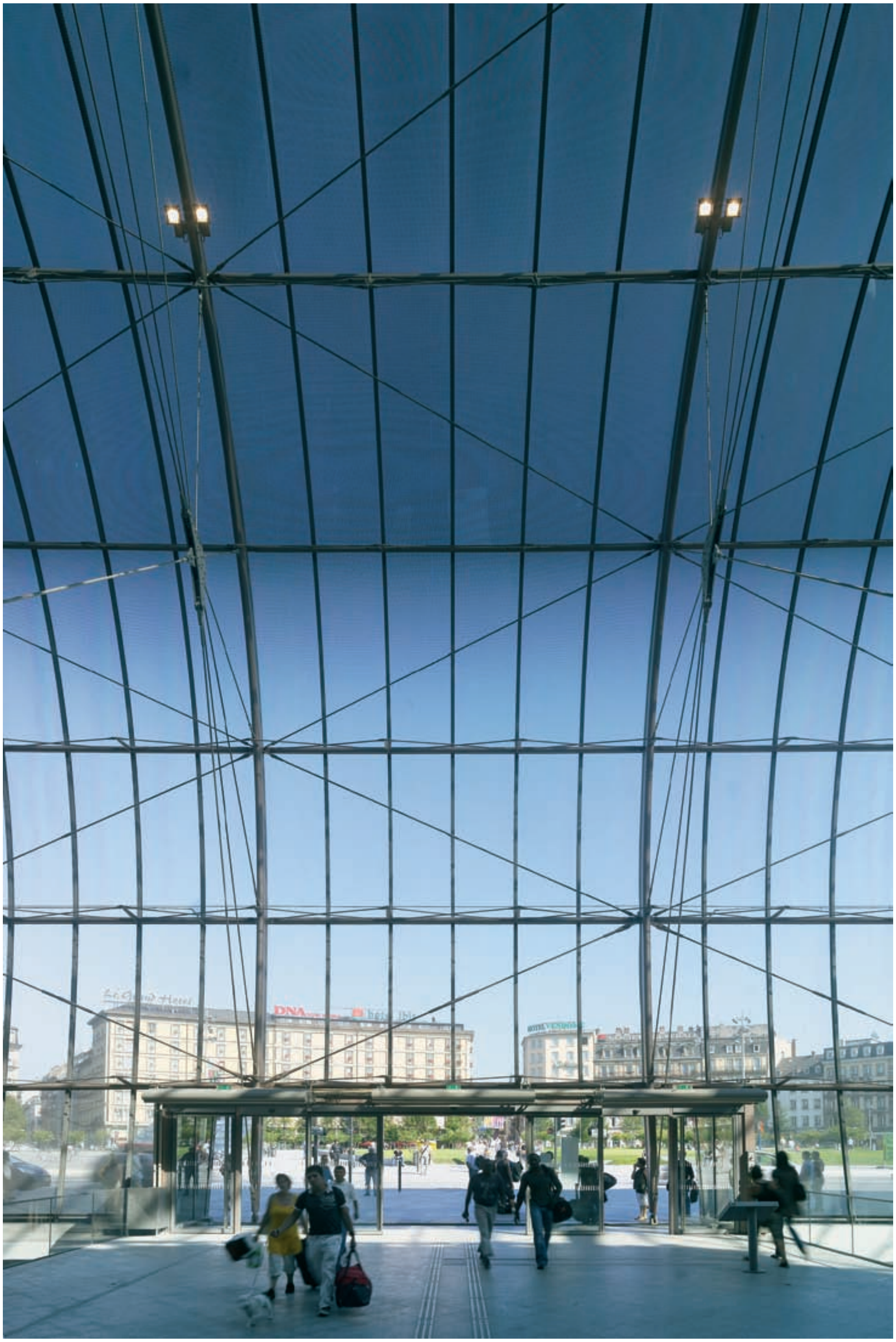


FIGURE 12.8 The structural system produces remarkable transparency.

optimized geometry for the glass enclosure and an innovative structural system to realize the form. The participation of Seele was solicited to benefit from their equally extensive glass and structure fabrication expertise. Transsolar contributed their cutting-edge climate design expertise. Working together in an intensely collaborative effort, they developed the initial concept into a functional, efficient, and constructible enclosure.

Testing

Seele, working with consultant CSTB, performed a number of tests in an effort to proof the performance of the cold-formed material. The material was subjected to air, water, and impact testing and a simulation of the laminate performance over a 10-year period.[3]

Installation Strategy[4]

Two tower cranes were located just outside the enclosure perimeter and were used to set the structural elements. The columns and arches were set simultaneously, starting near the middle of the enclosure. The cable bracing for each arch was assembled and attached to the arch prior to setting, and was secured along with temporary guys as required to support the arch. This was followed by the installation of the horizontal cable trusses and cable bracing between the arches. Once several bays were assembled, the structure was stable enough to support the installation of additional arches with only minimal temporary bracing. The installation of the tertiary transverse ribs that subdivide the bays and define the glazing grid finished the bay structure (Figure 12.9). Glass installation could proceed once several bays had been completely installed and accurately positioned.

The glass panels were fixed in place by an extruded aluminum pressure gasket glazing system that provides four-sided support. Silicone and EPDM [ethylene propylene diene Monomer (M-class) rubber] gaskets provide a double weather barrier.

Strategies for Sustainability

The Strasbourg glass enclosure benefits from another application of the novel approach to thermal control developed by Transsolar. The elements here include in-floor radiant cooling and heating, low-volume conditioned air distribution, natural ventilation, summertime evaporative cooling, and thermal stratification of the interior volume of air to focus comfort on habitable areas close to the ground. The glass panels incorporate a ceramic frit, a solar film, and a low-e coating as part of a solar control strategy. The frit is of varying density, depending on the location of the glass in the structure; the glass higher in the curvature has a dense frit that limits solar transmission, where it is most needed, while the frit has been excluded at the lower levels to provide unrestricted view. An XIR film by Southwall Technologies is laminated between two layers of PVB interlayer material as a means to reflect solar heat while remaining transparent to the visible light spectrum. Finally, a low-e coating on the no. 4 surface keeps radiant heat within the space to minimize heat loss during cold weather. The thermal operation of the enclosure has two distinct modes, corresponding to the temperature extremes of summer and winter. In winter the natural ventilation path is closed, and the low-angle winter sun is allowed to warm the interior air. Supplemental heat is provided through the in-floor radiant system and through low-volume pylons. In the heat of summer, the natural ventilation pathways are opened to exhaust heated air at the top of the structure, with the radiant and low-volume systems supplying supplemental cool air as required.

Summary

The design for the new extension of the Strasbourg Rail Station is a fascinating and successful marriage of cutting-edge high technology and nineteenth-century European architecture. The minimalist glass shell provides a highly functional solution to a complex architectural program that includes the development of a transition space between the outside and the access of an array of public transportation options, as well as the protection of a fragile nineteenth-century stone facade. The elegance of the lightweight structural system and the distortion-free optics of the cold-formed glass combine to produce a stunning effect (Figure 12.10).

The project has spawned a burst of interest in cold-formed glass, and the material is finding increasing application on innovative building projects worldwide.

FIGURE 12.9 The steel arch and horizontal cable truss detailing is visible in this image during construction.

FIGURE 12.10 The shell's transparency is also effective at night, clearly revealing the old station within.

Chapter 13

Eli and Edythe Broad CIRM Center for Regenerative Medicine and Stem Cell Research

Los Angeles, California

FIGURE 13.1 The east elevation, here under construction, is dominated by a full- building-height double-skin facade. Note mast-climber rig used to set glass.

General Information	
Year completed	2010
Building size, sq ft (sq m)	87,537 (8132)
Building type	Research facility and laboratory
Building cost, USD	Approx. 87 million
Project Credits	
Owner	University of Southern California
Architect	ZGF Architects LLP
	Doss Mabe, FAIA, Design Partner; Ted Hyman, FAIA, LEED AP, Partner in Charge; Stacey Hooper, AIA, LEED AP, Senior Project Designer; Clause Best, AIA, LEED AP; Mitra Memari, AIA, LEED AP; Natalie Thurman
Facade consultant	CDC
Civil and structural engineer	KPFF Consulting Engineers Inc.
Mechanical, electrical, plumbing (M/E/P) engineer	Affiliated Engineers Inc.
Facade modeling consultant	Affiliated Engineers; TESS
Cost estimator	Davis Langdon
General contractor	Morley Builders
Facade contractor/installer	Walters & Wolf
Facade design, engineering, and supply	W&W Glass, LLC
Cable system supplier	TriPyramid Structures
Glass supplier	Pilkington, Viracon
Facade System: Cable Wall	
Structure type	Cable mullion system; glass shade fins
Facade system cost, sq ft (sq m)	295 (3175)
Total facade area, sq ft (sq m)	10,500 (975)
Glass grid module orientation	Vertical
Grid dimension height × width ft-in. (mm)	8 × 5-3 (2438 × 1600)
Glass type	Cable wall glazing
	¾ in. (19.52 mm) laminated
Cable wall glazing: metric units specified, imperial units approximated.*	starting outboard:
	¼ in. (6 mm) fully tempered (FT)
	0.06 in. (1.52 mm) SentryGlas (SG)
	½ in. (12 mm) FT
	Optiwhite low-iron, heat-soaked, custom frit no. 2 surface
Glass fins: imperial units specified, metric units approximated.*	Glass fins
	9/16 in. (13.52 mm) laminated
	½ in. (12 mm) FT
	0.06 (1.52 mm) PVB
	½ in. (12 mm) FT
	Guardian UltraWhite w/beveled polished top edge, three sides polished arris, custom frit no. 2 surface
Glass system type	Point-fixed bolted
Maximum span, ft (m)	64 (19.5)
Project delivery	Design-build to facade contractor with specialty subcontractor providing design, engineering, and material supply

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The Eli and Edythe Broad CIRM Center for Regenerative Medicine and Stem Cell Research at the University of Southern California (USC) is located within the USC Health Sciences Campus, just northeast of downtown Los Angeles. The Center, devoted to stem cell science, is housed in a new research and laboratory facility designed by ZGF Architects LLP (ZGF). The building is designed around a 10 ft 6 in. (3.2 m) standard laboratory module defined by the width and clearance of research tables and support equipment. The building program includes two floors of laboratory and meeting spaces and four floors of support space, including extensive mechanical and air-filtering systems for the laboratories.

The predominant features of the building are the glass facades, which take a distinctly different form on the two lengths of the rectangular building. One face is a double-skin cavity wall incorporating a vertical cable system (Figure 13.1); the other face is a unitized system with unusual exterior glass shading fins. The facades complement the passive design strategies intended to optimize building energy use. The Broad Center is currently on target for a LEED Gold rating. The building opened in October 2010.

Building Structural System

The building structural system is a reinforced concrete frame. The ground floor to ceiling height is 22 ft (6.7 m), with all other floor-to-floor spans at 16 ft (4.9 m). The floor slabs cantilever out 5 ft (1.5 m) from the frame and support the facades. The entire building is laid out on a 10 ft 6 in. (3.2 m) grid, based on a multiple of the standard laboratory module of 5 ft 3 in. (1.6 m). Most of the plan alternates bays of 33 ft (10 m) (three laboratory modules including structure, a long span for concrete) and 19 ft (5.8 m) at the office/laboratory support.

Facade Program

The two main facades reflect important differences in design intent and performance. The west facade is a conventional unitized curtain wall system, augmented with vertical frosted glass shading fins to protect the interior from late afternoon solar exposure. The east facade is a double-skin design with a cavity spanning the full height of the facade. Both facades run nearly the entire length of the building.

Facade Structure

West Facade

The west facade is a simple unitized system, with the glass structurally glazed to an aluminum frame that spans between the top and bottom of the floor slabs. The interesting element of this facade is the vertical glass shading fin described below (Figure 13.2).

East Facade

The same curtain wall–type system used on the west facade is used as the inner leaf of the east wall's double-skin system. The units sit on the top edge of the floor slab, spanning to the bottom of the floor slab above, providing the weather seal for the interior.

A vertical cable mullion system defines the exterior leaf of the double-skin facade (Figure 13.3). The glass is supported from vertical cables aligned with the glass grid. Painted steel outriggers anchored to an upturned beam at the roof cantilever the cables about 3 ft (914 mm) out from the face of the floor slabs below (Figure 13.4). Kickers anchored to embeds at each floor slab also extend out to attach to the cables, providing lateral support to the facade. Thus, while the cable prestress of 15 kips (67 kN) runs from the top of the facade to an anchoring beam at the base, the actual cable wall span is quite benign, limited to the dimension between floors, significantly limiting system deflections. The kickers at each floor level support aluminum grating between the facade and the slab face, providing easy maintenance access to the cavity without restricting airflow. The wire rope cables are ¾ in. (19 mm) 1 × 19 stainless steel, anchored at the base to a painted steel beam.

A glass parapet is created as the glass facade extends beyond the top cable termination, and an overhead glass lite slopes slightly back to sit atop an operable louver system extending up from the roof curb. The vertical cable run is just over 64 ft (19.5 m), while the total facade height is just over 68 ft (20.7 m).

Glass System

Following the laboratory grid module, the glass panels for the system are 5 ft 3 in. (1.6 m) in width and 8 ft (2.4 m) tall, subdividing the 16 ft (4.8 m) slab-to-slab span with two glass lites. One-inch (25 mm) insulating glass units (IGUs) are used on the interior weather-seal leaf of the double-skin wall. The outer cable-supported leaf is a ¾ in. (19.5 mm) laminate (see the glass makeup in the table above). The glass plies of the laminate are both low-iron Optiwhite by Pilkington. Both plies are tempered and heat-soaked. A silk-screened ceramic frit and acid etch are applied vertically to half of the no. 2 surface, providing alternating bands of opacity along the facade.

Visual mockups were assembled to aid in glass selection for the facades. Pilkington was selected for the exterior cable wall glass, while Viracon provided the interior skin. The reason for splitting the source of supply was cost. The Viracon glass was less expensive, but the Pilkington glass was required to accompany the point-fixed application on the cable wall. There were problems in trying to match the frits between the two suppliers, as the companies utilize different frit materials and processes. European standards required that Pilkington use a more environmentally friendly water-based frit material instead of the oil- and metal-based material used by Viracon, which produced a fritted glass that was visually flat in comparison. The Viracon glass included a low-e coating, which also affected the appearance of the frit. The result was noticeable to the design team, but after evaluating several full-size visual mockups of the Pilkington glass compared to the Viracon glass, they elected to proceed with the two sources of supply.

FIGURE 13.2 The west facade is glazed with a simple curtain wall system but incorporates a novel glass fin shading element.

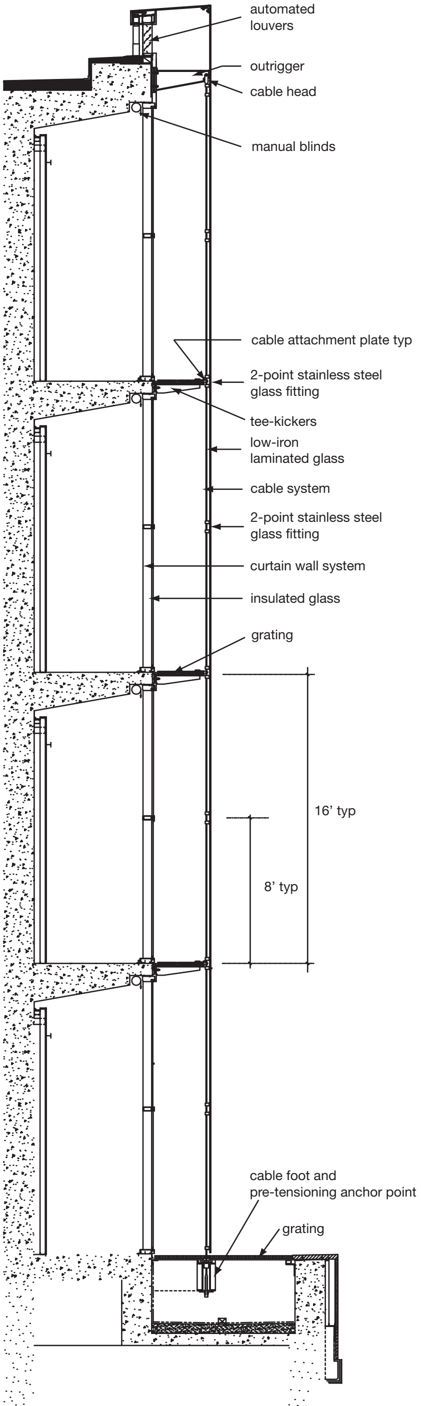


FIGURE 13.3 Typical section of the double-skin wall.

The same vertical frit banding on the interior skin is applied to the opposite half of the glass, such that in normal elevation it appears that the entire facade is fritted. When the double-skin facade is viewed at an angle, however, vertical bands of transparency are revealed (Figure 13.5). The Pilkington glass has an arris edge ground flat.

