WIND ISSUES

in the Design of Buildings

Structural Wind
Engineering Committee

ASCE

WIND ISSUES IN THE DESIGN OF BUILDINGS

PREPARED BY
Structural Wind Engineering Committee
of the Technical Council on Wind Engineering
of the American Society of Civil Engineers

EDITED BY
Leighton Cochran, Ph.D., CPEng

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Preface

Every day, structural engineers must explain wind-related issues to clients, architects, builders, building officials, and owners. This publication is intended to help structural engineers make their concerns more easily understood by other members of a project team. This task of putting together this volume was formally started in 2003 by the members of the Wind Effects Committee, which was then part of ASCE's Structural Engineering Institute. That committee was dissolved when the Technical Council on Wind Engineering was created in early 2007. Thus, this work straddles the creation and demise of some entities within ASCE.

It is likely that this volume will be of value in the educational engineering and architecture arenas as well. The reader will see the nature of various extreme wind types (hurricanes, tornados, downbursts, and such) and how designers try to codify the impact on the anthropogenic environment. Contributions to this booklet came from people within the TCWE's Structural Wind Effects Committee and members of similar professional societies in other nations who have a well-established knowledge of wind issues. Their contributions are all greatly appreciated. All the knowledge and ideas come from their efforts and any errors are mine. Thanks also go out to the other individuals from independent engineering, architecture, developer and construction firms along with some building authorities who reviewed the draft prior to submission for publication by ASCE.

Leighton Cochran
Editor

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Contributors

Richard Aynsley	Big Ass Fans Australia Pty. Ltd, Loganholme, Australia
Daryl Boggs	Cermak Peterka Petersen Inc., Fort Collins, CO, USA
Arthur Chiu	University of Hawaii, Moana, USA (deceased)
Leighton Cochran	Cermak Peterka Petersen Inc., Fort Collins, CO, USA
Roy Denoon	Cermak Peterka Petersen Inc., Fort Collins, CO, USA
Elizabeth English	University of Waterloo, Ontario, Canada
John Holmes	JDH Consulting, Melbourne, Australia
Noriaki Hosoya	Cermak Peterka Petersen Inc., Fort Collins, CO, USA
Peter Irwin	Rowan Williams Davies Irwin Inc., Guelph, Canada
Anurag Jain	Weidlinger Associates Inc., Marina Del Rey, CA, USA
Nick Jones	Johns Hopkins University, Baltimore, MD, USA
Kenny Kwok	University of Western Sydney, Sydney, Australia
Chris Letchford	Rensselaer Polytechnic Institute, Troy, NY, USA
Marc Levitan	NIST, Maryland, USA
Bill Melbourne	MEL Consultants, Melbourne, Australia
Joseph Minor	Texas A&M University, Kingsville, TX, USA
Jon Peterka	Cermak Peterka Petersen Inc., Fort Collins, CO, USA
Doug Smith	Texas Tech University, Lubbock, TX, USA
Ted Stathopoulos	Concordia University, Montreal, Canada
Arn Womble	Texas Tech University, Lubbock, TX, USA
Jiming Xie	Rowan Williams Davies Irwin Inc., Guelph, Canada

Chapter 1

Wind Issues in the Design of Buildings

The Wind and the Built Environment

Humans spend most of their lives within the lowest 600 m (2000 ft.) of the atmosphere. Our buildings, bridges, towers, and chimneys are nearly all contained in this region known as the atmospheric boundary layer. This portion of the air around us moves over, under, and through our structures, due to a variety of mechanisms such as hurricanes (Fig. 1.1), thunderstorms, and tornadoes. These higher speed winds generate loads that must be resisted by the buildings we create, and form one core component of the structural design process. Wind loads and wind motion about the manmade environment are discussed in this document, in a fundamental sense, so that engineers, architects, builders, and inspectors who are new to the issues of wind may benefit most.

The extreme wind event has the potential to destroy everything from homes in the suburban setting to tall, engineered buildings in a city center. The first part of Chapter 1 will illustrate the damage that can occur during a high-wind event, and show why the responsible designer needs to be fully aware of the destructive power the wind contains. The middle portion of the chapter discusses the less dramatic effects of more modest common winds around a project that may define the architectural success of a design: wind speeds in public areas, interaction with water features, natural ventilation, and air quality. The last portion highlights how regulations and building codes endeavor to fulfill some of the wind requirements in a new development.

Damage to Single Family Homes

Single-family homes are among the buildings that sustain the most damage in severe windstorms. Single-family homes account for a majority of the structures in most cities; however, due to the lower cost relative to commercial buildings, these structures are not generally reviewed by engineers and design professionals with an understanding of wind effects on structures, and may not always be subjected to the same level of quality control in the construction phase (Fig. 1.2). In hurricane regions this situation is especially troubling as single-family houses are where many coastal residents are likely to be when a hurricane strikes.

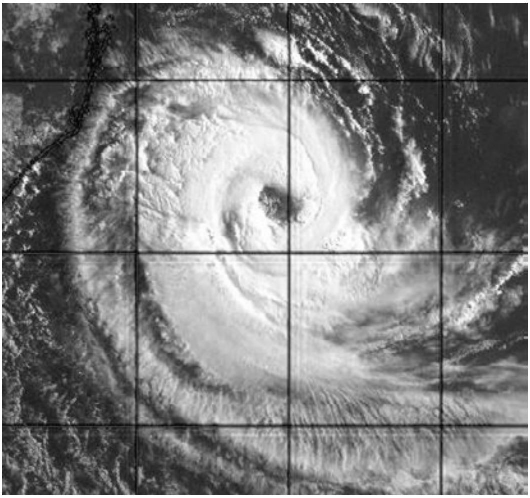


Fig. 1.1: Hurricane Catarina (1-T-alfa) off the coast of Brazil (2004).
Courtesy of NOAA.

Fig. 1.2: Repeated, gable-roof-end failures on neighboring homes during Hurricane Andrew, Homestead, Florida, 1992.

Wind damage to single-family homes commonly involves the removal of the roof covering material, which subsequently permits moisture and wind to damage the contents of the homes. In more severe storms, a home may lose the entire roof structure, prompting a subsequent collapse of the walls (Fig. 1.3). Thus, the attachment of the roof structure through the walls to the foundation is of paramount importance.

Openings in a home's exterior can also exacerbate the wind-induced damage. Such openings may consist of open or broken windows, doors, and garage doors. Doors and windows may be left open by occupants of the home, or may be breached due to wind pressures or the impact of windborne debris. As discussed in the section on internal pressures, such openings allow pressures inside the home to combine with external pressures to create larger net pressures on the exterior surfaces, resulting in greater damage.