The laminated panels are point-fixed with a bolted connection. Both plies are perforated at the corners, with the outer ply countersunk so that the bolt sits flush with the outer glass surface. Spider castings were considered during the visual mockup phase for the glass-fixing component but were ultimately rejected as too visually heavy and obtrusive. Instead, simple machined cable clamps were designed that provide attachment for a standard Pilkington 905 fitting that ties the glass to the cable. The fittings are designed to provide lateral stability in the glass joint, as well as to easily accommodate in-out, up-down, and side-to-side field tolerances (Figure 13.6). The joints between glass lites are butt-glazed with field-applied silicone to partially seal the cavity of the double-skin wall. The mechanical connection between the top row of vertical glass and the skylight glass at the top of the wall is made with a stainless steel point-fixing component derived from the same vocabulary as the glass-to-cable connection.

Glass Fins

The glass fins on the west side are an interesting facade element. They are a 9⁄16 in. (14 mm) laminate with the same makeup used for the outboard leaf of the double-skin wall. The glass plies of the laminate are both low-iron UltraWhite by Guardian. A full-coverage acid etch and silk-screened ceramic frit are applied over the entire no. 2 surface.

The fins are 8 ft (2.4 m) long and 18 in. (457 mm) wide. The fins are perforated to receive through-bolts that tie to three-pronged spider fittings, which in turn connect to 6 in. (152 mm) long × 2 in. (51 mm) deep brackets that penetrate through the weather seal and fix to a reinforced wall of the vertical aluminum mullion.

FIGURE 13.4 East facade under construction before the setting of the outboard skin. The cables are hung from the outriggers, and the grating is in place.

FIGURE 13.5 Exterior of the double-skin facade showing the visual effect of the offset vertical banding in the interior and exterior skins.

FIGURE 13.6 Outboard glass connection detail. The cable is attached to the end of a kicker extending from the floor slab that also supports the grating at each floor level. Note the up-down, in-out, and side-to-side adjustment mechanisms to accommodate installation tolerances.

The fins are bolted to the brackets after the curtain wall unit installation (Figure 13.7). Six spider fittings (18 connection points) are required per fin to accommodate the stresses occurring under wind load conditions. There was much concern about the performance of the fins in high winds, so mockup tests were conducted to verify adequacy. The tests were video recorded and demonstrated significant buffeting of the fins under test conditions, but they nonetheless passed the test without a problem.

The glass fins have a polished bevel on the top edge, required by Viracon as a condition of warranty.

Facade Concept Development

The original design conceived by ZGF architect Stacey Hooper for the double-skin facade incorporated a cable truss system occupying the cavity, with the spreader struts extending outward in both directions to support a glass skin on either side of the trusses. Rather than having a separate structure to support each skin, this strategy would seem to benefit from the integration of a single structure supporting both skins. The design team reached out to the industry for estimating support with this concept, and was soon provided with feedback indicating that the concept was well beyond the allocated budget, at a cost of approximately 575 USD per square foot. The reasons cited for the high cost were the complex movements and deflections resulting from the two glass skins being tied to the same structural system. Had the architect continued to implement this concept without consulting industry experts early in the schematic phase, budget problems may have surfaced later in the process, when they could have been much more challenging to manage. Hooper then worked closely with this same specialty facade contractor, W&W Glass of Nanuet, New York, to develop an alternative concept, which ultimately led to the cable wall design. The strategy of using a conventional system for the inner wall combined with an outer cable wall simplified the design, engineering, fabrication, and installation of the east facade, resulting in significantly reduced cost compared to the original concept while providing an aesthetic solution satisfying to the architect.

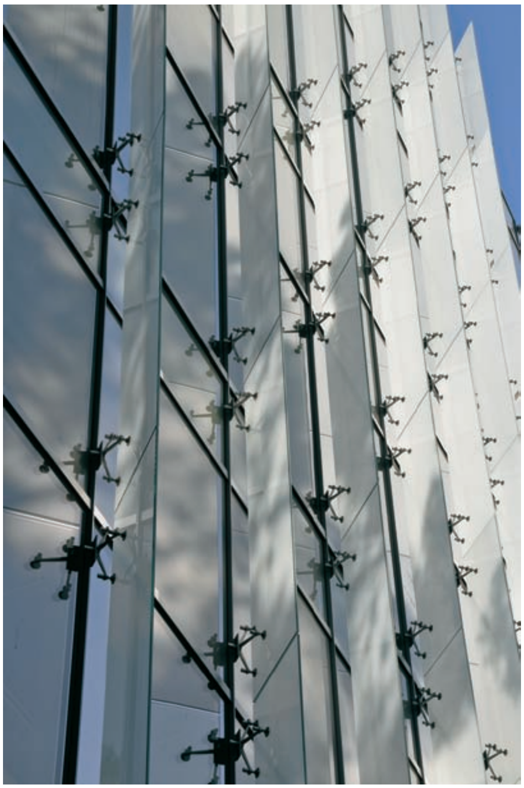


FIGURE 13.7 The laminated fins are point-fixed from cast spiders supported from the curtain wall framing.

Testing

Performance testing was conducted on full-scale mockups at Construction Consulting Laboratory West. The mockup was tested for air infiltration and water penetration. One area of water infiltration was identified and modified at the test site, which later passed testing.

It had been assumed that the project fell within a wind corridor for the region's prevailing high Santa Ana winds, requiring higher design wind speeds. A careful review of the wind maps for the region revealed that this was not the case. The tests were conducted with the corrected design pressures, and the mockup passed without issue. The fins were also tested, as discussed previously.

Project Delivery

The facades for the Broad Center were delivered under a characteristic design-build strategy. The facade program was defined in project plans and performance specifications, indicating a scope of work that included such facade interface elements as the cable wall outriggers and base girder. W&W Glass, a specialty facade company out of New York, worked closely with the architect and contractor during the schematic design phase, developing the initial concept and budget. CDC provided design assistance during design development until the Walters and Wolf/W&W Glass team was finally brought on board, based on an agreement with the general contractor that they would be awarded the job if their final numbers fell within the established budget parameters. This strategy allows much of the more complex detailing at the system perimeter and interfaces to be deferred until the facade contractor is finally selected and able to bill for the time spent in final detailing. ZGF would have preferred that the design-build team be brought in earlier.

This project was competitively bid. W&W Glass teamed up with Walters and Wolf, a regional facade contractor, in pursuing the bid, and the team was ultimately successful in securing the project. Most of the specialty contractors do not retain their own construction crews, and often employ a strategy of partnering with local or regional curtain wall firms in pursuing national work. The specialty contractor provided design, engineering, material supply, and technical supervision (during installation) for the cable facade.

Installation Strategy

The unitized panels of the conventional facades were installed with a crane, a glass suction lifting rig, and a mast-climber scaffolding. The unitized panels weigh approximately 1200 lb (544 kg) and the setting rate on this job was quite fast, at about one unit every 10 minutes. A unit was set by tying into preset anchor embeds in the floor slab. As workers secured the units, the lifting rig was released to begin the next lift cycle.

Installation of the cable wall proceeded after the interior leaf of the double-skin was in place. Once the position of all embeds was confirmed to be within tolerance, the outriggers, base girder, and other boundary anchor steel components were installed. The prestretched cables were then hung from the top outriggers, secured to the base girder, and their positions checked. The base cable connection detail was designed to accommodate the hydraulic gear used to pretension the cables (Figure 13.8).

The cables were tensioned one at a time, typically overtensioned by approximately 5% to compensate for the cable relaxation that occurs shortly after tensioning. A tension meter was used to verify the correct prestress forces. The system was allowed to stretch for a period of time, then rechecked and adjusted as required. The kickers were then installed at each floor level, followed by the gratings spanning between the kickers along the floor slabs. A final check revealed no significant change in cable prestress.

The cable clamps were next fixed to the cables and surveyed for accuracy. The bolted fittings were secured to the glass panes and lifted in the same manner as the curtain wall units, starting from the

FIGURE 13.8 The cable base connection detail. The cable passes through a protective bushing to the bottom of a supporting girder that runs the length of the cable wall.

bottom tier and working up with successive tiers (Figure 13.9). The overhead glass was installed last. Finally, the joints of the entire facade were sealed with structural silicone caulking.

Strategies for Sustainability

The Broad Center design team has attempted to use a number of green strategies in its pursuit of a LEED Gold rating. Passive strategies include the shape and orientation of the plan, with the intent of mitigating harsh solar exposure, and the use of concrete walls and stone cladding to provide thermal mass to help moderate temperature fluctuations.

The facades are an important part of the green strategies. The west facade incorporates fins to limit solar exposure and the penetration of direct sunlight. Double-skin facades in warm climates provide arguable benefit, and the Broad Center is no exception. However, careful attention to horizontal and vertical shading within the cavity and high-performance glass selection do provide sustainable benefit to the interior environment. The wall functions as a passive system, using the double skin to provide a thermal buffer against the outside temperatures. The cavity is open at the bottom, with automated louvered vents at the top. When heated cavity air is unwanted, the louvers are opened and the stack effect ventilates the cavity through the top (Figure 13.10). Otherwise, the louvers remain closed and the cavity acts as a large airspace to mitigate the effects of thermal transfer through the inner skin. Both unitized curtain walls have a U-value of 0.40. No U-value was established for the double wall as an assembly.

FIGURE 13.9 Construction workers install the outboard glass of the double-skin wall. Note the mast climber supporting the workers outside the wall, which provides access along the entire length of the facade.

The glass facades combined with a narrow floor plate are intended to significantly reduce electricity consumption for artificial lighting by maximizing daylight throughout the interior. Analysis of the lighting was done in-house by ZGF using the green building software tool Ecotect. The performance of the glass fins on the west facade was a particular concern, however. The simulation and analysis requirements were especially complex in determining the influence of the fins, and the project's M/E/P engineering consultant (Affiliated Engineers Inc.) was called upon to assist in determining fin configurations, optimum angles, and glass type. Because the fins are fixed and do not track with the sun, their angle was determined to provide the best year-round shading performance for peak loads, and any remaining late afternoon glare will be accommodated by manually operated shades located inside the facades. Motorized shades were designed for both facades, tied into the building's management system, and highly recommended within the cavity of the double wall to increase performance, but were later value engineered to interior manual shades.

The facades contributed to EQc8.1 and EQc8.2, Daylighting and Views, LEED points, with daylighting providing 92% of the interior lighting needs per LEED requirements.

Summary

Structural glass facade (SGF) technology is famous for applications of dazzling complexity: cable nets spanning hundreds of feet, gridshells of intricate surface geometry, highly crafted minimalist fabricated steel systems. The Broad Center facades are an excellent example of the opportunity to be found in applying the technology of SGFs to a more modest building program in combination with conventional facade systems. The spans are larger than typical floor-to-floor spans but small for the usual SGF application. There is little elaborate geometric complexity in the facades. Even the double-skin system is accomplished efficiently and with little fanfare. Yet, the results are elevated well beyond the aesthetics, and performance, of conventional facade technology.

FIGURE 13.10 Diagram of airflow through cavity wall.

What easily could have been a nondescript building in less skilled hands has been rendered distinctive and sophisticated, largely through a sensitive and skilled treatment of the building's facades. The simplistic economics of a homogeneous building skin were eschewed in favor of facade elements differentiated in their functional and visual response to contextual considerations, including site, surroundings, climate, occupant needs, and sustainability issues. The facade designs are not in the least extravagant or ostentatious, but reflect a considered response to pragmatic issues and an appropriate integration of advanced with conventional facade technology.

Compromises, while frustrating to the design team, are a part of most building projects, and the Broad Center was no exception. The double-skin wall in combination with the narrow floor plate presented an excellent opportunity for natural ventilation of the building, but the ventilation requirements for a laboratory building exceeded what a natural strategy could ensure. The double skin would have been more effective as a west-facing facade, but site and other contextual considerations ultimately precluded this. Maintenance concerns are blamed for an unfortunate decision to replace an automated blind system located within the cavity of the double-skin wall, where it would have been optimally effective in preventing heat gain to the building interior, with a manually operated roller-blind system inside the building envelope. AEI is establishing as-built performance data in an effort to provide ZGF a baseline design model against which to compare actual building performance through postoccupancy monitoring.

While the architect expressed some frustration at the lack of timely detailed design development support from the selected design-build team (due solely to a delayed selection process), the project did benefit from an intensive collaboration in the schematic design phase between an industry specialist (W&W Glass), the design team and general contractor, providing both design and budget information. The delivery strategy employed here appears to have produced a top-quality facade, on time and on budget (Figure 13.11).

FIGURE 13.11 The cavity of the double-skin wall provides a thermal buffer for the building's interior.

Chapter 14

Richard J. Klarcheck Information Commons, Loyola University[1]

Chicago, Illinois

FIGURE 14.1 The east facade is within a few yards of Lake Michigan.

General Information	
Year completed	2008
Building size, sq ft (sq m)	70,495 (6549)
Building type	Education; digital library
Building cost, USD	28.3 million
Project Credits[2]	
Owner	Loyola University Chicago
Architect	Solomon Cordwell Buenz design team
Facade consultant	CDC
Building engineer	Halvorson & Partners
Mechanical, electrical, plumbing (M/E/P) engineer	Elara Engineering
Climate consultant	Transsolar
LEED consultant	Sieban Energy Associates
General contractor	Pepper Construction
Design-assist, design-build facade specialist	Enclos Corp with ASI Advanced Structures Inc.[3]
VS-1 System design	Innovation Glass
VS-1 System installation	Trainor Glass (east wall)
	Enclos Corp. (west wall)
VS-1 System supplier	Innovation Glass
Operable vent windows	Inner skin west facade: building automation system (BAS)-controlled four-bar parallel hinge with chain actuators by Quasar East facade and west wall parapet: BAS-controlled awning windows with chain actuators by Supermaster
Shading systems	Roller shades: BAS-controlled Lutron® with Verosol SilverScreen® fabric Louver blinds: BAS-controlled Warema with 4 ft (1220 mm) aluminum 8% perforated slats
Glass supplier	Viracon monolithic and insulating glass Eckelt insulating glass with integral shading louvers
Facade System: Cable Net	
Structure type	Flat cable net
Facade system cost per sq ft (sq m)	Approx. 230 (2476) cable net
Total facade area, sq ft (sq m)	Approx. 6720 (624) cable net
Glass grid module orientation	Vertical
Grid dimension height ft-in. × width ft-in. (mm)	8 × 5 (2438 × 1524)
Glass type, cable net	½ in. (12 mm) fully tempered (FT) monolithic, low-iron
Glass system type	Point-fixed clamped
Maximum span, ft (m)	56 (17)
Deflection criterion	L/50
Project delivery	Design-build; all services provided in-house except for material supply

Facade System: Mullion System	
Structure type	Mullion system
Facade system cost $ per sq ft (sq m)	Approx. 98 (1055)
Total facade area, sq ft (sq m)	Approx. 8736 (778) VS-1 (west wall) Approx. 7738 (719) VS-1 (east wall)
Glass grid module orientation	Vertical
Dimension height × width ft-in. (mm)	16 × 5 (4877 × 1524) with three submodules:
Vision glass	12 × 5 (3658 × 1524)
Operable vent	2-6 × 5 (762 × 1524)
Spandrel	1-6 × 5 (457 × 1524)
Glass type	West wall
	1 in. (24 mm) insulating glass unit (IGU)
Imperial units specified, metric units approximated.*	¼ in. (6mm) FT low-iron ½ in. argon airspace (AS) argon ¼ in. (6mm) FT low-iron Low-e no. 2 surface East wall 1¼ in. (32 mm) IGU ⅜ in. (10 mm) FT low-iron ½ in. (12 mm) AS argon ⅜ in. (10 mm) FT low-iron Operable vent: same as for vision glass Spandrel: insulated metal panel
Glass system type	Point-fixed clamped
Maximum span, ft (m)	16 (4.9) structure; 12 (3.7) glass
Deflection criteria	L/175 for structure, L/140 for IGU glass
Project delivery	Design-build; mullion system furnished by industry provider

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The Information Commons by architect Solomon Cordwell Buenz is dramatically sited immediately adjacent to the shore of Lake Michigan on the campus of Loyola University Chicago (Figure 14.1). The building is a four-story digital library embodying the design intent of transparency combined with energy efficiency. The objective, in addition to creating an engaging environment for scholarly pursuits, was to provide an unimpeded view of the lake through the building from the campus courtyard to the west. The body of the building is essentially a rectangular glass box on a north–south axis spanning between limestone blocks at either end.

Facade Program

The east and west facades are both full-height, 150 ft (45.7 m) long, fully glazed facades, but with significant differences between them. The east facade employs a novel mullion system utilizing point-fixed IGUs. The west facade is a double-skin wall fully integrated into the building's mechanical systems (Figure 14.2). The inboard skin utilizes the same system as the east facade. The outboard skin is clear monolithic glass supported by a cable net structure. The two skins are separated by a 3 ft (914 mm) cavity (Figure 14.3).

VS-1 Facade System

The east facade and the inboard skin of the west facade employ a proprietary product called the VS-1 System (patent pending) (Figures 14.4 and 14.5). The structure is a custom aluminum extrusion that spans the full floor-to-floor height of 16 ft (4.9 m) without horizontal members. A T-shaped slot is extruded into the outboard face of the extrusion. A custom cast aluminum glass-fixing component is designed to engage the slot, where it can be slid into position and secured. The component is used to clamp a glass panel in place, penetrating through the narrow gap between glass panels to provide a point support without the need for perforations in the glass. Multiple point supports are easily accommodated. The glass plane is stepped away from the face of the extrusion, providing an exterior glass membrane interrupted only by the small rectangular faceplates that act as the clamping mechanism.