The shape of a home's roof also plays an important role in its performance under severe windstorms. Hip roofs are, in general, less susceptible to windstorm damage than gable roofs. Hip roofs are more streamlined in shape than gable roofs, and therefore, experience smaller uplift pressures. In addition, hip roofs usually have a more complex internal structure and so have more effective load paths. Although hip roofs and gable roofs both need to be connected correctly to the walls, gable roofs also require special bracing to ensure that the end walls of the gables do not fail in a windstorm, as shown in Figure 1.2.

Fig. 1.3: Total suburban destruction during Cyclone Tracy, Darwin, Australia, 1974.

Damage to Low-Rise Engineered Structures

As distinct from single-family homes, lowrise commercial and industrial buildings usually have engineering input into their design. Consequently, they usually perform better in an extreme-wind event than a typical home. Cladding failures on the walls and roofs of commercial lowrise buildings, as shown in Figures 1.4 and 3.5, may occur during a hurricane or a tornado, but it is quite rare for the internal structure to be deformed or damaged beyond repair. Possible exceptions include failed steel portal frames in older industrial buildings and concrete, precast, tilt-up construction when inadequate ties connect the walls and roof as shown in Figure 1.5 (the Levitz Furniture Warehouse in Miami after Hurricane Andrew in 1992). Even a modicum of engineering input and quality control during construction can ensure that even relatively low-cost, code-designed, industrial, and commercial buildings can survive well in the extreme wind event. Securing each part of the structure, like links in a chain, yields a building better able to resist the ferocity of the design hurricane.

Fig. 1.4: Paver damage on a lowrise office complex during Hurricane Andrew in 1992.

Fig. 1.5: A roof deck failure during Hurricane Andrew left the precast walls unsupported and so they failed along the internal floor slab line.

Damage to High-Rise Engineered Structures

High-rise engineered structures are designed for lateral loads, including earthquake and wind loads. Earthquake loads typically govern designs of the structural strength of the frame in areas of high seismic activity, although these designs are commonly checked for wind effects—particularly top-floor accelerations. Additionally, wind loads will generally govern the design of cladding on these buildings. Where seismic activity does not govern, wind loads specified in building codes or defined in wind-tunnel evaluations are used in the design of the structural frame and cladding. These loads have proven to be adequate in protecting the structural frame from collapse, even when design loads are exceeded in tornadoes and hurricanes.

High-rise engineered structures have been subjected to the effects of extreme winds on several occasions. There are no records of collapsing high-rise buildings under the affects of extreme winds. A direct hit by an F-4 tornado on the Great Plains Life Building in Lubbock, Texas on May 11, 1970, induced yielding in the structural steel frame (Fig. 1.6). The top of the south end of the structural frame was permanently displaced 300 mm (12 in.) to the east, relative to the ground. Even with this damage, analysis indicated that the frame did not approach collapse, and the building has been restored to service. An F-3 tornado engulfed the Bank One Building in Fort Worth, Texas, on 28 March 2000 (Fig. 1.7). The building was stripped of its glass cladding, but the reinforced concrete structural frame was not damaged.

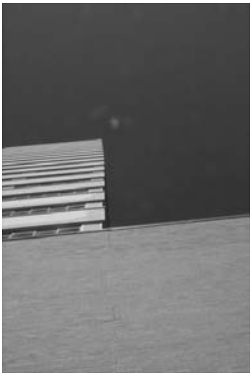


Fig. 1.6: Permanent deflection (note the twist near the top) in the Great Plains Life Building in Lubbock, Texas (11 May 1970).

Fig. 1.7: Bank One Building, Fort Worth, Texas (28 March 2000).

Fig. 1.8: Cladding damage in Miami, Florida after Hurricane Andrew (1992).

Hurricane force winds affected high-rise buildings in Miami, Florida in 1992, Houston, Texas in 1983, and Mobile, Alabama in 1979. Although occupants reported perceptible motions during the storms, structural frames were not damaged. There was, however, damage to cladding on high-rise buildings in each city caused by wind pressures and by windborne debris (Figures 1.8 to 1.10).

Fig. 1.9: Buildings in Houston, Texas August 18, 1983 following Hurricane Alicia.

Fig. 1.10: Buildings in Mobile Alabama, 1979 following Hurricane Frederic.

Wind loads on high-rise buildings are divided into loads on the main wind force resisting system (MWFRS) and loads on components and cladding (C&C). Code specified MWFRS loads are the largest loads obtained from many wind-tunnel tests on high-rise buildings; hence, these design loads tend to be conservative. C&C loads are also the largest loads obtained from many wind-tunnel tests, but it is more common for these loads to be actually experienced on some areas of some buildings during extreme windstorms. As illustrated in Figures 1.8 to 1.10, window failures can be significant. However, wind pressures acting alone do not cause all window failures.

Hurricane and tornado related winds can lift debris from the ground, debris from rooftops, and debris from failures of building facades and inject it into the airflow. This debris tends to be larger near the ground (fascia, timbers, sheet metal, roofing materials) and smaller at higher elevations (roof gravel, shingles, broken roofing tile).

Sustained winds, such as those present in hurricanes, can generate large volumes of windborne debris as building components fail progressively during the hours that it may take for a storm to pass. If this debris is air borne, it is travelling at velocities sufficient to break windows. Most of the windows broken in Houston, Texas in 1983 were broken from windborne debris (Fig. 1.9). Windows broken at high elevations on buildings in Miami in 1992 were the result of wind pressure, although windborne debris was a factor in some instances.

Flow and Pressure Fields Around Buildings

Architectural aerodynamics is an area of study with specific, and also subtle, distinctions from the broader field of aeronautics. While the design of airplanes and cars, for example, requires knowledge of flows over streamlined bodies, the design of buildings and other structures deals with bluff (or sharp edged) bodies. As such, the action of complex flow phenomena such as separation (flow detaches from the external surface), reattachment (the flow may reconnect with the downwind surface, once passed a sharp corner, if the building length is sufficient), and vortex formation (a small, but powerful, rotational flow at breaks in the building continuity) all come into play. These mechanisms are nonexistent or are minimized in the study of streamlined shapes in the larger field of aeronautics. Wind engineering and general industrial aerodynamics focus on the problem of wind interacting with bluff manmade structures and topography.