Horizontal mullions are not used with the system. In the Loyola facades, the vertical 8 in. (203 mm) deep extrusions are spaced on 5 ft (2.5 m) centers. The 16 ft (4.9 m) vertical module is subdivided into three different-sized panels. The lower panel is 12 ft (3.7 m) tall vision glass: an IGU with a low-e coating on the no. 2 surface. The middle panel is a 2 ft 6 in. (3.7 m) tall automated vent of the same glass makeup. The upper panel is an insulated metal spandrel that conceals the floor slab and fire-safing. A 1 in. (25 mm) wide butt-glazed silicone joint between the glass panels provides the weather seal, except for around the automated vent, where a $\frac{3}{8}$ in. (10 mm) silicone joint width is achieved (the glass-to-glass joint width even at the operable vent is maintained for a zero site-line window).

FIGURE 14.2 The entry of the west facade during construction. Note the view to Lake Michigan beyond.

The facade system is exposed to a two-story height just inside the east wall entry, where a large opening in the second-floor plate provides an atrium feel to the space. At the west facade entry, the inboard facade radiuses inward to define interior circular staircases on either side, and to enclose a large vestibule space that becomes part of the cavity buffer between the inner and outer skins of the double wall.

Cable Net Facade

The cable net structure used as the outboard skin on the west facade is yet another example of structural glass facade (SGF) technology applied as part of a strategy for energy efficiency. A cable net provides an ideal solution for the outer skin of a multistory double-skin wall. The Broad Medical Center (Chapter 13) makes similar use of a cable net.

FIGURE 14.3 Technicians work within the double-skin cavity. The cable net is the outboard skin to the left, and the inboard skin is the VS-1 system.

Facade Structure

The cable net structure is a two-way grid of prestressed vertical and horizontal cables. The cable grid defines the glazing module at 8 ft (2.4 m) tall by 5 ft (1.5 m) wide, with 29 vertical cables intersected by 6 horizontal cables. The vertical cables are hung from the top of the structure from "hangman" outriggers, stepping up and out approximately 4 ft (1.2 m) from the inner facades. The hangmen are base supported from and anchored back to the building roof structure with cable ties. At the base of the cable net, the vertical cables are anchored to a concealed spring assembly with a spring of 1.25 in. (32 mm) wire (Figure 14.6). The spring is slightly compressed during installation and is designed to provide a predictable, controlled deflection to the vertical cables. As the facade deflects under load, the spring will be further compressed, accommodating the deflection without overstressing the cable and mitigating any shock effect from rapid load changes.

The six horizontal cables create six vertex locations along each vertical cable. The cables are clamped at these locations with a four-part cast stainless steel clamp. Every 30 ft (9.1 m) along the length of the facade, the vertical cables are tied back with a kicker strut at each vertex location to a building column, thus minimizing the horizontal span and deflections of the cable net (Figures 14.7 and 14.8).

The vertical cables are ⅝ in. (16 mm) and the horizontal cables are 1⅛ in. (28 mm) stainless steel strand. The spring cans accommodate the higher deflections of the vertical cables, which are prestressed to only about one-sixth of the 44 kip (195 kN) prestress force in the horizontal cables. Deliberately concentrating the loads in the horizontal cables provided significant cost advantages by minimizing cable sizes and anchor steel requirements for the far more numerous vertical cables. The maximum allowable deflection was just under 7¼ in. (184 mm) (L/50), and the design deflection was just under 6¼ in. (159 mm) (L/58).

FIGURE 14.4 The VS-1 system spans two floors in the atrium area of the east facade.

FIGURE 14.5 A view through the ground floor of the east facade. Note the automated roller shades at the top.

Glass System

The glass on the east wall is 1¼ in. (32 mm) IGU, while the sheltered inboard skin of the west wall is 1 in. (25 mm) IGU. The outboard skin of the double-skin facade is clear monolithic glass, in this case ½ in. (13 mm) thick and fully tempered and heat-soaked. The cast assembly that clamps the cables together at the vertex also functions to support and fix the glass in place. An exterior plate fixes four adjacent corners of glass (Figure 14.15).

FIGURE 14.6 The base connection detail of the cable net structure during installation.

FIGURE 14.8 Four-part cast stainless steel cable clamp and glass-fixing assemblies (minus the cap plate). The glass sits on the blades to the right side of the assembly.

FIGURE 14.7 A view up the facade from inside the cavity reveals the kickers that tie the cable net to the building structure every 30 ft (9.1 m).

FIGURE 14.9 Construction shot showing the shark-fin cable anchor at the right and the glass-fixing strut at the glass return. Note the penetration of the cable through the glass at the joint.

An unusual detail occurs as a partial module at either side of the facade (Figure 14.9). The glass plane returns perpendicular to the cable net before reaching the supporting perimeter structure, forming an open notch between the facade and the limestone block. The horizontal cable terminations are exposed to the exterior within this notch. Special kicker struts at the last building column are modified to include clamp assemblies to fix the glass returns in place. This detail requires that the cable penetrate the glass plane before the termination. A semicircular cutout in the edge of adjacent glass panes accommodates the penetration and silicone provides the weather seal, as it does for the entire glass membrane, with a ⅝ in. (16 mm) butt-glazed joint between glass panels.

A ⅝ in. (16 mm) laminated glass is used to cap the top of the cavity. The glass slopes slightly toward the building to provide drainage. The inboard side at the top of the wall encloses the back of the hangmen and incorporates operable vents that accommodate airflow from the cavity (Figure 14.10). Cable anchors penetrate through the glass skin to tie the hangmen back to the building structure. These anchors are prestressed to over 8 kips (36 kN).

Facade Concept Development

Design-assist services were provided by the design-build contractor. This afforded early involvement during the schematic design phase by a specialist capable of facilitating concept development with the design team. The cable net wall was the particular focus because of its interface with the building structure. The design-assist team developed a conceptual solution and modeled it using Space Gass®

FIGURE 14.10 The hangman tieback at the top backside of the double-skin wall. The automated windows open to vent the cavity as part of the whole-building ventilation system.

to analyze performance. Variations in the cable net design were assessed through an iterative process until a working solution was found that met all relevant criteria. The design-assist specialist provided ongoing budgeting information for consideration by the design team so that design decisions could be made in the context of cost. Preliminary reactions were developed to a ±10% level of accuracy and provided to the building engineer. Design-assist services included plan, elevation, and typical section, representation of the concept, as well as typical detail drawings and a performance specification, all of which were included by the architect in the contract documents.

Testing

Performance testing on the cable net wall was not required because it does not act as the primary weather barrier for the building. Testing was required for the VS-1 System, however. A full-scale mockup was constructed and subjected to the usual battery of water and air infiltration tests. Problems with the operable vent panel were identified. Modifications to the gasketing strategy ultimately resolved the issue, and the mockup passed.

Project Delivery

In addition to the design-assist services described above, Enclos ultimately provided complete design-build services, including in-house design and engineering, procurement, and installation. Off-site fabrication requirements were minimal on this project. This was the first commercial use of VS-1, a unique proprietary facade system. A strong Enclos site operations team enabled this first-time use of a highly innovative system without delays to the project.

Installation Strategy

The VS-1 System is stick assembled, with the mullions being set first. The system includes a cast aluminum dead load bracket as well as a point-fixing clamp. The dead load bracket is installed where the bottom edge of a glass panel is to sit. The point-fixing clamps are also positioned and secured, with the exterior clamp plates removed (Figure 14.11). The 16 ft (4.9 m) vertical module is filled with three panels, as described above. The 12 ft (3.7 m) tall vision glass panel is held with three point fixings on either side. The operable vent and insulated spandrel are framed and secured directly to the extrusions in this application. The panels are set following the installation of the brackets and fixings, and the vision glass is secured with the exterior clamp plates. A silicone joint filler gasket is inserted from the interior to finish the joint and provide backer for the exterior caulk. The weather seal is applied last with Dow Corning 756 silicone sealant.

The cable net wall involved the installation of the hangmen at the top (Figure 14.12), the spring

FIGURE 14.11 The VS-1 System before glass installation.

FIGURE 14.12 Hangmen being installed at the top of the double-skin wall. The tiebacks are pretensioned to 8 kips (36 kN).

anchors at the base, and the plate anchors at either side, which were dubbed "shark fins." The horizontal cables were then hung, followed by the verticals, placing the vertical cables to the outside. The horizontal cables were then tensioned from the shark fin anchor (Figure 14.13), followed by the tensioning of the verticals from the base anchor. Prestress forces were documented, and once the required force was confirmed in all cables, the cable clamps were installed and surveyed for position within a tolerance of ± $\frac{1}{8}$ in. (3.2 mm). Finally, the glass was installed, working from the top down, and the silicone weather seal was applied (Figures 14.14 and 14.15).

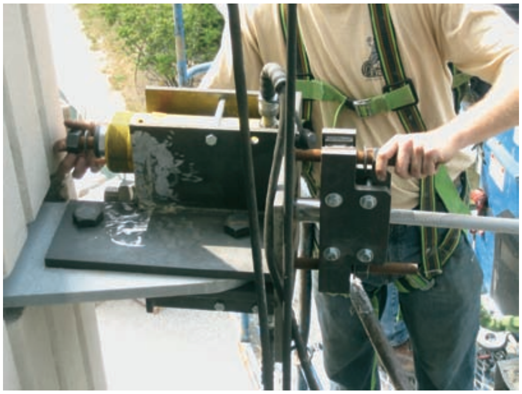


FIGURE 14.13 A horizontal cable is fixed to the shark fin and prepared for pretensioning.

FIGURE 14.14 Cable net glass being installed from a swing stage.

Strategies for Sustainability

The architect had an aggressive green agenda for the Information Commons, of which the glass facades were a part, and the double-skin wall was a primary element. The large expanses of clear glass along both sides of the long axis of the building provide abundant daylight to the interior, significantly reducing the need for artificial lighting. A large entry vestibule on the west side was incorporated into the double-skin design, adding to the buffer space of the building interior (Figure 14.16). Controls and sensors work to continuously dim artificial lighting in response to daylight levels. The east facade is equipped with operable roller blinds to control direct solar penetration and glare during the morning hours. An automated blind system is located within the cavity of the double-skin wall to control afternoon solar exposure. The cavity is an optimum location for the blinds to mitigate heat gain through the inner skin, as well as to minimize maintenance requirements because the blinds are

FIGURE 14.15 A field-applied butt-glazed silicone joint provides the weather seal.

FIGURE 14.16 A vestibule located inside the main entry of the west facade is actually part of the double-skin cavity. The opening through the inboard skin is just to the left of the picture frame.

protected from direct exposure to the elements. The position of the blinds varies, based on the time of day. Throughout the morning hours, the blinds are fully retracted. By late afternoon they are fully deployed and closed, blocking direct solar penetration through the west facade (Figure 14.17).

Cold winter weather and lake exposure presented certain challenges in a building with such a high percentage of glazed envelope; heating loads dominate in this climate, although cooling is required throughout a significant portion of the summer months. The architect worked with climate consultant Transsolar to develop a highly responsive heating, ventilation, and air conditioning (HVAC) system that incorporated natural ventilation and thermal buffering. Again, the double-skin wall was effective in providing a thermal buffer between inside and outside environments and was integral to the natural ventilation system. In the summer, heated cavity air rises and is exhausted through operable vents at the top of the cavity, resulting in a stack effect that can be used to draw air from the building's interior, which itself is replaced by air drawn through vents in the east facade in proximity to the cool lake air. If interior temperatures exceed comfort levels, the vents to the interior close and outside air supply vents at the base of the cavity open to exhaust the heated cavity air to the outside.

Through these and an array of other sustainable features, the energy consumption of the Information Commons is claimed to be nearly 50% less than that of a standard comparable building. It is not known if any postoccupancy monitoring of the building will be undertaken. The U.S. Green Building Council awarded the Information Commons a LEED Silver rating.

FIGURE 14.17 The main entry through the west facade on a summer afternoon, with the automated blinds fully closed.

FIGURE 14.18 The horizontal cable terminations are expressed by a setback in the glazing plane.

Summary

The Information Commons brilliantly combines an aesthetic of transparency with high performance, repudiating the contention expressed by some that the only way to improve energy performance in buildings is to prescriptively reduce the amount of glass in the building facade. Clear glass and large areas of highly transparent facade are central to the efficiency gains of the building The cable net provides an ideal solution for the outboard skin of a double-skin facade (Figure 14.18). The double-skin facade was integral to an advanced thermal control system that combined active and passive strategies. The VS-1 mullion system with point-fixed glass represents another adaptation of SGF technology to the less spectacular, lesser span facade applications, again combining high functionality with a unique and appealing aesthetic. The building stands as an inspirational expression of a commitment to green architecture by Loyola University and the entire design team, and as an outstanding example of the opportunity presented by the masterful application of SGF technology.

Chapter 15

Newseum

Cable Mullion Facade
Washington, D.C.

FIGURE 15.1 The Newseum building presents a dramatic facade to Pennsylvania Avenue.

General Information	
Year completed	2008
Building size, sq ft (sq m)	Eight-story, 531,000 (49,332)
Building type	Cultural (museum), mixed use
Building cost, USD	Approx. 450 million
Project Credits	
Owner	The Freedom Forum
Architect Facade team	Polshek Partnership Architects (Now Ennead Architects LLP) James S. Polshek, Robert D. Young, Kate M. Kulpa
Facade consultant	RA Heintges & Associates
Building engineer	Leslie E. Robertson Associates (LERA)
Construction manager	John J. Lowery, American Institute of Architects (AIA)
General contractor	Turner Construction Company
Design-assist, design-build facade specialist	Enclos Corp. with ASI Advanced Structures Inc.[1]
Cable supplier and termination covers	Brugg
Custom cable clamp supplier	Clamp castings by Image Casting (California) Cruciform arm castings by Hycast with machining by Nupress (Australia)
Machined components	Nupress (Australia)
Architecturally Exposed Structural Steel (AESS) steel fabricator	TrussWorks International
Perimeter truss fabricator	CANAM Steel Corp.
Glass supplier	Cristacurva (Mexico)
Facade System	
Structure type	Horizontal cable mullion system with vertical dead-load hangar bars
Facade system cost per sq ft (sq m)	Approx. 230 (2472)
Total facade area, sq ft (sq m)	Approx. 4200 (390)
Glass grid module orientation	Vertical
Grid dimension height × width ft-in. (mm)	10 × 5 (3048 × 1524)
Glass type Imperial units specified, metric units approximated.*	13/16 in. (21.52 mm) laminated 3/8 in. (10 mm) fully tempered (FT) low-iron 0.06 in. (1.52 mm) SentryGlas (SG) 3/8 in. (10 mm) FT low-iron
Glass system type	Point-fixed bolted with custom cast stainless steel cable-supported fittings
Maximum span, ft (m)	40 (12.2)
Deflection criterion	L/120 (±4 in. [102 mm] for the central span)
Project delivery	Design-build

* The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

A new museum dedicated to the First Amendment occupies 215,000 sq ft (19,974 sqm) of this 531,000 sq ft (49,332 sqm)mixed-use building, located prominently on Pennsylvania Avenue across from the National Gallery, in our nation's capital. The building also incorporates residential, office, and ground-level retail space (Figure 15.1).

Architectural firm Polshek is yet another company to equate transparency with democracy, the reason that structural glass facades (SGFs) have found such frequent application in federal and state government buildings. As designers with a command of transparency in architectural form, there is little surprise concerning their masterful expression in a museum celebrating the principles of free speech and a free press. A large, deep penetration in the building facade is closed by a transparent glass facade providing unobstructed views from the street to a mega-sized media screen. The facade was nicknamed during design and the name followed to the field, where construction workers talked about the progress on the "Big Window" (Figures 15.2 and 15.3).

Facade Program

The facade program for the entire project was large, diverse, and complex, involving many different system types. The SGF application here is small in size, but as is often the case, it is a prominent feature element of the architecture.

Facade Structure

The structural form here is simple but novel: a one-way cable system with the cable pairs oriented horizontally and spanning between two perimeter trusses. Five sets of paired cables span 84 ft (15.6 m) across the opening, spaced at 10 ft (3 m) vertically to define the glazing grid. The cables pairs are tied back to building columns spaced 40 ft (12.2 m) apart and centered in the facade opening, creating

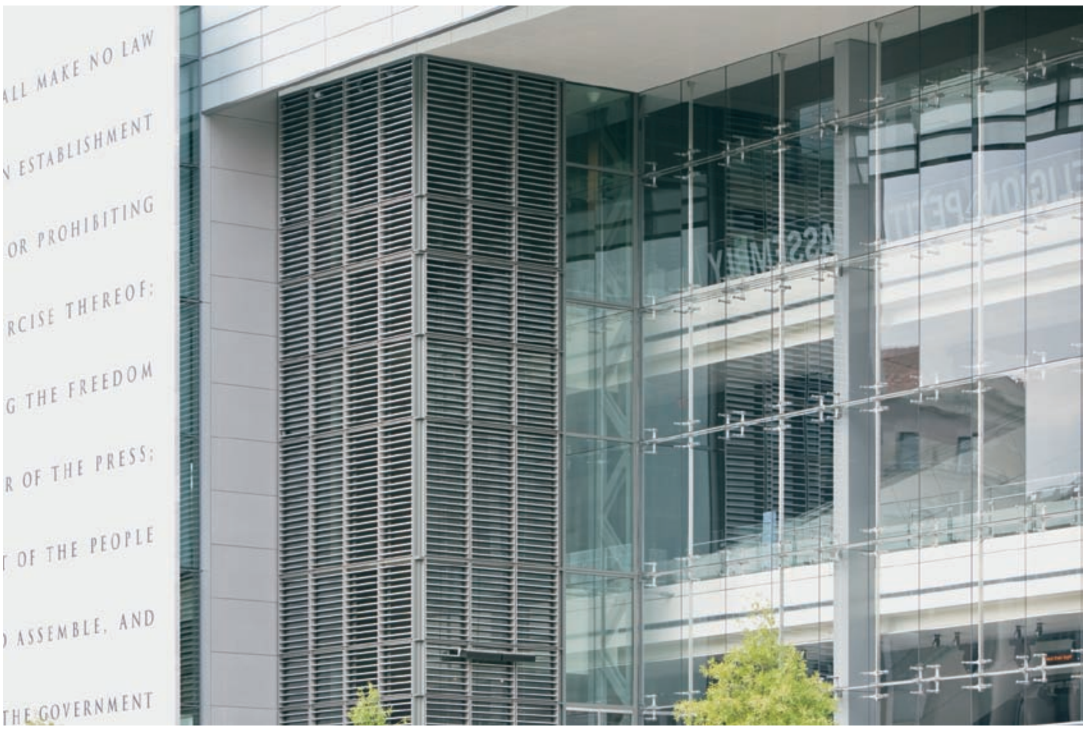


FIGURE 15.2 The highly transparent cable wall is a predominant architectural feature.

three spans of 22 ft (6.7 m), 40 ft (12.2 m), and 22 ft (6.7 m). The cables are fixed at the perimeter to custom-designed exposed steel trusses that were designed by LERA to act as part of the facade system (Figure 15.4). The trusses were designed to facilitate cable pretensioning. The 1⅜ in. (34 mm) 1 × 91 stainless steel strand cables are prestressed to 71 kips (316 kN). The deflection criterion of L/120 provides a much stiffer structure than is typical of most cable structures, which frequently have specified deflection criteria near L/50 and as low as L/35 (see the Alice Tully Hall case study in Chapter 16). The original specification was even tighter, so tight that stainless steel cables strong enough to handle the consequent prestress are uncommon. ASI demonstrated that the deflection criterion was overly tight and was successful in getting it relaxed to L/120. Even this relaxed criterion produced quite high cable prestress. Maximum cable reaction live loads (wind) were 84 kips (374 kN) at each cable termination.

Suspended vertical dead-load tension bars, referred to as *hangar bars*, are located on alternating modules of the glass grid and carry the self-weight of the glass and cables, leaving the cables themselves to contend with lateral wind loads (Figure 15.5). The hangar bars are A316 stainless steel in approximately 10 ft (3 m) lengths, chained together by pins. Four full-length bars are pinned to a shorter bar at the top. The hangar bars terminate above the bottom glazing module at the lowest horizontal cable.

Glass System

The design team developed a cast stainless steel clamping assembly for the double horizontal cable scheme (Figure 15.6). The clamp facilitates the clamping of the cables to the hangar bars. Armature castings were also developed that attach in pairs to the hangar bars in a cruciform configuration. Custom-designed machined stainless steel fittings

FIGURE 15.3 The horizontal cables are braced at two building columns to limit the overall span to 40 ft (12.2 m).

FIGURE 15.4 AESS perimeter trusses support the cable prestress loads of 71 kips (316 kN).

mate with the armatures to receive a glass bolt that point-fixes the glass. The 13⁄16 in. (21 mm) laminated low-iron glass is perforated and the outer lite countersunk to receive the glass bolt.

Since the hangar bars fall only on every other vertical division of the glass grid, another detail was developed for the cable-to-glass attachment where there is no hangar bar (Figure 15.7). Here, the same armatures are attached to the top and bottom of a modified clamp to pick up the glass attachment. Two of these clamps are required at each intersection of the glass grid where there is no hangar bar.

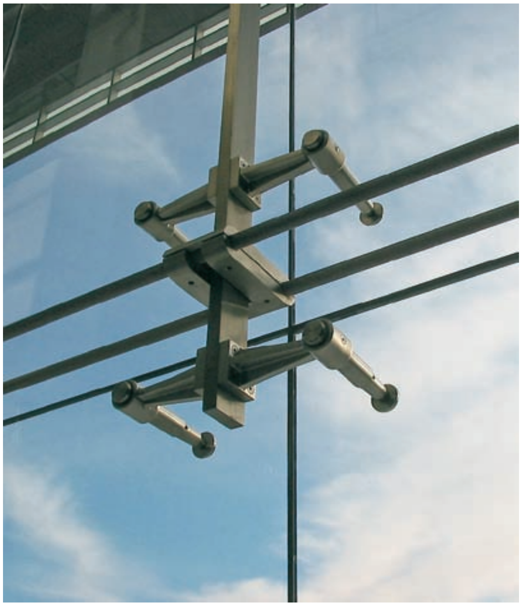


FIGURE 15.5 Hangar bars support the glass and cable dead loads, and the cables resist lateral wind loads.

It seems to be a quite simple system. As usual, the complexity is in the details. The concept called for the dead load of each glass lite to be carried by a single point fixing because the absence of the hangar bar at every other gridline meant that the glass panel could potentially rotate in plane toward the cable bar. Some of the specialty contractors bidding on the project expressed doubt that the system could work as drawn. The point fixings that all appear identical in Figures 15.5, 15.6, and 15.7 are not. Mark Dannettel, the lead designer for Enclos/ASI, described three different types of fittings for fixing the glass to the cast armatures. "We carried the dead load at the top fitting of the lite adjacent to the hangar rod. A glass lite was about 500 lb. (227 kg) The fitting immediately below was restrained from side-to-side movement, thus carrying the rotation force, which was about 125 lb (57 kg). The two fittings on the opposite side were designed to only resist lateral loads."[2]

Another complexity was handling the out-of-plane rotational forces resulting from the offset of the glazing plane from the hangar bar structure. The dimension from the centerline of the armature to the outboard face of glass is 11 in (279 mm). The design team wanted to accommodate the rotational forces without the addition of any bracing

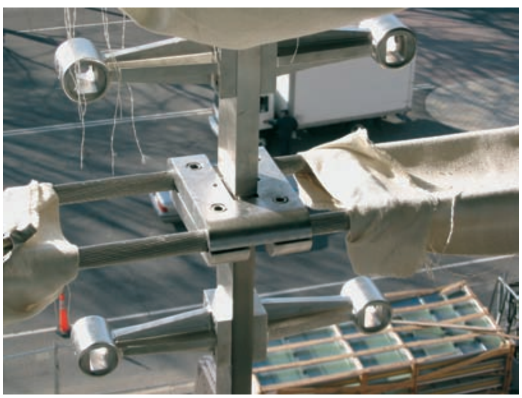


FIGURE 15.6 Hangar bar detail at the cable grid.

FIGURE 15.7 Visual mockup of the glass connection at the gridline away from the hangar bar.

component, for which there was no easy solution in any case. Instead, they took all of the tolerance out of the system to prevent the rotation and designed the system to carry the load. For example, the attachment of the armatures to the hangar bars is accomplished with a pattern of machine-tapped holes in the hangar bar and a matching pattern of countersunk holes in the armature, both to tolerances of within a few thousandths of an inch. All of the machined parts are to similarly high tolerances. According to Dannettel, this approach presented certain fabrication challenges (discussed below) but effectively solved the problem.

Facade Concept Development

The concept in this case was developed by the architect, engineer, and facade consultant. The concept drawings and a performance specification were incorporated into the contract documents as a design-build package, and the project was bid by facade contractors qualified per the performance specification.

Testing

While there were no formal test requirements for the cable-supported wall, the ASI design team felt that it was imperative to carry out some basic tests of the unprecedented system. Several prototypes for the cruciform armatures and related struts were fabricated and used for small-scale tests to confirm load capacity and deflection values. Additionally, a full-scale mockup was built at the steel fabrication shop, and was used to confirm fit-up and test the proposed installation techniques. Installation supervisors from the East Coast flew out to Los Angeles to review the system and experiment with the installation procedures firsthand, removing and installing glass until an exact methodology was defined. Dannettel commented that this was a practice integral to the ASI process, which often resulted in refinements to the system design.

Project Delivery

The design-builder self-performed all work except fabrication.[3] System detailing and engineering were submitted to the architect and engineer for review and approval. The perimeter supporting trusses discussed above were unfortunately not included in the facade package, but were designed by LERA and fabricated by a Canadian steel fabricator. The trusses provided for very little field tolerance. The ASI design thus required exceptionally tight tolerances for the location of the trusses. Prior to the start of the facade installation, one of the trusses was found to be out of tolerance and had to be cut loose and repositioned.

Largely because of the tight tolerances, the machining of the armature castings and the machined glass fittings that connect them were ordered from the same Australian supplier to ensure fit-up. The armatures, however, had themselves to fit up with the hangar bars to an equally tight tolerance. When the setup for machining the armature castings went into production, a template was first produced and sent to the steel fabricator in California. It was used to accurately locate the mating holes in the hangar bars.

Figures 15.8 to 15.13 document the casting of the clamp body.

Installation Strategy

The cables were first hung and pretensioned, using two 60 ton (54.43 metric tons) cable jacks for each cable pair, and were then prestress verified. The cables stretched 3½ in. (89 mm) after being fully prestressed. The hangar bars were next installed, followed by the installation of the clamps and armatures. A crisis loomed when the casting supplier was delayed and the installation crew was short of clamping components. As is typical of facade work, there was enormous pressure from the general contractor to get the building enclosed. The design team developed a temporary fix, using wood blocks and shims, which allowed the installation to continue and the schedule to be maintained (Figure 15.14). The high tolerance of the components actually facilitated the ease of assembly, and glass installation proceeded even before all of the clamping elements were in place. The glass bolts were installed on the ground,

FIGURE 15.8 The next five figures document the casting process for the cable clamps. Shown here is the mold for making the wax patterns. The die is open, showing a pattern ready to be removed.

FIGURE 15.9 A pattern is made for each part to be produced.

FIGURE 15.10 A ceramic slurry creates a shell around the pattern, which is fired to harden the ceramic and melt out the wax; molten metal is then poured into the void.

FIGURE 15.11 The ceramic is broken away to reveal the cast metal.

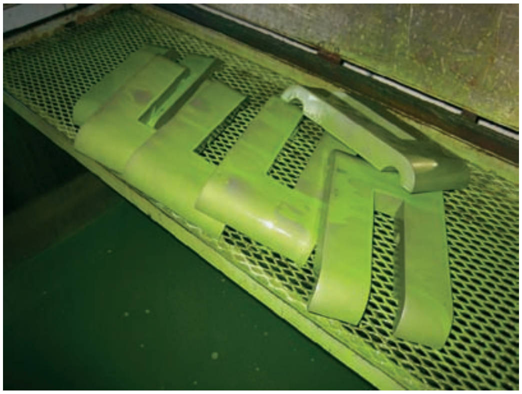


FIGURE 15.12 Each casting is tested for surface cracks using a die-penetrant technique. A percentage of parts are also radiographed to detect the presence of voids.

FIGURE 15.13 Each casting is inspected to ensure conformance with the required tolerance prior to machining.

and the glass was lifted and plugged into the machined receptacles attached to the armatures (Figure 15.15).

Summary

Once again, the striking thing is the diversity of design, scale, complexity, and application of SGF projects. Here, a small but highly innovative SGF design becomes a prominent focal element and architectural feature, an integrated component of a complex and sophisticated total building facade. The transparency of the cable facade at the Newseum provides a functional corollary to its metaphorical representation of democracy: an unobstructed view from the street to the large light-emitting diode (LED) display within.

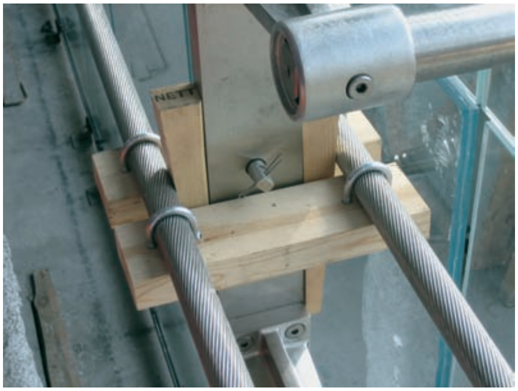


FIGURE 15.14 A delay in the delivery of castings to the site prompted this quick fix, which allowed the installation to proceed without delaying the project schedule.

FIGURE 15.15 The truss and cable termination are exposed at the perimeter of the facade.

Chapter 16

Alice Tully Hall at Lincoln Center

New York City

FIGURE 16.1 Alice Tully Hall is the latest renovation to the Lincoln Center complex.

General Information	
Year completed	Summer 2009
Building size, sq ft (sqm)	79,524 (7388)
Building type	Cultural (performing arts music hall)
Building cost, USD	Approx. 159 million
Project Credits	
Owner	Lincoln Center
Architect	Diller Scofidio + Renfro (DSR) with FXFowle Architects
Facade consultant	RA Heintges Architects Consultants
Structural/mechanical, electrical, plumbing (M/E/P) engineer	Arup
Lighting design	L'Observatoire International
Construction manager	Turner Construction Company
Glazing design-builder	W&W Glass, LLC
Cable system designer and supplier	TriPyramid Structures
Glass supplier	Pilkington with SentryGlas
Facade System	
Structure type	Cable mullion system
Facade system cost in USD per sq ft (sq m)	240 (2583)
Total facade area, sq ft (sq m)	Approx. 10,000 (929)
Glass grid module orientation	Vertical
Grid dimension height × width ft-in. (mm)	Approx. 16 × 5-10 (4877 × 1778)
Glass type Metric units specified, imperial units approximated.*	13⁄16 in. (19.52 mm) laminated start outboard: 1⁄4 in. (6 mm) fully tempered (FT) 0.06 (1.52 mm) SentryGlas (SG) 1⁄2 in. (12 mm) FT Ceramic frit (various), both lites low-iron Optiwhite, beveled edge treatment
Glass system type	Point-fixed clamped primary Point-fixed bolted intermediary
Maximum span	Approx. 45 ft (13.7 m)
Deflection criterion	L/35
Project delivery	Design-build with specialty facade contractor

*The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The new glass facade for Alice Tully Hall at Lincoln Center is part of a renovation project by architect Diller Scofidio + Renfro (DSR) with FXFowle Architects (Figure 16.1). The 1100-seat music hall is located in the Juilliard School of Music at the northern end of Lincoln Center for the Performing Arts, on the corner of 65th Street and Broadway in Manhattan (Figure 16.2). The most predominant feature of the new design is a dramatic three-story glass cable-supported facade enclosing the outer lobby of the facility. Due to the design intent of merging inside and outside spaces and opening the performing arts center to the street, the highly transparent facade opens the music hall lobby to the surrounding cityscape, transforming this venue into one of the city's most dynamic public spaces. The project was the recipient of a 2010 Honor Award from the American Institute of Architects.

Building Structural System

The renovation involved an intricate steel framing system of complex geometry to articulate the spatial form and support the facades. Exposed vertical columns and diagonal braces are set inboard of the facade membrane, providing structure-free spans for the highly transparent glass skin (Figure 16.3).

FIGURE 16.2 The facility is prominently located on the corner of 65th Street and Broadway in Manhattan.

FIGURE 16.3 From the street, the building's structural system becomes sculpture behind glass.

Facade Program

The glazing contractor provided five different custom facade systems for this project. Two of these involved structural glass facades (SGFs): an outer lobby is enclosed by a cable mullion structure, and a glass fin wall separates the inner lobby from the music hall. The flat one-way cable system provides a simple and elegant solution as a highly transparent membrane enclosure. Two sides of the facade enclosure angle up to a corner, where the facade reaches its maximum elevation (Figure 16.4).

Facade Structure

The cable system is comprised of vertical cables only, with spacing defined by the horizontal spacing of the glass grid module. The stainless steel strand cables vary in diameter from $\frac{3}{4}$ to $1\frac{1}{4}$ in. (19 to 32 mm) and are placed on approximately 5 ft 10 in. (1.8 m) centers along the perimeter of two building sides that meet at a corner to enclose the outer lobby. The cable prestress ranges from 13 to 72 kips (58 to 320 kN), with the latter cables having a design load of over 100 kips (445 kN). Most of the cables are designed to elongate in response to building movement, but some of the higher-loaded cables use custom spring packs to limit prestress in high-load conditions. The cable system supports a point-fixed glass system, as described below.

A double vestibule is integrated into the facade near the interface of the two walls, the portal assembly suspended from custom patch fittings (Figure 16.5).

Glass System

The laminated glass lites are quite large, with vertical dimensions up to 16 ft (4.9 m). The glass makeup is approximately $\frac{1}{4}$ by 0.060 by $\frac{1}{2}$ in. (6 by 1.52 by 12 mm), with both lites fully tempered and heat

FIGURE 16.4 The two facade faces slope upward to meet at a corner with an elevation of approximately 45 ft (13.7 m).