Since most buildings and structures have sharp edges, the wind is unable to remain attached to the body as it passes around a corner. The flow separates and may, or may not, reattach to the downwind face. The smoke in Figure 1.11 shows an example of separated flow. The building surface under the high-speed separated shear layer (dense smoke flow region) will experience large peak negative suctions that are trying to pull the glazing off the building (Region 5 in ASCE 7).

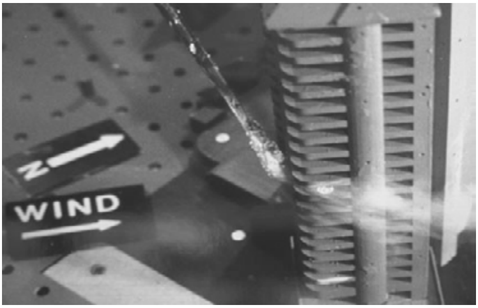


Fig. 1.11: Separated flow off a sharp buildings edge within these balconies.

Another phenomenon that generates large suctions (also known as negative pressures) on a building surface is vortex formation. This mechanism typically occurs on the side of a building when there is a break in the vertical line of the building, such as above a podium or below the roofline (Fig. 1.12). These rotational flows (like small tornadoes adjacent to the building surface) often generate the highest peak suction pressures on a building facade. A similar flow feature may occur above a flat or low-pitched roof near the corner, for wind approaching at approximately 45 degrees to the building edge. In this case, the separation at the roofline of the building rolls up into two counter-rotating vortices that grow in the windward direction along the roof surface (Fig. 1.13). These vortices often produce the largest uplift pressures on the roof (region 3 in ASCE 7) and will frequently scour roof ballast, if it is being used. The large negative, or uplift, peak pressures on the roof surface diminish in magnitude as the vortices grow with downwind distance from the roof corners.

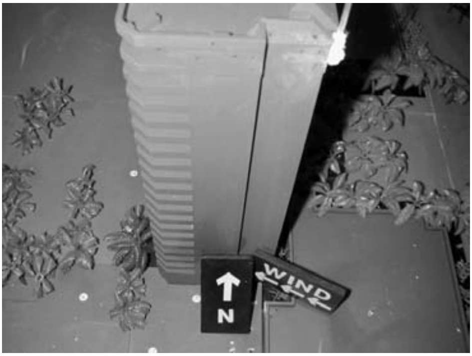


Fig. 1.12: Wall vortex reaching down from the roof generates large peak negative pressures on the upper wall corner.

Fig. 1.13: A pair of roof corner vortices at the corner of an inclined, overhanging theater roof.

As noted in the damage discussion, these bluff body flow phenomena will equal or even exceed the design loads on a building or structure. However, the same mechanisms at lower wind speeds will impact issues as diverse as pedestrian-wind conditions (at ground level, balconies, or roof-terrace areas), the success of water features and fountains (spray keeping people away from these examples of public art), and the dispersion of air pollution from local sources such as peak power generators or laboratory exhaust stacks.

Winds in Public Areas and Water Features

In public areas of the built environment, it is essential that wind speeds do not pose a risk to public safety, and it is desirable that they are limited to comfortable levels. Some cities now require, as part of planning approvals procedures, demonstration that new developments will not generate dangerous or uncomfortable wind conditions. This objective is usually achieved by submission of expert commentary from a wind engineering specialist or (where required) by wind-tunnel testing.

The wind speeds that will be acceptable in an area are dependent on the activities that will be conducted in that area. Wind speeds need to be lower to achieve comfort in areas where it is expected that people will linger (for example, outdoor cafes or pools) rather than on sidewalks where people might be expected to be walking briskly between locations. Sudden changes in wind speed, as may be experienced at building entrances or around building corners, are also undesirable.

A number of wind-speed comfort criteria are used for assessing the acceptability of winds in public areas, and these are discussed further in Chapter 5. Methods of mitigating excessively strong winds are also discussed in Chapter 5.

Although most effort in designing for the pedestrian-level wind environment is concentrated on the avoidance of excessive wind speeds, in hot and/or humid climates, a breeze can be very beneficial in increasing the thermal comfort of pedestrians.

It is common to include water features in public plazas or around building entrances. Such water features need to be carefully designed for the local wind environment to ensure that water is not blown outside the confines of the feature. Two methods of achieving this include choosing a water feature suitable for the local wind environment at all times, or installation of a control system to alter the performance of the feature depending on the ambient wind conditions.

Water features with fine aerial sprays are generally unsuccessful in windy environments as the wind will disrupt the form of the spray and will transport the aerosol droplets over a long distance. With jets of water, the distance which spray can be carried by the wind is dependent on the height of the jets. This is a case where a control system can work successfully to alter the height of the jet depending on the wind speeds.

Fig. 1.14: Public awareness of architectural aerodynamics at the level of the pedestrian. Drawing by W.E. Green. Reproduced from Cochran 2004c, ©ASCE.

Control systems for water features are normally based on anemometers mounted at some distance from the feature. It is important to ensure that the anemometer wind speeds are representative of the wind speeds incident to the water or alternatively to know the relationship between the wind conditions at the two locations. Such measurements are easily made in the wind tunnel during pedestrian-level wind environment studies.

Examples of unsuitable and suitable water features for windy environments are given in Figures 1.15 and 1.16.

Natural Ventilation

Wind pressures can be used to provide natural ventilation in buildings. Modest airflows through small openings can maintain the freshness of indoor air in occupied spaces. Natural ventilation may also ease the HVAC load on a building and thereby reduce energy costs in "green building" design. Building codes specify the minimum number of air changes per hour for spaces in buildings, related to their use and occupancy. Higher airflow rates from breezes flowing through larger openings can improve summer indoor thermal comfort, particularly in humid climates.

Stack effect, generated by air temperature difference between the bottom and top of a vertical flue or building space, can also be used to ventilate buildings. Airflow due to stack effect is proportional to the square root of the product of height between inlet and outlet, and the temperature difference. In the case of an industrial furnace with a tall stack, the stack effect can be very significant. In the case of buildings, with lower temperature difference and difference in height between inlet and outlet openings, the stack effect is not very significant but it can be useful for achieving modest fresh air change rates.

Fig. 1.15: A water feature that is unsuitable for windy locations. High water jets are blown over pedestrian areas.

Fig. 1.16: Water feature that is suitable for windy locations. Water flows over a surface within a deep channel.