FIGURE 16.5 A double vestibule is located near the intersection of the two walls.

soaked. The interlayer is SentryGlas, which adds strength and stiffness to the large glass lites, helping to reduce panel thickness and the number of point fixings (Figure 16.6). Still, the vertical span of the glass panels was too large to be accommodated by corner fixings alone.

Two types of glass fixings are used on the cable wall. One is at the vertices of the glass grid, where a 4 in. (1.2 m) round machined stainless steel clamp assembly secures four adjacent corners of glass to the cable (Figure 16.7). The other is an intermediary fitting, required because of the height of the glass lites. Pilkington Integral™ fittings are used between the corner fixings, as required to provide additional support to the long edge of the glass lites. The fittings at

FIGURE 16.6 Cable systems are the most minimalist of the facade structure types.

these intermediary points are secured to simple machined stainless clamps that tie the glass back to the cables (Figures 16.8 and 16.9).

Facade Concept Development

The facade contractor was brought in early in the project program to assist the design team in meeting the demanding aesthetic requirements of the architect. This early involvement also provided for critical input to the building's structural engineers regarding the loads applied to the building structure by the cable facade. An iterative process involving the facade contractor, the design team, and the building engineer resulted in a facade structure that provided the transparency the architect was seeking while accommodating very large, varying building movements and loading the building in very specific ways, as desired by the building engineer.

Testing

A full-scale performance mockup was tested to one and a half times design wind pressures (Figure 16.10). After the specified testing regime was successfully completed, the wall was tested incrementally in excess of twice the design wind pressure, with no failure.

Project Delivery

The facade contractor provided complete design-build services for the lobby enclosure as part of an overall design-build facade package for the renovation. W&W Glass, LLC is based in the New York area and was able to provide installation services on Tully

FIGURE 16.7 Clamp fitting at the glass grid vertex.

FIGURE 16.8 Interior view of the intermediary point fixing.

FIGURE 16.9 Exterior view of the intermediary point fixing.

FIGURE 16.10 The performance testing mockup nearing completion.

Hall directly with its own crews. W&W designed and engineered the system, procuring the glass and fittings from Pilkington and the cable system from TriPyramid Structures.

Installation Strategy

The cable anchors were positioned and the locations verified. The prestretched cables were then hung from above from the top anchors and attached to the base anchor supports. The cables were snug tightened, the positions were verified, and pretensioning began one cable at a time, starting at the corner and working in both directions down the length of the facade walls. Cables were pretensioned to 110% of prestress requirements. Like the strings of a guitar, cable tensions change as additional cables are tensioned and the boundary structure deflects and shapes itself to the varied strain. Once all of the cables were installed and tensioned, the installation crew swept through the entire structure again, retensioning the cables to prestress requirements. At the end of this cycle, after all cables had been pretensioned, prestress values were checked with a tension meter and adjusted as required. Follow-up checks verified that the cable tensions had stabilized and that no further adjustments were required. Anchor locations were surveyed before and after pretensioning to determine that the boundary structure had moved within the predicted limits, thus ensuring that the tolerances designed into the system would accommodate installation of the glass.

FIGURE 16.11 The structural form and transparency present an open invitation.

With the cable tensioning complete, the corner clamps of the glass system were installed on the cables and the positions verified. Glass setting commenced at the uppermost bay of the facade and proceeded across until the bay was completed, after which installation of the next lower bay commenced. The intermediary Integral fittings were preinstalled on the glass panels prior to installation. After the glass panels were set into the corner clamps and their position adjusted, the intermediary clamps were positioned on the cables and tied to the fitting. The prestress loads were high enough that the supporting structure did not deflect appreciably under the added weight of the glass (Figure 16.11).

Summary

There are more grandiose examples of SGFs that could have been included as case studies, but the focus here tends toward diverse applications of the technology that are well integrated into the building architecture and the surrounding environment. The new cable-supported glass facade for Alice Tully Hall at Lincoln Center is a masterful application of SGF technology to a challenging renovation project. Not only does the facade integrate well with the building (a challenge in any renovation project), it integrates the building with the surrounding streetscape, blurring the boundary between inside and outside and creating a dynamic interplay between the public space and the performance hall.

The cable system design for this project is a formula for transparency: the facade structure dematerialized to a vertical cable inboard to the vertical seam of the glass grid, with a minimal number of point fixings and large laminated clear glass panels with a slender silicone seam providing the weather seal between adjacent glass panels (Figure 16.12). It is easy to envision variations of the formula being applied to many diverse future applications. The Broad Center (Chapter 13) reveals a similar one-way cable strategy applied to a multistory double-skin facade.

FIGURE 16.12 View through the glass wall to the interior café.

Chapter 17

TKTS Booth and Revitalization of Father Duffy Square

The Glass Grandstand
New York City

FIGURE 17.1 Show tickets are sold from a white fiber-glass shell located within the glass enclosure.

FIGURE 17.2 The TKTS glass structure, with its glowing red steps, is located in the heart of Times Square.

General Information	
Year completed	2008
Building size, sq ft (sq m)	18,000 (1672), plaza 2200 (204), booth and grandstand
Building type	Public plaza
Building cost, USD	Approx. 20 million (9.8 million for glass building)
Project Credits	
Owner	Times Square Alliance, Theater Development Fund, and the Coalition for Father Duffy
Architect	Perkins Eastman L. Bradford Perkins, Fellow American Institute of Architects (FAIA), Nicholas Leahy, American Institute of Architects (AIA), Charles Williams, Kazuki Iwamoto, Shang Shuri, Zhanxi Fang, Virginia Shou, Luke Yoo, Amra Kulenovic, Jessica Dorf, Meredith Harmon, Philip Tidwell, Yazmin Crespo, Virginia Shou
Concept architect	Choi Ropiha (winner of the Van Alen Institute Design Competition)
Plaza architect	PKSB Architects PC
Glass structure design consultant and structural engineer	Dewhurst Macfarlane and Partners Tim Macfarlane, Lawrence Dewhurst, Michael Ludvik, David Shea, Peter Arbour, Radhi Majmudar
Design and fabrication engineering	Haran Glass Antony Smith, Neil Davis, Gordon Kerr, Duncan McClean with Innovation Glass, Franz Safford
Mechanical, electrical, plumbing (M/E/P) engineer	Schaefer Lewis Engineers
Construction manager	D. Haller Inc.
General contractor	David Shuldiner
Glass structure installer	David Shuldiner
Custom metal fittings and fabrications, railing components	Laser Fabrications (Edinburgh, Scotland)
Glass supplier	Eckelt Glas GmbH (Austria)
Glass Enclosure	
Structure type	All-glass grandstand
Glass system cost, USD per sq ft (sqm)	463 (4984) [1]
Total glass system member area sq ft (sqm)	9,284 (863) See Table 17.1.
Glass type Metric units specified, imperial units approximated.*	Midwall and front wall load-bearing glass: $2\frac{1}{16}$ in. (52.6 mm) four-ply laminate ½ in. (6 mm) fully tempered (FT) 0.06 in. (1.52 mm) SentryGlas (SG) ½ in. (12 mm) FT 0.06 in. (1.52 mm) SG ½ in. (12 mm) FT 0.06 in. (1.52 mm) SG ½ in. (12 mm) FT

Glass Enclosure (cont.)	
Glass type (cont.)	Stringer beams
Metric units specified, imperial units approximated.*	Spliced assembly of three two-ply laminates
	$1\frac{1}{16}$ in. (25.52 mm) two-ply laminate
	$\frac{1}{2}$ in. (12 mm) FT
	0.06 in. (1.52 mm) polyvinyl butyral (PVB)
	$\frac{1}{2}$ in. (12 mm) FT
	Treads
	$1\frac{1}{2}$ in. (39 mm) three-ply laminate
	starting with top ply:
	$\frac{1}{2}$ in. (12 mm) heat-strengthened (HS) with custom antislip frit
	0.015 in. (0.38 mm) deep red
	0.015 in. (0.38 mm) clear PVB
	0.015 in. (0.38 mm) clear PVB
	0.015 in. (0.38 mm) clear PVB
	$\frac{1}{2}$ in. (12 mm) HS
	0.015 in. (0.38 mm) clear PVB interlayer
	0.015 in. (0.38 mm) red PVB interlayer
	0.015 in. (0.38 mm) white PVB interlayer
	0.015 in. (0.38 mm) red PVB interlayer
	$\frac{1}{2}$ in. (12 mm) HS
	Vanceva® interlayers used for color
	Canopy
	$2\frac{7}{16}$ in. (61.6 mm) four-ply laminate
	$\frac{1}{2}$ in. (12 mm) FT
	0.06 in. (1.52 mm) red PVB
	$\frac{9}{16}$ in. (15 mm) FT
	0.06 in. (1.52 mm) SG
	$\frac{9}{16}$ in. (15 mm) FT
	0.06 in. (1.52 mm) SG
	$\frac{9}{16}$ in. (15 mm) FT
	All low-iron, all heat soaked
Glass system type	Point-fixed bolted
Maximum span, ft (m)	28 (8.5 m)
Deflection criteria	N/A
Project delivery	Design-bid-build; midstream failure of glass contractor resulted in significant delivery strategy modifications

*The measurements are shown in both metric and imperial, with the specified units indicated because they represent the precise dimensions. The conversion of the measurements to the alternate system is an approximation only, based on local industry conventions.

Introduction

The TKTS glass enclosure at Times Square in the heart of Manhattan is said to be the largest load-bearing glass structure constructed to date (Figures 17.1 and 17.2). It is small by facade standards, a mere 2163 sq ft (201 sqm) of plan area, but is utterly unique, highly innovative, and a lesson—rather, an entire curriculum—in the implementation of cutting-edge structural glass technology.

TKTS is operated by the Theater Development Fund and sells discounted tickets for various theatrical, music, and dance events. The original facility at the north end of Times Square (at Father Duffy Square) opened in 1973. Developed in a context of numerous constraints, financial chief among them, the ticket sales operation was housed in an innovative construct of rented construction trailers. And so it remained until it was replaced by a $20 million renovation of the site that included a new facility for TKTS.

Times Square is an irregularly shaped space resulting from the cross-grid meandering of Broadway Avenue as it impedes upon Seventh Avenue at their intersection at 42nd Street. The project site, between 46th and 47th Streets, is an elongated triangle that historically found use only as a public space. The glass enclosure is placed at the north end of the site and mimics the triangular configuration in plan. The steps are 31 ft 9 in. (9.7 m) wide at the base and taper out to 45 ft (13.7 m) at the top, with a vertical rise of 16 ft (4.9 m). The overall plan dimension for first step to top step is 59 ft (18 m). The thusly created ramp is stepped with translucent red glass stairs, forming a kind of glass bleacher or grandstand as the roof of the glass enclosure. The grandstand faces outward to the panorama of big-city lights that comprise the environment of Times Square, an unparalleled urban nexus.

As is often the case with highly innovative building projects, the ultimate success of the TKTS project was as much about the dedication, commitment, and perseverance of an extraordinary building team as it was about innovative design, materials, and processes.

Glass Structure

The entire enclosure consists of laminated glass and includes 26 load-bearing wall panels, 28 stringer beams (14 upper, 14 lower), 27 stair treads, perimeter balustrades above the sidewalls, and 7 canopy panels that cantilever out over the ticket windows (Figure 17.3). The structural diagram is simple, belying the enormous complexity of the actual load transfer design, connection detailing, and fabrication of components. As a fail-safe redundancy measure, a simple steel perimeter frame is designed to engage in the case of catastrophic failure of the glass structure.

Lamination is the primary strategy for employing glass as a structural material. All lamination was originally specified to use the SentryGlas (SG) interlayer by DuPont, a significantly stronger and stiffer material than PVB. Haran, the selected specialty glass subcontractor providing the glass structure, attempted to substitute PVB for all of the SG interlayer. SG is provided as a semirigid panel material in contrast to highly flexible PVB material. The material is different than PVB and requires a different fabrication technique. Glass fabricators unfamiliar with the material must learn to master its use. For this reason, some fabricators are reluctant to use SG, preferring the familiar PVB. At the time that the TKTS material was fabricated in 2006, very few fabricators had experience with SG, and no known fabricators had experience with multi-ply lamination using SG interlayers. The TKTS project required various four-ply panels using SG, some of them quite large and heavy.

Pull tests were part of the glass quality assurance program for the project, and some early tests revealed problems. There were claims that the adhesion characteristics were different between the tin side of the glass (the side that lies on the bed of molten tin during the production of float glass) and the air side and that a different surface preparation was required. With a multi-ply laminate, simply laminating air side to air side was not an option. Some delamination problems surfaced with the large four-ply north wall panels that support the top end of the risers (Figure 17.4). The fabricator worked through the problem, ultimately determining the cause to be very small distortions in the tempered glass. Heat treatment distorts the very flat surface characteristic of annealed float glass. One of the challenges of glass tempering is keeping the glass as flat as possible. The glass produced for TKTS was well within the highest conventional standards for this distortion (roller-wave), but the fabrication team learned that this was not enough; the glass had to be flatter when used in multi-ply laminates. There are few fabricators capable of producing glass this flat. Fortunately, the Austrian fabricator Eckelt is one of them, and the problem was solved.

These developments, however, probably influenced the decision to accept Haran's proposal to use heat-strengthened glass with a PVB interlayer for the stringer beams and treads. The contractor argued that PVB was easier to work with and that the stronger heat-strengthened glass (twice as strong as annealed glass) would compensate for the less strong and less stiff interlayer material. Proof testing was required and is documented below. Since the completion of the TKTS project, SG has experienced significantly increasing use, owing to the important performance advantages it provides. A growing number of glass fabricators are now familiar with the use of SG, and some have even integrated it into their production lines. Perkins Eastman architect Nick Leahy likes the material for its postbreakage performance.

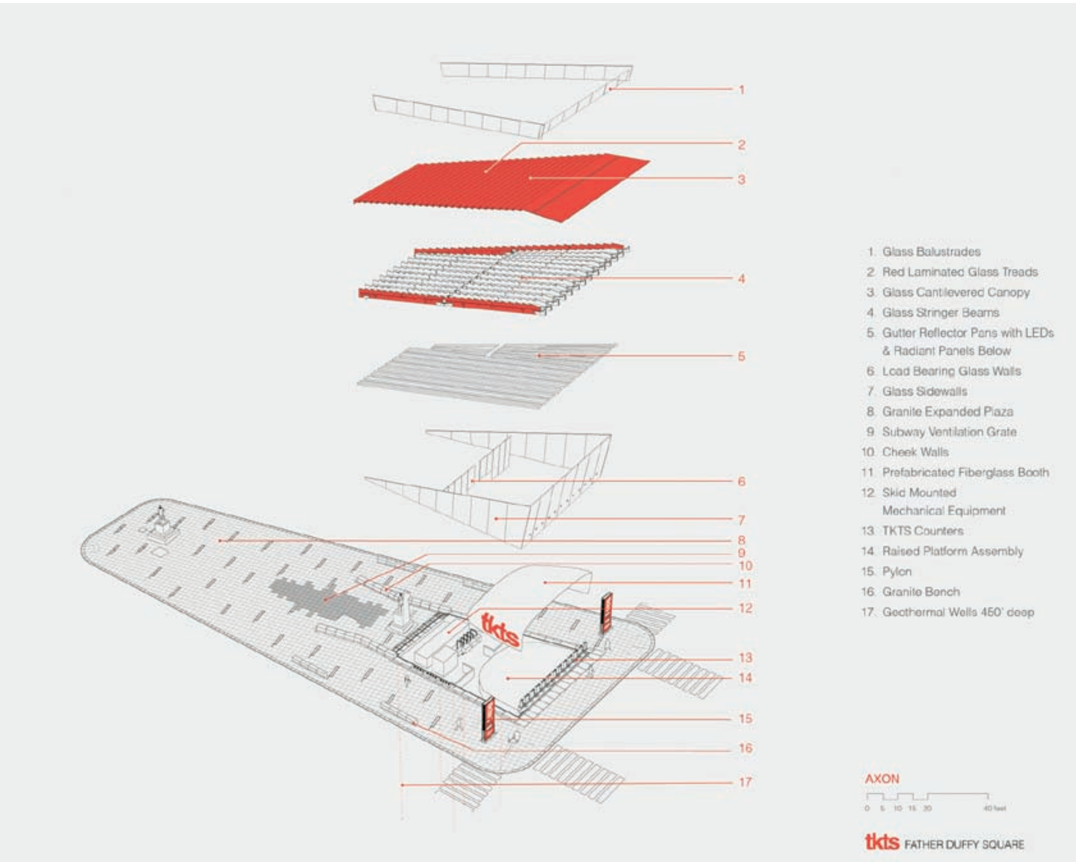


FIGURE 17.3 The layers of structure that comprise the glass enclosure.

Glass Stringer Beams

The 28 ft (8.5 m) long upper and lower stringer beams are the heart of the structural system (Figures 17.5 and 17.6). They are constructed as a bolt-up three-layer composite of overlapping two-ply laminates. The laminates are of $\frac{1}{2}$ in. (12 mm) tempered glass. The beams are too long to produce in single pieces of glass, so a splicing strategy is necessary. The beams are comprised of a sawtooth laminated core that is two lengths of approximately 15 ft (4.6 m) each. Two 15 ft (4.6 m) laminated reinforcing panels straddle either side of the sawtooth core, overlapping the joint between the two sawtooth sections and acting as a splice, referred to as an *overlap splice*. Each laminated section is perforated along its length in two places to receive a pin assembly. With two pins per piece of glass, the system is statically determinate and the forces in each pin can be exactly determined.[2] The laminated segments are also variously notched at their ends to provide for the attachment of stainless steel brackets of various design that accommodate the load transfer from the beams to the supporting structure. Fabrication tolerances are held to a tight 0.08 in. (2 mm) over the length of the beam. Each beam weighs approximately 3000 lb (1361 kg). The perimeter stringer beams are red, like the stair treads, with a red PVB interlayer.

Glass Treads and Risers

If the stringer beams are the heart of the structural system, the treads are the aesthetic heartbeat. Twenty-seven translucent red glass treads span across stringer beams and provide the lateral

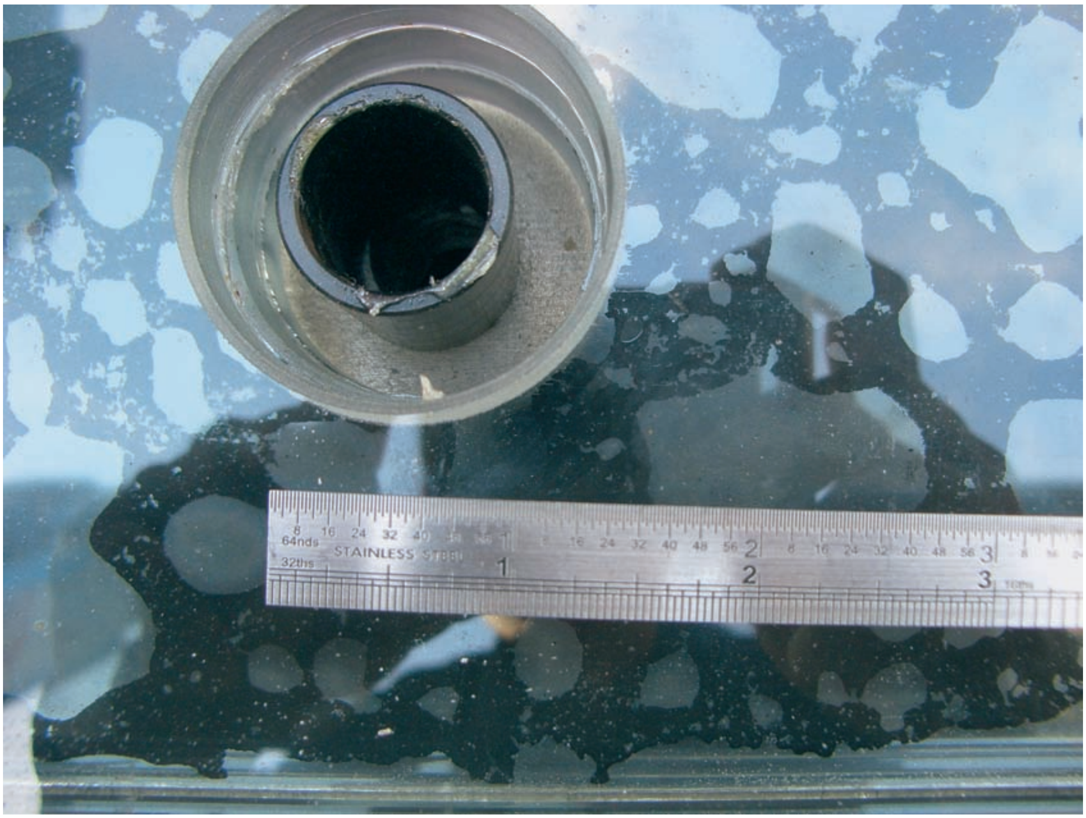


FIGURE 17.4 Delamination was a problem with some of the early laminated glass panels.

bracing for the structure. The treads are a three-ply laminate of heat-strengthened glass with red diffusing PVB interlayers. The treads vary in length, growing longer as they ascend and the bleacher broadens, weighing between 400 and 800 lb (181 to 363 kg) each (Figure 17.7).

The glass area and weights of the TKTS booth are given in Table 17.1.

Achieving the correct color and translucency was one of the bigger challenges for the architect. A multitude of samples were prepared, experimenting with various glass and interlayer materials in combination with various light sources until the correct combination was discovered—a complex layering of thin, clear white and red PVB interlayers—that yielded the desired intensity of glowing red. The color picks up the red from the TKTS graphics and integrates it with the surrounding continuous light show of Times Square. Glass samples and visual mockups are an important part of the glass selection process on many projects; Leahy comments that he has a red glass museum as a TKTS project archive resulting from the search for the right combination of glass and laminate composite.

The treads were originally to be fabricated from annealed glass and laminated with SG. This is the technique used for the stair treads in the Apple stores and provides certain advantages: the glass edges can be machine worked after lamination, easing the problem of layer alignment in multi-ply glass

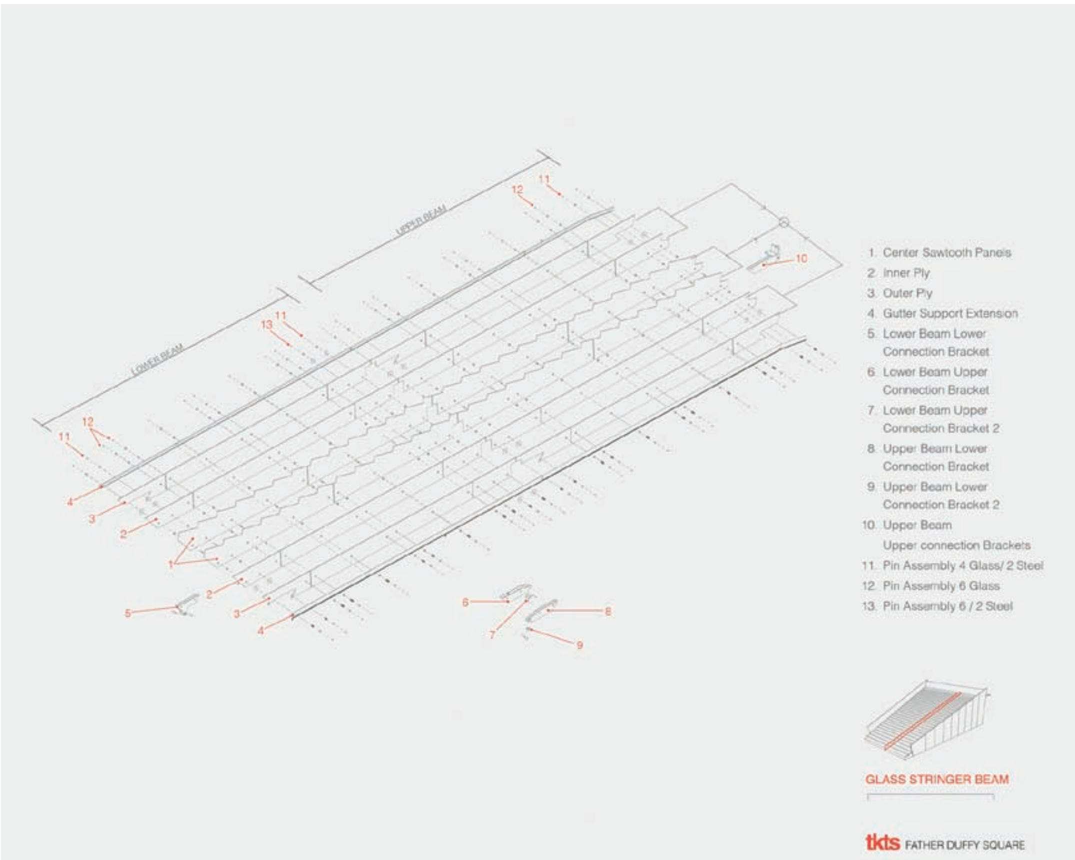


FIGURE 17.5 Exploded view of the glass stringer beams.

FIGURE 17.6 The glass beams were fully assembled by the fabricator of the laminated glass panels and shipped in 30 ft (9.1 m) lengths to the job site.

FIGURE 17.7 The top tread. Note the metal nosing.

TABLE 17.1 TKTS Glass Area and Weights[3]

Element	Area sq ft (sqm)	Number	Plies	Total Area sq ft (sqm)	Thickness per Ply in. (mm)	lb/sq ft (kg/sqm)	Weight lb (kg)
Side walls	754 (70)	2	2	3016 (280.2)	0.5 (12)	6.49 (31.7)	19,574 (8879)
Front wall	959 (89.1)	1	4	3836 (356.4)	0.5 (12)	6.49 (31.7)	24,896 (11,293)
Midwall	315 (29.3)	1	4	1260 (117.1)	0.5 (12)	6.49 (31.7)	8177 (3709)
Beams							
Center pieces	67 (6.2)	25	2	3350 (311.2)	0.5 (12)	6.49 (31.7)	21,742 (9862)
Outer laminations	60 (5.6)	25	4	6000 (557.4)	0.5 (12)	6.49 (31.7)	38,940 (17,662)
Risers	518 (48.1)	1	2	1036 (96.2)	0.0156 (4)	2.02 (9.9)	2093 (949)
Treads	2163 (200.1)	1	3	6489 (602.8)	0.5 (12)	6.49 (31.7)	42,114 (19,102)
Canopy	323 (30)	1	3	969 (90)	0.625 (16)	8.11 (39.6)	7859 (3565)
	323 (30)	1	1	323 (30)	0.5 (12)	6.49 (31.7)	2096 (951)
Totals	9284 sq ft (863 m)			26,279 (2,441)			177,444 (80,487)

Typical front wall panel weight: 6 ft 10 in. × 16 ft 6 in. × 6.49 psf × 4 ply = 2927 lb (1328 kg)

Typical beam weight: 374 × 6.49 = 2427 lb (1101 kg)

lamination and making it easier to achieve a monolithic look at the glass edge; in addition, the break behavior is more favorable than that of tempered glass. A mere chip to a tempered edge will often cause the entire lite to instantly break into nugget-size pieces, losing most of the structural properties tempered glass brings to a laminated panel. Annealed glass, while not as strong as tempered glass, typically exhibits a more localized break pattern of much larger shards that continue to provide strength to a laminated panel. A compromise measure is the use of heat-strengthened glass. While it is only half as strong as tempered glass, it is twice as strong as annealed glass. It cannot be edge-worked after heat treatment, but its break pattern is much closer to that of annealed glass. Haran proposed to substitute the SG interlayer for the annealed treads for heat-strengthened material with PVB. After the satisfactory completion of a break test requested by the architect (described in the following section on testing), the substitution was approved.

Load-bearing Wall Panels

These panels include a midspan wall support for the stringer beams within the enclosure. These are 2 1⁄16 in. (52.6 mm) thick, four-ply, ½ in. (12 mm) low-iron glass laminated with SG interlayer material. At the front of the structure are the north wall ticket booths. Here the largest glass panels in the project are found, reportedly the heaviest laminated glass panels ever manufactured at the time: seven panels measuring 16 ft 8 in. tall by 6 ft wide, each weighing nearly 3000 lb (1361 kg) (Figure 17.8). The glass fabricator had to reinforce their entire production line to produce the panels, including the roller conveyor systems. Two panels were dropped on site during installation, apparently too heavy for the massive suction-cup lift used to move them. With the same four-ply makeup as the midspan walls, these panels have a round hole in all four plies through which money and tickets are exchanged. There are also holes at the top of the panels to which rotule connections are fixed, supporting the stringer beams at their upper end. The cantilevered canopy panels are also supported at the top of these panels.

The east and west side walls are a two-ply laminate, with the tops cut to angle down with the bleacher steps, nine panels to either side with each panel becoming progressively smaller as

FIGURE 17.8 The ticket wall glass panels are 6 ft (1.8 m) wide and nearly 17 ft (5.1 m) tall, and weigh nearly 3000 lb (1361 kg). The glass stringer beams are supported from a rotule connection at the top of the panel.

the steps approach grade. The side walls only support the lateral wind and the dead load of the balustrades.

Cantilevered Canopy

The architect believes the glass canopy at the front of the project over the ticket booth windows to be the longest single-panel glass cantilever to date, at just over 6 ft (1.8 m). The canopy is simply a 2 in. (51 mm) thick four-ply laminated glass panel supported along a single edge using a stainless steel clamp plate (Figures 17.9 and 17.10).

Balustrades

The balustrades surround the elevated sides of the stepped roof structure. They are a two-ply tempered laminate of ½ in. (12 mm) low-iron glass with a PVB interlayer.

Edge Treatment

Edges are an important consideration when using glass in structural applications. Improperly cut or machined edges can significantly weaken a glass panel, with microscopic cracks and fissures that can potentially propagate under applied loads. Edges for glass to be used in structural applications are usually specified as ground and polished to remove as many of these microscopic cracks as possible. Glass edges are also susceptible to impact loads in certain applications, stair treads among them. The anticipated heavy public usage of the grandstand made the exposed glass edges

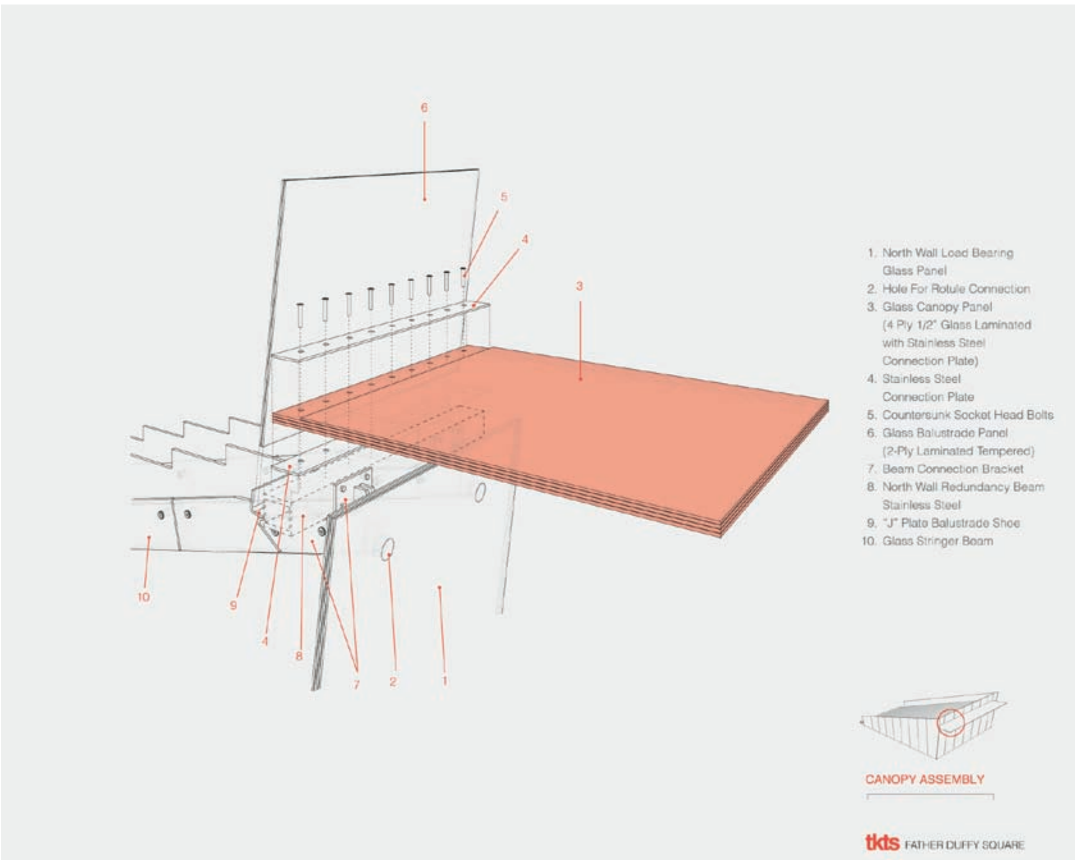


FIGURE 17.9 The four-ply glass canopy cantilevers out 6 ft (1.8 m) from the top of the ticket wall.

a particular concern, and the strategy was to use metallic protection in key localized areas.

Treads: A $\frac{1}{2}$ by $\frac{3}{4}$ in. (12 by 19 mm) stainless steel nosing is silicone glued to the top front edge of the treads. The top ply is set back from the tread edge to accommodate the nosing.

Load-bearing walls (middle and front): A blade of stainless steel is inserted into the joint between panels and left slightly protruding from the face of the glass to protect against accidental impacts to the glass edges.

Balustrades: The leading edge of the glass balustrades has a stainless steel cap detail.

Connections

While the strategy employed to strengthen glass for use as a structural member involves heat treating and laminating, that is the easy part. The real challenge comes in detailing the connections between the glass structural members and perimeter anchors to ensure efficient load transfer. The intent is to avoid concentrated point loads to the greatest extent possible and to minimize bending loads. All of the structural glass members in the grandstand were ultimately designed around the connections. The primary structural details are along the stringer beams and include the base connection, the midwall connection, and the rotule connection at the top of the steps. All three are illustrated and discussed in Chapter 6.