Airflow past the skin creates a beneficial cooling sensation for building occupants in warm humid environments. The cooling sensation comes from heat loss from the skin to the air by conduction, convection, and evaporation of moisture from the skin. This cooling sensation is approximately 3.6°C for each meter per second of airflow above 0.2 meter per second (0.03°F for each foot per minute of airflow above 40 fpm). A practical limit to indoor airflow for indoor thermal comfort is disturbance of loose papers, which begins to occur around one meter per second (200 feet per minute). Some building occupants in warm humid climates secure papers in order to allow airflow up to around three meters per second (600 feet per minute) to achieve an increased cooling sensation. The cooling effect of air flow on people is influenced by a number of modes of body heat exchange. For a more detailed assessment of body cooling from airflow, the thermal sensation index Standard Effective Temperature (SET) should be used as it incorporates the effects of skin wettedness, an essential consideration in warm to hot environments. SET can accommodate factors such as air temperature, mean radiant temperature, humidity, air movement, metabolic rate, and clothing insulation. The SET for all these variables for a particular situation, minus the SET for the same settings with air movement set to 0.15 m/s (29.5 fpm), indicates the cooling effect of the initial air movement setting for that situation.

Fluctuations, in wind speed and direction, result in fluctuations in natural ventilation. Some locations have more reliable wind speeds and direction than other locations. Average annual wind speeds are significantly less near the equator than at higher latitudes. Frequency distribution of wind speeds at a location (Fig. 2.6) can be used to estimate the probable percentage of time when wind energy is likely to be sufficient for natural ventilation of buildings. Ventilation and indoor air movement during periods of calm can be provided by appropriate use of energy-efficient fans.

Most estimates of wind-driven natural ventilation make use of data on the wind pressure distribution over buildings from wind-tunnel studies, or by direct wind-speed measurements in those studies (Fig. 1.17). The former data, expressed as pressure coefficients, are gathered for application in estimating wind loads on buildings (Fig. 1.18). Wind pressure coefficients are ratios of the wind pressure measured on a building surface to the reference dynamic pressure of the approaching undisturbed wind, usually at eaves height above the ground.

These wind-pressure data are measured on solid models, often without ventilation openings. Recently, computational fluid dynamics (CFD) computer software has been used to study the pressure fields and airflow through and around naturally ventilated buildings in simple surroundings (Fig. 1.19). Wind pressures on individual buildings surrounded by other similar sized buildings can be estimated using data from boundary-layer, wind-tunnel studies. These wind tunnels can also be used to measure indoor airflow by using miniature hot-film anemometer probes (Fig. 1.17).

Fig. 1.17: Hot-film anemometer used to collect local wind-speed data in the wind tunnel around buildings.

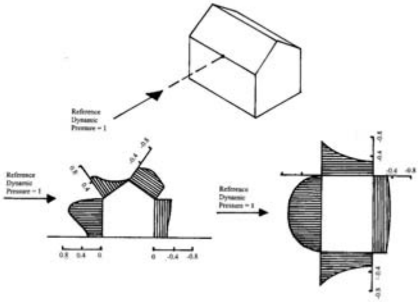


Fig. 1.18: Typical wind pressure distributions over building surfaces with wind at normal incidence to one of the long walls with no openings.

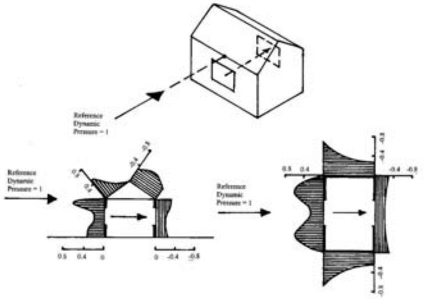


Fig. 1.19: Wind pressure field around a naturally ventilated building (openings) from CFD analysis.

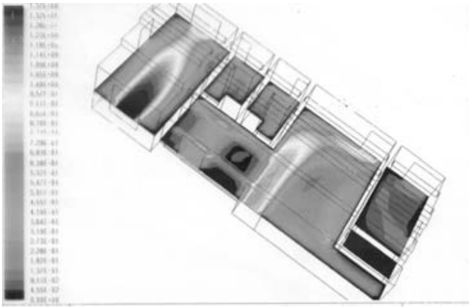


Fig. 1.20: Wind driven airflow through a building may be generated by CFD software.

Wind pressure distribution over a building's surfaces varies significantly with changes in wind direction. The average wind pressure difference between the windward and leeward walls of a rectangular building at inclined incidence to the wind is at a maximum when the diagonal of the floor plan is perpendicular to the wind direction. Careful orientation to prevailing winds, hinged casement window sashes, and doors that catch the passing breeze, combined with minimizing resistance of airflow passages or breezeways through buildings, can significantly enhance natural ventilation. Insect screening over an opening will reduce airflow through the opening by about half.

Volumetric airflow, Q, through buildings naturally ventilated by wind pressure is proportional to the square root of the difference between the sum of dynamic and static pressure at the windward opening and static pressure at leeward opening, ΔP in Pascals, and inversely proportional to the square root of the resistance, R, to airflow through the building.

$$Q \; \% \; (\Delta P/R)^{0.5} \text{ m}^3/\text{s}$$

Airflow efficiency, or discharge coefficient, of window and door openings should be determined by full-scale tests referenced to the pressure difference being used. Use of a single discharge coefficient of around 0.6 with wind pressures on surfaces can result in underestimation of air flow by up to 50 percent for efficient openings, or overestimation of air flow by up to 66 percent for inefficient openings. Computational fluid dynamics computer software has been used to study airflow patterns through and around naturally ventilated buildings (Fig. 1.20). Airflow through windward openings is reduced significantly when inclined to the wind direction. Airflow through leeward openings is less affected than through windward openings. If winds at a location have a dominant prevailing direction, airflow through a building will be increased if leeward openings are larger than windward openings.

Air Quality

Both locally and distantly produced pollutants affect air quality in the built environment. High concentrations of both may occur during still weather conditions, which may be exacerbated in some locations by temperature inversions trapping the polluted layer close to the ground. Locally produced pollutants may also include vehicle exhaust or emissions from buildings and tunnels.

Control of vehicle exhaust build-up requires traffic management and macro-scale urban planning to ensure adequate wind flows are achieved along the urban canyons in which excessive concentrations are most likely. Achieving adequate wind flows for dispersion is often, however, contrary to the aims of minimizing wind speeds for pedestrian comfort, especially in cold climates.