Facade Concept Development

The concept derived from a 1999 winning competition entry. The Australian firm Choi Ropiha was selected as the winner from among 643 entries. The concept included the red stairway-bleacher

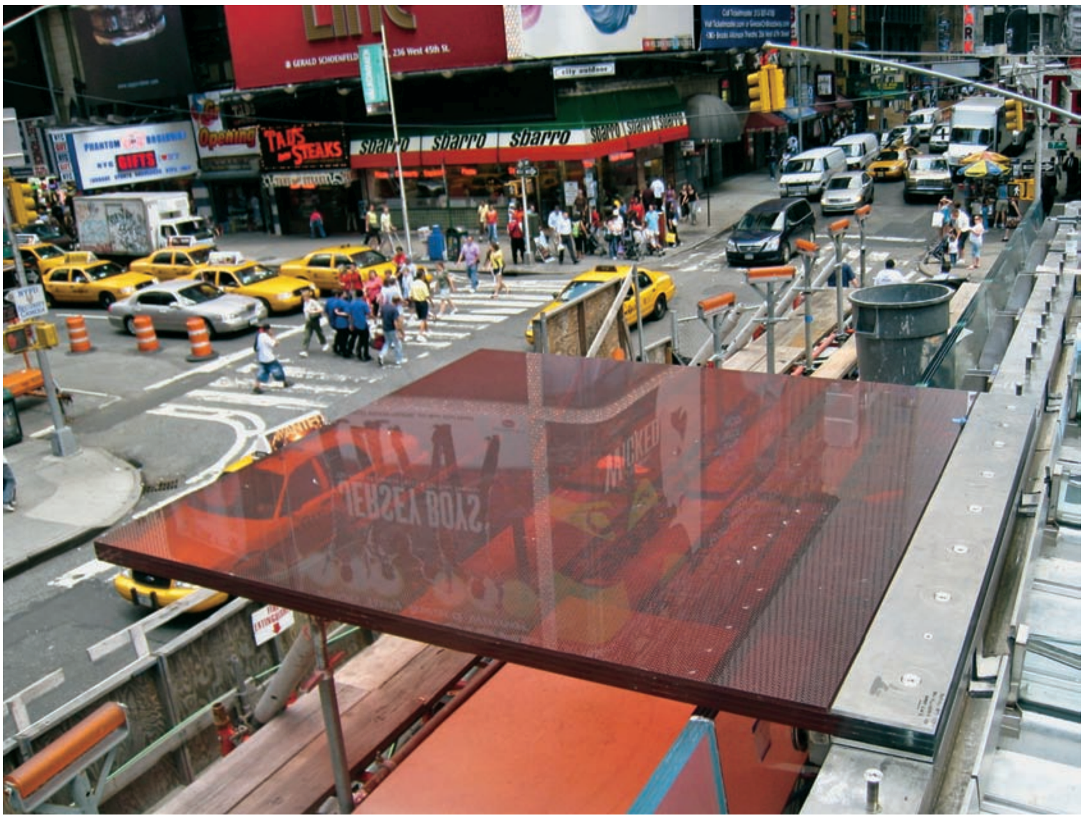


FIGURE 17.10 The first canopy panel is installed. Note the connection detail.

form with the TKTS booth tucked underneath. The structural concept was for a steel frame supporting red stair planks. The project languished for a couple of years until Perkins Eastman was commissioned to do a feasibility study. Given the freedom to explore divergent concepts, architect Leahy recognized the brilliance of Choi Ropiha's concept but reconceived the materials and technique, making the leap to an all-glass construct enclosing the freestanding lozenge-shaped fiberglass TKTS ticket booth. Leahy envisioned a twenty-first-century city landmark using twenty-first-century materials and technology. The long red glass stair treads cover the roof of the enclosure and, especially when lit from below at night by light-emitting diodes (LEDs), appear to "float, hover and hum," in the words of Leahy,[4] amid the visual tumult of Times Square.

Prefabrication was also central to the concept, a response to the constrained site, which necessitated as much work as possible to be accomplished off site. Structural glass facade (SGF) technology is optimally suited to this approach to construction. The glass structure was conceived as a kit of parts that could be entirely fabricated in the factory and shipped to the site for assembly.

The structural concept was facilitated by the involvement of structural and facade engineering firm Dewhurst Macfarlane and Partners immediately after the culmination of the feasibility study. Key material suppliers were also identified and brought into the project team early on.

Testing

Ad hoc design mockups were built early on by the architect and other stakeholders in the absence of any significant up-front research and development funding. Visual mockups and samples were vital in determining the combination of low-iron glass, and colored and diffusing interlayers, to yield the desired color and glow of the stair tread glass.

Once the project was underway, an ongoing testing program included pull testing to verify splice detailing (Figure 17.11), destructive testing of load-bearing panels and treads, pull tests on the balustrades, and shear and adhesion testing of the silicone.

Haran proposed a substitute for the specified glass and interlayer materials for the treads, as described above. The intent was to substitute, for the three-ply tempered glass and SG interlayer, heat-strengthened glass and a PVB interlayer. A proof test was proposed to demonstrate compliance with relevant performance requirements. Dewhurst Macfarlane developed the testing criteria, which were summarized by Haran as "The total fracture of all three layers of heat-strengthened glass at both the point of support and the middle of a spanning element."[5] The stipulated requirements were that after being broken, the tread would be point loaded to 250 lb (113 kg), first on the cantilever section at the end of the tread and then on the midspan. The load was to be maintained for at least 60 seconds, and deflections were to be measured. The report states that it took "30 heavy blows" to break all three layers

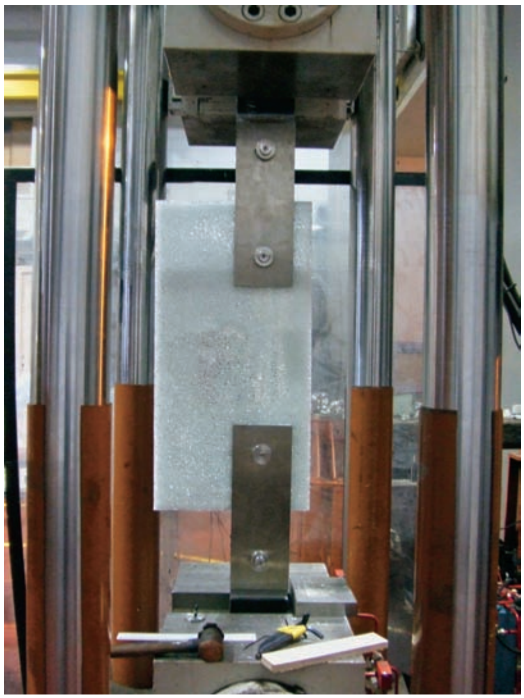


FIGURE 17.11 Pull testing was conducted to determine the capacity of the laminated panels.

of glass. The sample used for the test showed no apparent sign of deformation, and there was no visible deformation when the load was removed. The substitution was ultimately approved.

Fabrication

The large glass sizes and demanding laminating technique limited the potential suppliers for the glass components to a mere handful of fabricators, mostly located in Europe. The Austrian glass fabricator Eckelt, with a long history of pioneering work in structural glass applications, was selected as the fabricator for the TKTS project. They first machined the glass as required, ground and polished the edges, and then tempered the glass. Eckelt also completely assembled the stringer beams for the project, including the installation of all of the stainless steel pins and end fittings (Figure 17.12). The beams were then shipped to the site in 30 ft (9.1 m) lengths, crane lifted, and set into place.

Fabrication drawings were generated directly from a sophisticated three-dimensional computer model built with Autodesk® Inventor® software.

Project Delivery

The architectural firm was cognizant of the innovative nature of the glass enclosure they were promoting, and of the conservative tendency of the New York City construction industry. It was also aware of the lack of a significant budget for research and development, and understood that the structural solutions needed to support the concept would have to be found within the context of a unique construction project. The response was to work long and

FIGURE 17.12 The perimeter stringer beams are prepared for assembly at the fabricator's plant.

hard to build a consensus and raise money for the project. Ultimately, it was the project's uniqueness that inspired the necessary interest and support, building a constituent base that started with the key client group and reached all the way to the city's mayor.

Leahy also credits much of the success of the project to the early involvement of leading specialists. "As soon as we could, right after the feasibility study, we added a structural engineer who is world renowned for glass engineering to the team: Dewhurst Macfarlane and Partners," Leahy said. "We refined the concept and design together." Contractors and material suppliers were recognized as equally important. Leahy continued, "Early on we kept a short list of the contractors and suppliers worldwide who we felt had the true capabilities to do this, visiting their shops and trying to get their input as much as possible as early as possible."[6] A comprehensive testing program, as discussed above, and a peer review were also key components of this project's well-conceived delivery strategy.

In spite of an intensive and comprehensive prequalification process, the selected specialty contractor became insolvent during the project and was unable to complete its work. The project at this point was halfway through shop drawings, and fabrication activities were well underway. A scramble immediately ensued whereby the architect and construction manager went on tour, visiting critical suppliers, encouraging them to continue with their work, and assuring them of compensation. While this resulted in significant disruption, the project team came together in heroic fashion to mitigate the impact, with the general contractor ultimately assuming direct responsibility for the installation of the glass structure. Leahy credits the project team for the ultimate success of the project. "The fact that it actually got built is a testament to the energy and ingenuity of everybody who got involved, from the suppliers to the installers to the design team," claims Leahy; "they all felt that this was a unique project and something worth building."[7] Innovative projects often succeed in overcoming adversity because of the extraordinary commitment they inspire in project participants.

Installation Strategy

The installation of the glass structure was complex enough in itself, given the vulnerable nature of the large, heavy glass components and the extremely tight tolerances required for fit-up, but the cramped site amid one of the most dense urban environments on earth, the complex integration of the various systems, and the demanding coordination required between trades resulted in extreme installation challenges. In spite of extensive preplanning, a great deal of creative problem solving and out-of-the-box thinking was required on site throughout the installation process. Among the challenges was determining how to lift the unwieldy, heavy glass pieces without overstressing the material. Many of the glass panels were required to be set in position with only millimeters of clearance between adjacent panels and the fiberglass booth, which had to be positioned before the glass enclosure could be built around it (Figures 17.13 and 17.14).

The glass structure required a significant amount of on-site grouting, as discussed in Chapter 6. This is a difficult process in the best of circumstances, and the building site seldom presents anything close to favorable conditions. Detail design involving grouting should fully anticipate and accommodate the installation method.

Strategies for Sustainability

A novel hydrothermal system was developed for the project, powered by five wells drilled 450 ft (137.2 m) into the bedrock below Times Square. Consistent with the prefabrication strategy, the mechanical equipment was tightly bundled on a skid and crane set into position before the glass enclosure was constructed over it. The system is used to heat radiant panels that warm the stair treads, preventing the accumulation of ice and snow.

FIGURE 17.13 The first ticket wall panels arrive at the site.

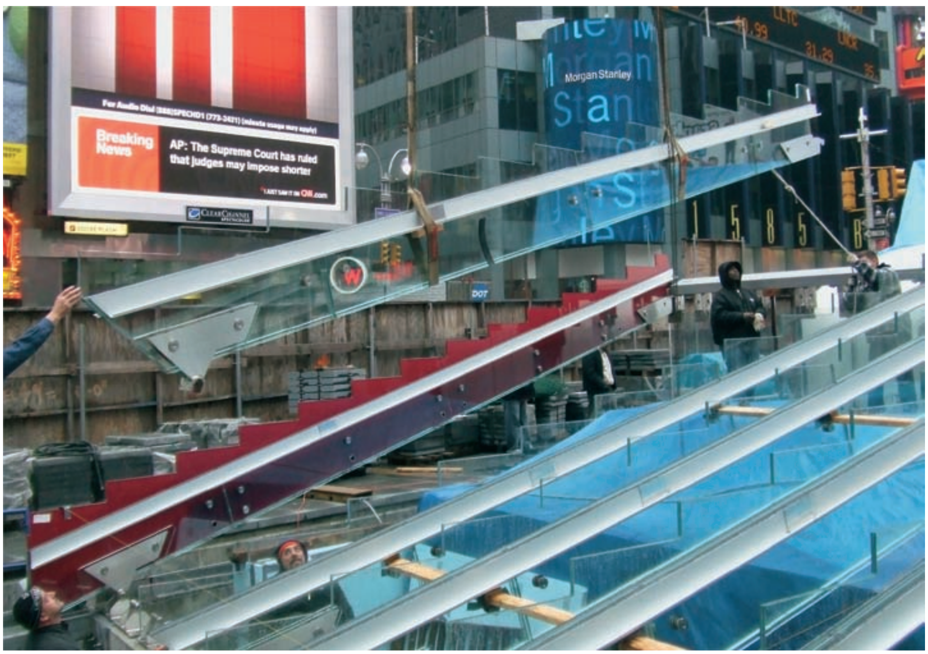


FIGURE 17.14 A lower stringer beam being set in position.

Summary

A high percentage of SGF projects incorporate some level of innovation. As the technology diffuses into the marketplace this level will inevitably decrease, but there will always be projects intent upon advancing the state of the art, projects that leading-edge practitioners of SGF technology are particularly fond of. The all-glass enclosure for TKTS is just such a project (Figure 17.15). This case study does no more than scratch the surface of this epic undertaking. Highly innovative projects present very special considerations, calling for well-thought-out project delivery strategies and management practices. The strategies and practices employed by the TKTS project team ultimately supported them in successfully overcoming the numerous obstacles they encountered. This project provides a useful road map to negotiating the risks inherent in innovative projects, and an informative and valuable example of managing the process of innovation.

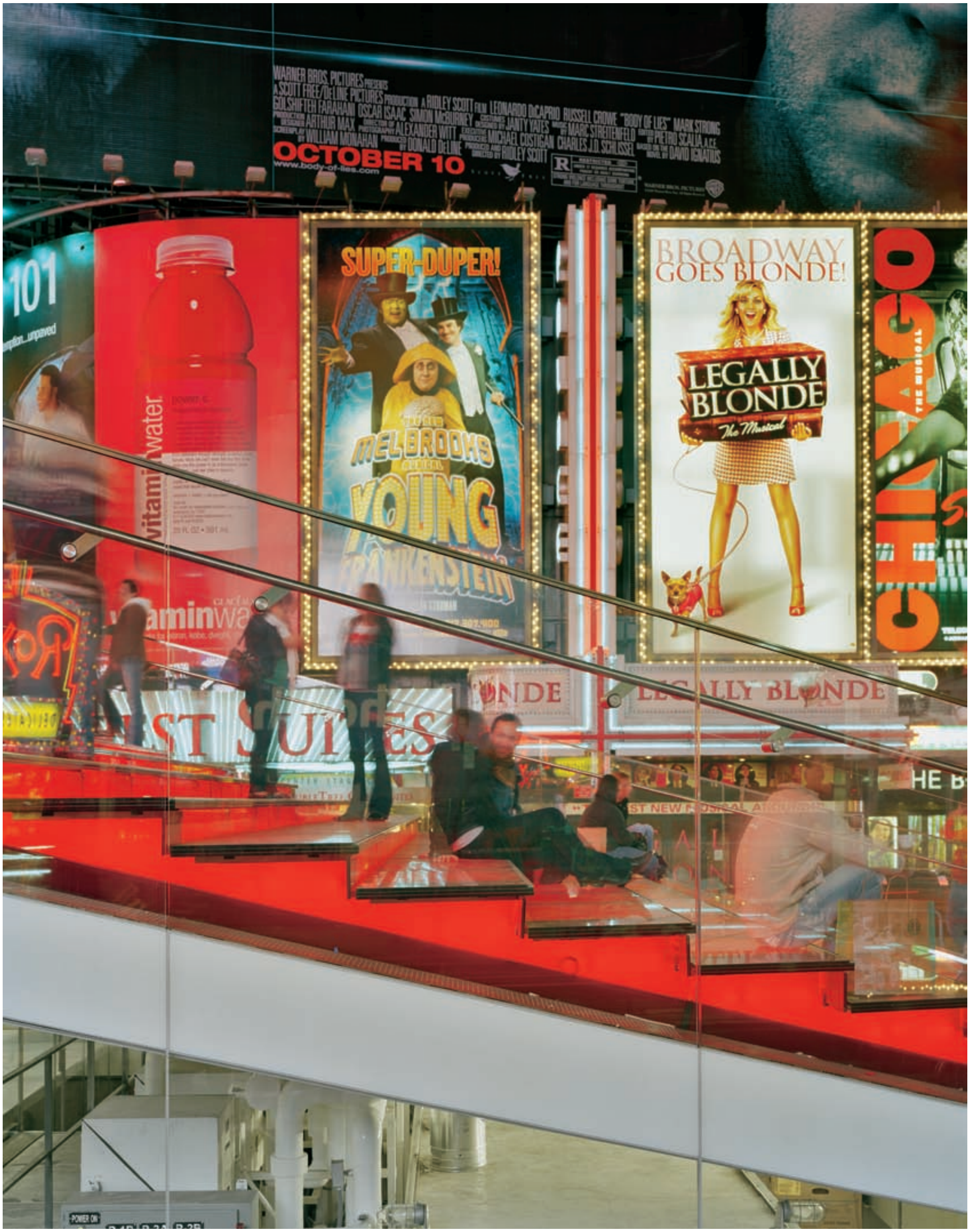


FIGURE 17.15 The glowing red of the illuminated treads and risers blends perfectly with the unique cityscape of Times Square.

Introduction

1. A. Compagno, *Intelligent Glass Facades* (Birkhauser, Basel, 1999), p. 16.
2. http://www.sbp.de/en#build/show/16-Berlin_Main_Station

Chapter 1

1. M. Wigginton, *Glass in Architecture* (Phaidon, London, 1996), p. 6. This is an excellent and comprehensive book on the subject of glass in architecture, highly recommended to anyone interested in glass and its use as an architectural material.
2. S. Fleming, *Roman Glass: Reflections on Cultural Change* (University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, 1999).
3. There are certain notable exceptions, primarily involving the glass roofs of train halls and shopping arcades such as Pennsylvania Station (New York, 1905–10, McKim, Mead and White) and the Galleria Vittorio Emmanuele II (Milan, 1865–7, Giuseppe Mengone), but these represent unique building forms that typically interface rather than integrate with the adjacent architecture.
4. Ironically, Alastair Pilkington was no relation to the Pilkington brothers of glass production fame, but an employee of their glass company of the same name, currently one of the top four glass producers in the world. http://www.pilkington.com/pilkington-information/about+pilkington/education/sir+alastair+pilkington.htm (accessed 5 May 2010).
5. See the Richard J. Klarcheck Information Commons, the Vivian and Seymour Milstein Family Heart Center, and the Eli and Edythe Broad Center for Regenerative Medicine and Stem Cell Research case studies in Chapters 14, 15, and 13, respectively.
6. R. Saxon, *Atrium Buildings: Development and Design* (Van Nostrand Reinhold, New York, 1983).
7. N. Rappaport, *Support and Resist* (Monacelli Press, New York, 2007).
8. SentryGlas, a relatively new interlayer by DuPont, is used in many of the case studies included in this book.
9. Wiggington, *Glass in Architecture*, p. 102.
10. Ibid., p. 110.
11. Ibid., pp. 110–15.
12. Glass fin systems are sometimes referred to as *glass mullion systems*; the fin perpendicular to the glass plane on the glazing grid can be interpreted as a structural mullion.
13. See Wigginton, *Glass in Architecture*, for a case study of this project: pp. 110–15.
14. See ibid. for a case study of this project: pp. 132–7.
15. This is the project in which Martin Francis of RFR brought in Tim Eliassen, a master of rod rigging systems for high-performance sailing yachts, to assist with the tensile systems for the pyramid structure. Eliassen later went on to found TriPyramid Structures, becoming an influential enabler of SGF technology (see pages 16–17).
16. See Wigginton, *Glass in Architecture*, for a case study of this project: pp. 126–31.
17. Based on two decades of watching the man work and a telephone interview conducted on 28 April 2010.
18. Nick Leahy, Perkins Eastman Architects. Taken from written responses to questions from *I.D. Magazine* by Leahy in preparation for an interview used as the basis for an article in *I.D. Annual Design Review 2009*. Provided to the author by Nick Leahy.
19. Cable mullion systems are often referred to as one-way cable nets. While the term is intuitively descriptive, it is, unfortunately, not technically accurate, as the one-way system does not form a true net. The cable mullion could have been categorized as a linear system in Table 1.2, but it shares more attributes with cable systems.

Chapter 2

1. M. Bell and J. Kim, eds., *Engineered Transparency—The Technical, Visual, and Spatial Effects of Glass* (Princeton Architectural Press, New York, 2009).

2. Viracon,"Fully Tempered," 2008, http://www.viracon.com/index.php?option=com_content&view=article&id=113:fully-tempered&catid=64:heat-treated-info&Itemid=207 (accessed 12 March 2008).
3. Email exchange shortly after Ludvik's return from the "Challenging Glass" conference in Delft, 2 May 2010.
4. See the Testing section of the LA Live case study (Chapter 7) for an example of an elaborate visual mockup.
5. GANA, *Specifier's Guide to Architectural Glass*, available as a free download from http://www.glasswebsite.com/publications/ (accessed 25 May 2010).
6. GANA produces the *GANA Glazing Manual*, currently in its 50th edition, as a resource for the glazing community. It includes additional information regarding the glazing methods briefly described here.
7. P. Loughran, *Falling Glass: Problems and Solutions in Contemporary Architecture* (Birkhäuser, Basel and Boston, 2003).
8. The Vivian and Seymour Milstein Family Heart Center and the Eli and Edythe Broad Center for Regenerative Medicine and Stem Cell Research case studies (Chapters 11 and 13, respectively) both include examples of SGF spanning approximately 16 ft (4.9 m) from floor to floor.
9. P. Rice and H. Dutton, *Structural Glass* (E & FN Spon, New York, 1995).

Chapter 3

1. See the Richard J. Klarcheck Information Commons, Loyola University case study (Chapter 14).
2. M. Melaragno, *Simplified Truss Design* (Van Nostrand Reinhold, New York 1981).
3. P. Rice, *An Engineer Imagines*, 2nd ed. (Artemis, London, 1998).
4. G. Schierle, *Structure and Design* (University Readers, San Diego, CA, 2008), p. 324. Schierle credits Swedish engineer David Jawerth with developing the first cable truss, the precursor to those widely used in the 1960s by Lev Zetlin and others. Rice may have been the first to adapt this structural form for application in the building facade.
5. P. Rice and H. Dutton, *Structural Glass* (E & FN Spon, New York, 1995).
6. Schierle, *Structure and Design*, p. 324.
7. Ibid.

Chapter 4

1. G.G. Schierle, *Structure and Design* (University Readers, San Diego, CA, 2008).
2. The Crystal Cathedral, discussed in Chapter 1, is a welded space frame structure.
3. Meneringhausen started Mero, now Mero-TSK International GmbH & Co. KG, in Germany in the 1930s. The company is active in the United States as Mero Structures, Inc., acting as a space frame and specialty structures provider. http://www.mero-structures.com/
4. J. Chilton, *Space Grid Structures* (Elsevier, Oxford, 2000).
5. For examples, see the Yas Island Racetrack Hotel in Abu Dhabi, the Zlotey Tarasy in Warsaw, the British Museum in London, and the Ion Orchard Shopping Center in Singapore.
6. Schierle explains in *Structure and Design* (p. 294) that Walter Bauersfeld built the first geodesic dome in 1922 for a planetarium in Jena, Germany. Buckminster Fuller developed and patented his geodesic dome in 1940.
7. J. Coplans, "Interview with Kenneth Snelson," *Artforum*, March 1967, http://www.kennethsnelson.net/icons/struc.htm (accessed 16 February 2008).
8. R.B. Fuller, "Tensile-Integrity Structures," U.S. Patent 3.063.921 (1962), reprinted in *The Patented Works of R. Buckminster Fuller* St. Martin's Press, (New York, 1983), p. 180.
9. R. Motro, *Tensegrity* (Koban Page Science, London, 2003), pp. 17–19.
10. T. Robbin, *Engineering a New Architecture* (Yale University Press, London, 1996).
11. Wang Bin Bing refers to this structure type as *cable-strut* systems in his book, *Free-standing Tension Structures* (Taylor and Francis, London, 2004). He has undertaken extensive research on this structure type.

Chapter 5

1. W. Nerdinger, *Frei Otto: Complete Works* (Birkhäuser Architecture, Basel, 2001).
2. A. Holgate, *The Art of Structural Engineering: The Work of Jorg Schlaich* (Edition Axel Menges, Stuttgart/London, 1997).
3. A. Mazeika and K. Kelly-Sneed, "Getting Started with Cable-net Walls," *Modern Steel Construction*, April 2007, pp. 55–60.
4. ASI Advanced Structures acted as a design and engineering consultant to the Chinese facade contractor Yuanda and interfaced with SOM's San Francisco office during design development; this arrangement continued through completion of construction.
5. M. Sarkisian, N. Mathias, and A. Mazeika, "Suspending the Limits," *Civil Engineering*, November 2007, http://www.asce.org/Content.aspx?id=28969&css=print (accessed 9 October 2010).

Chapter 6

1. One such book is *Glass Structures* by Jan Wurm (Birkhauser, Basel, 2007).
2. Viracon, "Heat-treated Glass," 2008, http://www.viracon.com/heatTreated.html (accessed 12 March 2008).
3. Pilkington architectural memo, "Distortions in Tempered Glass," n.d., http://www.wwglass.com/PDF/Distortions_in_tempered_glass.pdf (accessed 30 March 2008).
4. Viracon, "Heat-soak Testing," 2008, http://www.viracon.com/heatSoaked.html (accessed 12 March 2008).
5. DuPont, "SentryGlas® Architectural Safety Glass Interlayer," product brochure, 2009. http://www2.dupont.com/SafetyGlass/en_US/assets/pdfs/sentryglas_brochure.pdf (accessed 5 April 2010).
6. Compiled from telephone interviews and email exchanges with Nick Leahy, Michael Ludvik, and Franz Safford in May 2010 and an extensive review of over 2000 photographs documenting this remarkable project. Any errors or misinterpretations belong solely to the author.

Chapter 7

1. Enclos acquired the assets and personnel of ASI during the course of this project and launched the Advanced Technology Studio, located in Los Angeles, which is focused on the research and development of advanced facade technology.
2. Cristacurva, Guadalajara, Mexico, http://www.cristacurva.com.
3. Southwall Technologies, "XIR Laminated Glass," 2010, http://www.southwall.com/southwall/Home/Commercial/Products/XIRLaminatedGlass.html (accessed 21 April 2010).

Chapter 8

1. Approximate initial construction contract of 1 billion USD plus estimated change orders of 300 million USD.
2. Approximation provided by ASI Asiatic. The total MTB facade contract value was approximately 30 million USD. This includes approximately 5 million USD relating to changes and delays.
3. A subsequent addition to the Hong Kong International Airport terminal building reestablished it as larger, at over 6 million sq ft (570,000 sqm). Both the Beijing Capital International Airport Terminal 3 and the Dubai International Airport Terminal 3 have likely surpassed both Hong Kong and Bangkok, certainly in total floor area, but the single enclosure size of these terminals is unclear. For a list of buildings with the largest floor area, see http://en.wikipedia.org/wiki/List_of_largest_buildings_in_the_world#Largest_area.
4. H. Jahn, W. Sobek, and M. Schuler, *Suvarnabhumi Airport Bangkok, Thailand* (Avedition, Ludwigsburg, Germany, 2007).
5. W. Sobek, "Suvarnabhumi International Airport Bangkok—Structure and Form Finding," *Detail Magazine*, July 2006, pp. 818–19.
6. R. Green and J. Perry, "Suvarnabhumi Bangkok International Airport Design Influences," Facade Doctor, The Façade Group, July 31, 2007, http://test2.facadedoctor.com/?p=99 (accessed 16 April 2009).
7. *Guyed struts, braced pylons*, and *trussed posts* are alternative terms for this structural assembly. The term *mast truss* is used here to relate the assembly to the structure types discussed in the book, the assembly being topologically similar.
8. Green and Perry, "Suvarnabhumi Bangkok International Airport Design Influences."
9. Ibid.
10. Jahn, Sobek, and Schuler, *Suvarnabhumi Airport Bangkok, Thailand.*
11. R. Green and J. Perry, "The Use of Heat Strengthened Laminated Glass in Bolted Applications at Suvarnabhumi Bangkok International Airport," Facade Doctor, The Façade Group, July 30, 2007, http://test2.facadedoctor.com/?p=82 (accessed 16 April 2009).
12. Spontaneous breakage of tempered glass results from the presence of the nickel sulfide contaminant in the glass melt. Its incidence in Western markets has been extremely low, and it has been virtually eliminated through the now common practice of heat soaking tempered glass. It is possible that the presence of the contaminant is more common among Asian sources of glass supply.
13. DuPont publication, "Laminated Safety Glass News," August 2006.
14. Jahn, Sobek, and Schuler, *Suvarnabhumi Airport Bangkok, Thailand*.
15. Green and Perry, "Suvarnabhumi Bangkok International Airport Design Influences."
16. Ibid.
17. W. Kessling, H. Stefan, and S. Matthias, "Innovative Design Concept for the New Bangkok International Airport (NBIA)," presented at Transsolar Energietechnik, Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, 2004.
18. Ibid.

Chapter 9

1. C. Pearson, "Broad Stage," *Architectural Record*, February 2009, http://archrecord.construction.com/projects/bts/

archives/perform/09_BroadStage/default.asp (accessed 15 May 2010).

2. State of California, 2007, CA.gov state architect, http://www.dsa.dgs.ca.gov/PlanRev/overview.htm#G (accessed 28 February 2010).

Chapter 10

1. This case study is a modified version of a paper titled "Structurally Transparent Juxtaposition," by Mic Patterson and Jeff Vaglio, presented to the BESS conference at the California Polytechnical Institute, Pomona, 1 May 2010. The version included here is presented with the knowledge and consent of the authors.
2. As listed on the architect's Web site. http://www.richardrogers.co.uk/render.aspx?siteID=1&navIDs=1,4,23,1268 (accessed 9 October 2010).
3. Enclos acquired the assets and personnel of ASI during the course of this project and launched the Advanced Technology Studio, located in Los Angeles, which is focused on the research and development of advanced facade technology.
4. Rogers Stirk Harbour + Partners Web site, http://www.richardrogers.co.uk/render.aspx?siteID=1&navIDs=1,4,25,1271,1273 (accessed 18 May 2010).

Chapter 11

1. TriPyramid test report, "TP4475-NYPH Short Strut Dead Load Support Test," prepared by Nate White and Michael Mulhern, 25 June 2007.

Chapter 12

1. J.F. Blassel, A. Pfadler, "La Gare de Strasbourg," Construction Métallique, n°1, 2008, pp. 15–36. This article details many aspects of the project, including the method of generating the geometric form. See also N. Baldassini, "Glazing Technology: The Hidden Side of Free-Form Design," from the conference proceedings of Advances in Architectural Geometry (Vienna, Austria, 13–16 September 2008) for more information on the geometrical form generation of this and other projects. http://www.epab.bme.hu/oktatas/2009–2010–2/v-CA-B-Ms/FreeForm/Geometry/AAG_2008.pdf (accessed 10 October 2010).
2. N. Baldassini, N 2008. "Hidden and Expressed Geometry of Glass," in *Challenging Glass*, ed. F. Bos, C. Louter, and F. Veer (IOS Press, Delft, the Netherlands, 2008).
3. CSTB, "Glass Cladding with ATEx for Strasbourg Station," http://www.cstb.fr/actualites/english-webzine/anglais/january-2008-edition/glass-cladding-with-atex-for-strasbourg-station.html (accessed 22 April 2010).
4. The installation sequence described here was derived from an analysis of photographs provided by Seele and found through various online resources, and was provided to Seele for comment but was not formally confirmed.

Chapter 14

1. This case study is derived from a similar case study for the same project titled "Double-Skin Cable-Net Facade Case Study: Loyola Information Commons" by J. Kirchhoff J. Vaglio M. Patterson, and D. Noble. This case study was prepared for and presented at the BESS conference at the California Polytechnical Institute, Pomona, in April 2010. The version included here is presented with the knowledge and consent of the authors.
2. General building information provided by architect Solomon Cordwell Buenz.
3. Enclos acquired the assets and personnel of ASI during the course of this project and launched the Advanced Technology Studio, located in Los Angeles, which is focused on the research and development of advanced facade technology.

Chapter 15

1. Enclos acquired the assets and personnel of ASI during the course of this project and launched the Advanced Technology Studio, located in Los Angeles, which is focused on the research and development of advanced facade technology.
2. Some of the material included in this case study derives from a series of discussions and email exchanges between the author and Dannettel during May 2010.
3. ASI Advanced Structures Inc. was awarded the contract for the cable facade and was acquired by Enclos Corp. during the course of this project. Enclos provided project management and installation services for the cable wall, as well as complete design-build services for the entire building facade program for the Newseum project.

Chapter 17

1. Deriving meaningful costing information in the context of SGF technology is challenging for such a unique glass structure as the TKTS enclosure. The following was developed with the help of architect Nick Leahy. As might be expected, significant cost overruns resulted from the bankruptcy of Haran, the specialty contractor for the glass structure, in midstream. Most of the cost overruns were associated with installation work and were exacerbated by the high cost of field labor in New York City. Leahy points out that the glass fabrication work accounted for only $162 per sq ft. Haran's original contract amount for the supply and installation of the glass structure, as figured above,

came to $355 per sq ft. Acknowledging the likely viability of some change order work on such a complex structure, Leahy and the author agree that $463 per sq ft represents a conservative budget number for such a structure.

2. Per Michael Ludvik in email correspondence, May 29, 2010. Ludvik sometimes refers to this as a "Macfarlane splice," as it is the same arrangement that Tim Macfarlane used for the first time with the glass cantilever canopy for the Yurakucho Station at the Tokyo International Forum in 1996.
3. Table provided by Nick Leahy, Perkins Eastman Architects.
4. Interview by the author with Nick Leahy, 2 December 2009.
5. From a Haran report, "TKTS Booth—Destructive Tread Testing Note," dated June, 2006, provided by the architect.
6. Nick Leahy, Perkins Eastman Architects. Taken from written responses to questions from *I.D. Magazine* by Leahy in preparation for an interview used as the basis for an article in *I.D. Annual Design Review 2009*. Provided to the author by Nick Leahy.
7. Ibid.

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