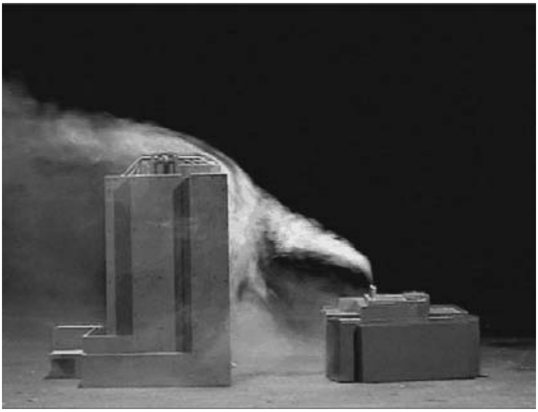


Fig. 1.21: Exhaust from one building may adversely impact the air intakes on another.

Emissions from buildings and tunnels are controllable by individual designers. These emissions may include exhaust gases from parking structures, emergency-generator plant rooms, rooftop heliports, and cooking odors from kitchens. Factors affecting dispersion from these sources include location of exhaust outlets, stack heights, emission velocities, toxicity of the pollutant, and levels of filtration of emissions.

As well as outdoor air quality, indoor air quality is affected by the locations of air intakes to buildings, whether these are windows or centralized air conditioning intakes (Fig. 1.21).

Existing Building Codes

Building codes are regulations intended to enforce a uniformity of construction quality and life safety. Building codes are adopted by local jurisdictions, so there are thousands of them in the United States. There is some movement toward adoption of building codes across wider jurisdictions, such as entire states. There may still be localities which have no adopted building code, or which have a severely outdated code. Until very recently, most communities adopted one of three model codes commonly used in the United States: the Standard Building Code, the Uniform Building Code, or the National Building Code. A few localities write their own codes (for example, New York City and Chicago). The three model code organizations joined forces in the 1990s to create the International Code Council, with the idea of promulgating a single model code for the entire country. The International Building Code (IBC) first debuted in 2000. This was the same year that development of new editions of the other three codes was discontinued. The wind load provisions of the International Building Code (IBC 2003) are based on the American Society of Civil Engineers Standard ASCE 7-02 with modifications for low-rise buildings and some residential structures. The data used within these codes were all derived from many wind-tunnel studies of buildings of various shapes over the last 50 years. Some data were also obtained from full-scale pressure and load studies on specific buildings, but these are less common.

Overseas, many nations have their own local codes and standards that pertain to wind loadings on structures (for example, AS1170, Eurocode). They vary from being quite sophisticated documents to simple guidelines that contain only a few paragraphs. Users of American codes are permitted to access data in the major overseas standards if the data are not provided in ASCE 7. Due to the varying definitions of wind-speed averaging time (such as 3-second gust, 1-minute mean, 1-hour mean) and pressure/load coefficient definitions used in other countries, the U.S. designer would be well advised to seek professional assistance before converting data from foreign codes to use in a local design. Codes used in Europe and Asia are currently going through an amalgamation and updating process to allow for more regional consistency.

Chapter 2

Extreme Winds (Storms)

The extreme wind events that control the design of buildings and structures come from several sources in the planetary atmosphere. Large rotational flows several hundred kilometers across, called hurricanes in North America, form in the tropics and typically move to cooler climes before dissipating. These major atmospheric disturbances cause a huge amount of damage, from gusting winds to extensive flooding, when they pass over populated coastal areas. Fortunately, in the modern world there are usually several days of warning before a hurricane, cyclone (India and Australia), or typhoon (Asia) hits. Extreme winds that come with less warning are caused by thunderstorms and tornadoes, and so they may pose more of a threat to life. The United States has the largest frequency of tornados in the world, although they also occur in Asia, Australia, Europe, South America, and Africa. All three storm types are capable of generating extreme design winds and they are discussed in more detail in this chapter.

Wind Characteristics

The objective of this section is to discuss wind characteristics, from an engineering viewpoint, in connection with their effects on structures. It is not intended to include all topics that would be presented in a comprehensive treatise on wind phenomena.

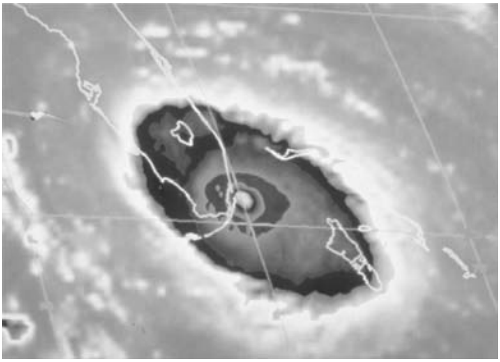


Fig. 2.1: GOES infrared image of Hurricane Andrew at landfall near Miami in 1992. Courtesy of Ray Zehr, reproduced with permission.

Wind is dynamic in nature, but for most design purposes its effects may be represented by equivalent mean and fluctuating speeds (Fig. 2.2). Of importance are the gust speeds, the peaks above the mean speeds. Wind speeds are also affected by elevation above ground, by the surrounding upwind terrain, and by local topography, as described in the following sections. Thus, for comparative purposes, it is necessary to characterize wind speeds with regard to the following items: the mean speed as measured over a particular time interval, terrain (exposure), topography, and probability of occurrence (return period or recurrence interval). Additionally, directionality (direction wind approaches the structure) is of importance in some design situations.

A description of mean wind speed effects on land for people has been derived from the old nautical Beaufort Scale, which originated from the Royal Navy in the 1800s. Table 2.1 shows this modified Beaufort Scale that is used by wind engineers to explain ambient wind conditions via a mean wind speed range and the commonly observed wind effects impacting people on land, as opposed to the ocean (Penwarden 1973). This descriptive table refers to the local mean wind speed felt by a person, rather than the peak gust on an individual.

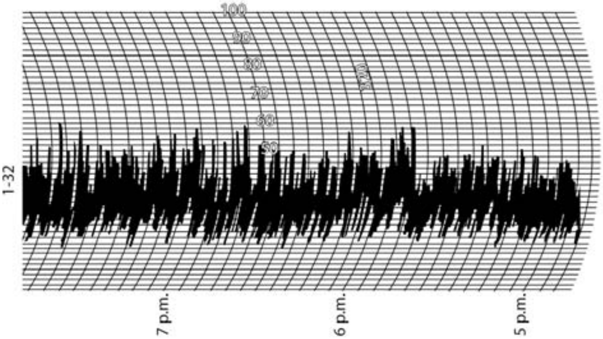


Fig. 2.2: Sample of wind trace with some of the characteristics indicated in Fig. 2.4.

Table 2.1: Summary of Wind Effects on People (Beaufort Scale)

Description	Beaufort Number	Mean Speed (mph)	Mean Speed (m/s)	Effects
Calm, light air	0, 1	0–3	0–2	Calm, no noticeable wind.
Light breeze	2	4–7	2–3	Wind felt on face.
Gentle breeze	3	8–12	3–5	Wind extends light flag. Hair is disturbed. Clothing flaps
Moderate breeze	4	13–18	5–8	Raises dust, dry soil, and loose paper. Hair disarranged.
Fresh breeze	5	19–24	8–11	Force of wind felt on body. Drifting snow becomes airborne. Limit of agreeable wind on land.
Strong breeze	6	25–31	11–14	Umbrellas used with difficulty. Hair blown straight. Difficult to walk steadily. Wind noise on ears unpleasant. Windborne snow above head height (blizzard).
Near gale	7	32–38	14–17	Inconvenience felt when walking.
Gale	8	39–46	17–21	Generally impedes progress. Great difficulty with balance in gusts.
Strong gale	9	47–54	21–24	People blown over by gusts.

These processes occur over a wide range of scales. The synoptic scale describes the largest-scale motions or events, with length scales of several hundred kilometers and lasting several days. Hurricanes, typhoons, and cyclones are good examples of synoptic events. The microscale covers small-scale events (temporally and spatially) with characteristic dimensions of several tens of kilometers and durations in terms of minutes (up to about an hour). Local winds such as thunderstorms, tornadoes, and Foehn winds are examples of microscale phenomena. Mesoscale events are loosely described as those “in between” these scales.

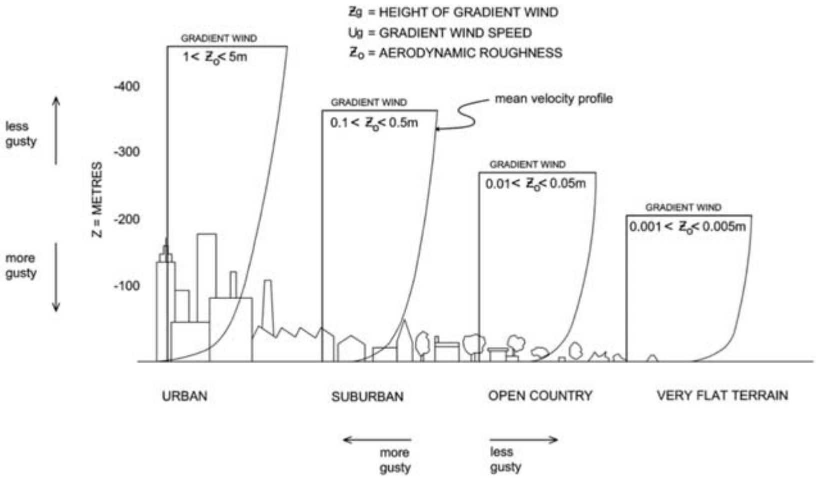


Fig. 2.3: The mean wind speed profile curvature and height depend on the surface roughness of the upwind fetch. That surface roughness is represented in the "log law" by the aerodynamic roughness (z_o) and in the "power law" by an exponent (n or α).

Of particular interest in wind engineering is the part of the general or local circulation that interacts with the surface of the Earth. This region is where the effects of friction are concentrated, and this surface drag has an important and influential effect on the characteristics of the wind. It is called the neutral Atmospheric Boundary Layer (ABL). The generally rough surface has two major effects on the free atmosphere motions. First, it retards the mean flow, slowing it considerably near the surface and less effectively at greater heights. This results in a mean wind speed "profile" that is a function of height (Fig. 2.3). Second, it causes mechanical mixing of the flows (frequently considerable), creating turbulence or random fluctuations in the wind speed whose intensity depends on the characteristics (specifically the "roughness") of the surface. The term "neutral" refers to the fact that the direct thermally induced convection is small relative to the mechanical mixing that is commonly assumed for most "normal" turbulent flows. Careful consideration of both of these effects is extremely important for wind engineering applications, and both need to be properly treated or modeled whether analytical or experimental techniques are used in analysis.

Mean Profile in the ABL

The form of the mean profile (U) within the atmospheric boundary layer can be derived theoretically from principles of fluid mechanics. In its simplest form, this leads to the so-called "log law" which expresses the mean wind speed as a function of height in terms of the height z, a "roughness length" z_0 that describes the characteristics of the ground surface, and a "friction velocity" u_* that is (indirectly) a measure of the surface drag.

An alternate form of the wind profile is the "power law" which expresses the mean wind speed as a ratio of two elevations raised to a power that depends on the surface roughness. While both forms are still in common use, the log law is becoming the more accepted form for meteorological and wind engineering applications.

Turbulence in the ABL

Wind turbulence is of critical relevance to wind engineering, as it results in time-varying loads on structures and it has the potential to produce large dynamic responses under some circumstances. Turbulence in a flow can be considered a stochastic or random variation of wind speed with time. Generally, the fluctuating component is separated from the mean flow, as described in the section on wind structure and gusts. This randomness is fully three dimensional, and the wind speeds vary randomly not only as a function of time but also of spatial location.

Turbulence in the ABL is characterized by a number of means derived from the study of random processes. The simplest approaches are the so-called single parameter descriptors. The most commonly used description is the turbulence intensity, which represents the average extent of the fluctuations as compared to the mean wind. Low turbulence intensities (less than 10 percent) are common, while higher values (20 percent to 40 percent) can be expected in some cases, such as in very rough terrain or in the wakes of other structures. The turbulence can also be represented by the average "size" or scale of the eddies in the flow (along-wind, across-wind, and in the vertical direction). These measures are not used as commonly as the simple turbulence intensity.

The other important means of characterizing the turbulent wind is through the energy spectrum. This is a more complex representation of the stochastic process, but is extremely important as it describes the energy in the flow as a function of frequency (or gust size). This quantity is crucial for understanding the dynamic nature of the loads acting on a structure, since most of the fluctuating energy occurs below 1 Hz in the wind. The fundamental shape of the spectrum can be again derived from theoretical considerations, and a number of common models (such as, von Kármán, Davenport, Harris, Kaimal, Hino, Solari) exist that are used in practice. It is beyond the scope of this booklet to go into the details of these spectral forms, but it is important to recognize that the variable frequency-dependent energy distribution associated with turbulent flow must also be carefully considered in either analytical or experimental modeling.

Other ABL Flows

Questions remain about the suitability of the approaches mentioned above for describing boundary-layer flows for special flows such as those associated with hurricanes or thunderstorm winds. These situations are the topic of ongoing investigation, but there is evidence that these flows may exhibit some fundamental differences from their “straight-wind” counterparts. Research efforts are focused on both analytical and experimental simulations (for example, full scale and wind tunnel), in which the evolving nature of the wind velocity and direction needs to be taken into account; non-stationary characteristics of these processes and uniqueness of each event are the challenges associated with such phenomena.

Measures of Mean Wind Speed

The movement of air is a three-dimensional, time variant phenomenon. Wind engineers have long represented wind velocity, $U(x,y,z,t)$, such as to capture this spatial and temporal variation as:

$$U(x,y,z,t) = U(z) + u(x,y,z,t) + v(x,y,z,t) + w(x,y,z,t)$$

Where

$U(z)$ = mean wind speed at a height z above ground, blowing horizontally
$u(x,y,z,t)$ = fluctuating component of wind velocity in the direction it is blowing to
$v(x,y,z,t)$ = fluctuating component of wind velocity in the horizontal transverse direction
$w(x,y,z,t)$ = fluctuating component of wind velocity in the vertical direction

The $v(x,y,z,t)$ and $w(x,y,z,t)$ components of wind velocity are small and have traditionally been neglected from analysis of typical buildings, but can be an important consideration in the design of complex structures such as long-span suspended bridges and the dispersion of pollutants.

Mean wind speed is a time-averaged quantity and a complete definition must include the units as well as the averaging time. Averaging times in which the mean wind speed is most often reported are fastest mile (historically important), 3-second gust, 1-minute, and hourly—although the first is no longer collected in the United States. For example, the threshold wind speed of 33 m/s (74 mph) above which a storm is classified as a hurricane is a 1-minute sustained wind speed. It is critical to consider the mean wind speed averaging time along with the magnitude. Conversion of mean wind speed from one averaging time to another is relatively straightforward. For example a comparison of fastest mile wind speeds to 3-second gust wind speeds is given in Table 2.2 (IBC 2000, Table 1609.3.1). In a more general sense the impact of averaging time on wind speed may be investigated using the Durst curve (see commentary section of ASCE 7).

Table 2.2: Equivalent Basic Wind Speeds (mph)

V_{3s}	85	90	100	105	110	120	125	130	140	145	150	160	170
V_{fm}	70	75	80	85	90	100	105	110	120	125	130	140	150

Wind Structure and Gusts

The specification for mean wind speed or gust depends on the length of the sampling period and the time at which the sample is taken (see Figure 2.2). The previous section discussed the various commonly used terms in describing these characteristics, e.g., hourly mean speed, 1-minute average, 3-second gust. The last term is being used more frequently in place of the formerly familiar "fastest-mile" wind speeds.

As seen from Figure 2.2, the wind speed is not constant but fluctuates continuously. The total wind speed can be separated into two parts: a mean wind speed and a fluctuating component. Figure 2.4 indicates that it is necessary to specify the period over which the mean wind speed is calculated as well as the time at which the sample is taken. A 10-minute mean speed, taken at 10-minutes before the hour, measured 10-meters above ground level, in open terrain is normally quoted in international weather reports (WHO standard). In the United States the data are two-minute means.

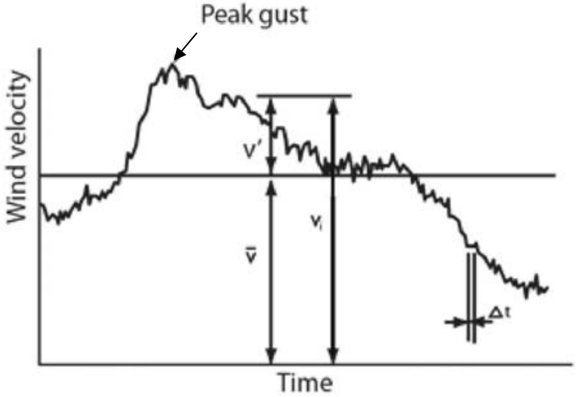


Fig. 2.4: An illustration of the long-term mean, ; instantaneous local peak, v_i; *and fluctuating component,* V', *of wind speed, along with a sample increment time period,* Δt

Figure 2.4 shows the fluctuations of the instantaneous wind speeds about the mean. The standard deviation of the fluctuating velocity is used to statistically depict the variation of the wind speeds about the mean (called a "turbulence intensity", when expressed at a percentage of the mean). The noticeable increase in wind speed relative to the mean speed over a short duration is called a *gust*. Most recent wind speed measurement stations in the United States may have instrumentation for recording only the *peak* gust. The term "3-second gust" has been introduced in the ASCE-7 for basic design speeds, and this comes from the physical limit of the typical mechanical anemometer's response time (two to three seconds).

The dynamic response of a given structure depends on the energy content and frequency of the loading input. Earthquake designers are familiar with the magnitude of the applied load and its variation with time. For typical buildings, the magnitude of the earthquake induced inertial loading is larger than the design wind load, but the frequency of shaking (earthquake) and buffeting (wind) may not be similar. In the case of wind, the buffeting action of gusts may adversely impact a wind sensitive structure. In some cases, flow around structures may generate dynamic loads with adverse effects on structural performance, e.g., the famous film clip of the Tacoma Narrows bridge failure in the 1940s.

Day-To-Day Winds

Everyone is familiar with the lulls and gusts on windy days. This is the result of turbulence, or 'gustiness', caused by strong winds blowing across the rough surface of the Earth (Fig. 2.5).

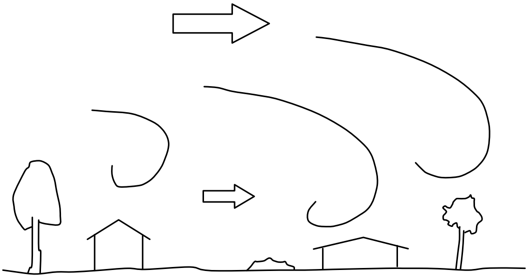


Fig. 2.5: Wind flow over the rough ground surface producing gustiness. From Holmes 2007, page 2; reproduced with permission from Taylor and Francis.

The times that the wind speed spends at different strengths can be recorded by a wind measuring instrument or anemometer. If the time spent in each wind-speed 'box' incorporating a small range of wind speed is accumulated, then eventually a pattern emerges in the form of a frequency distribution, as shown in Figure 2.6. Statisticians, meteorologists, and wind engineers know the smoothed form of the frequency distribution as a probability distribution; this is shown on the right side of Figure 2.6.

The frequency and probability distributions that result if the anemometer is left in position for a short time, for example, for the duration of a single windstorm, or for a period of several years, are quite different to each other. These are illustrated in Figure 2.7. The short-term distribution of wind speeds will be much narrower and will tend to be symmetrical (approximating the well-known bell-shaped normal distribution). On the other hand, over the long-term the anemometer will experience many high wind events and periods of no wind. The long-term probability distribution of wind speeds will stretch right down to zero at the left-hand end, with a skewed 'tail' at the right hand end to accommodate the extreme windstorms that can damage structures.

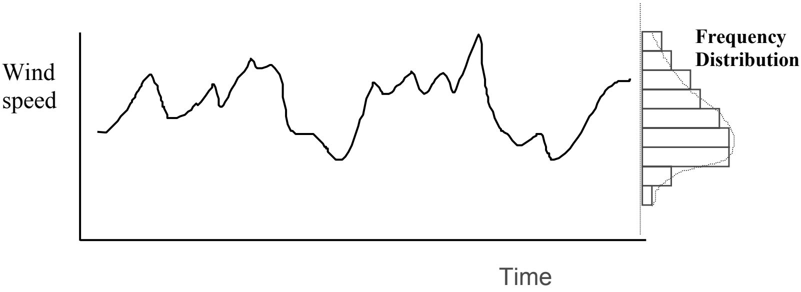


Fig. 2.6: Wind speed fluctuations and the frequency distribution.

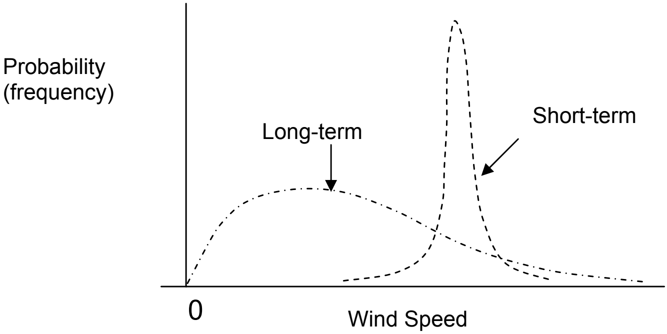
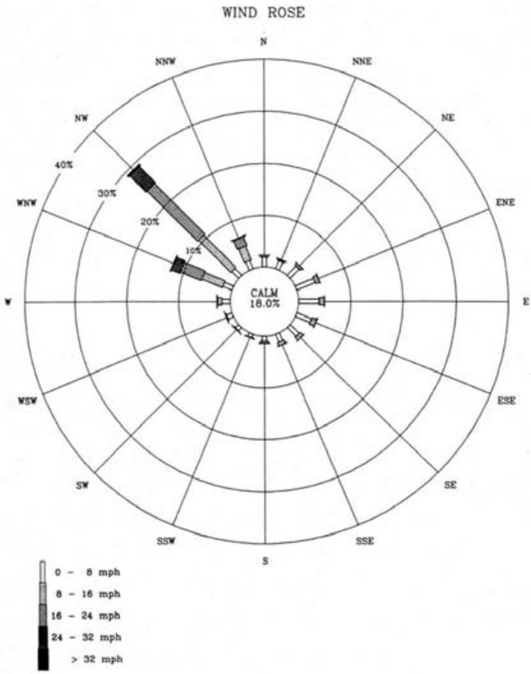


Fig. 2.7: Long-term and short-term probability distributions of wind speed.

There are also probabilities associated with the directional characteristics of the natural wind. These data are most typically presented as a wind rose, where both the directional frequency and strength are illustrated in a form similar to Figure 2.8 (a location in a valley surrounding Ellensburg, Washington). The local topography in this area constrains the surface-level winds to generally follow the axis of the valley in which Ellensburg lies. Other locations with less terrain will not show such directionally dominant wind statistics, and the resulting wind rose will be more axially symmetric.

Hurricanes

Tropical cyclones are synoptic-scale storms that form in the low latitudes (5° to15°) over warm, open waters, containing strong thunderstorm activity and cyclonic wind circulation patterns. The low-pressure center of the storm is a place of relative calm called the eye, which is typically tens of kilometers in diameter, while the entire storm is several hundred kilometers across. Maximum wind speeds occur near the center of the storm in the eye wall.



Bowers Field (#727883), Ellensburg, WA
10/1998–10/2003: ALL MONTHS, ALL HOURS
Source: NCDC DATSAV

Fig. 2.8: The northwesterly-dominated wind at Ellensburg, Washington, is due to the winds contained within the valley.

Northern Hemisphere tropical cyclones rotate counterclockwise, while Southern Hemisphere storms rotate in a clockwise manner (due to the Coriolis Effect caused by the earth's rotation). Storms typically gather strength as they pass over warm waters. As they approach land, the additional friction begins to disrupt circulation patterns. Storms decay rapidly after making landfall, as they move away from the warm oceans that provide the energy source. Wind speeds vary greatly at different locations, but are generally greatest in the right front quadrant of the storm (front being defined by the direction of motion of the overall storm) in the Northern Hemisphere. At this point, the rotational and translational components of motion are in the same direction and add together. The translational component (the forward speed of the storm system) varies during the life of the storm, ranging from near stationary to as much as 50 km/hour.

Tropical cyclones that form in the North Atlantic, Gulf of Mexico, and Eastern Pacific Oceans are called hurricanes. Those that form in the Northwest Pacific are called typhoons, while storms forming in the Southwest Pacific and Indian Oceans are called cyclones (Fig. 2.9). All are similar in nature; however, typhoons can reach greater wind speeds due to the larger fetches of open water in the Northwest Pacific.

Hurricanes pose many hazards in addition to the strong winds constituting the main circulation, all of which should be considered in design. Tornadoes are often formed on the advancing periphery of the storm. Storm surge is the dome of high water under the storm, caused by the extremely low atmospheric pressures and high winds. As the eye of the storm approaches land, storm surge can reach heights of 6 m or more, with wind-driven waves above that. In low-lying areas, the ensuing floodwaters can travel many kilometers inland, often causing massive devastation and loss of life. Storm surge can also transport large amounts of sand and soil, variously causing deposition of material in some places and erosion in others. Tropical cyclones, particularly slow moving ones, can produce large amounts of rainfall over very wide areas in the span of a few days (up to a metre or more in some cases), causing fresh-water flooding. Such intense rainfall can cause landslides in areas with unstable slopes. Decaying storm systems sometimes produce flooding rainfalls for thousands of square kilometers after making landfall. Flood-borne and wind-borne debris represent significant hazards that have only recently begun to be considered. All of the hurricane hazards described here pose threats to both life-safety and property, although flooding in its various forms causes the majority of deaths. Another significant hazard, wind-driven rain, is primarily an economic consideration only. It can cause significant damage to building finishes and contents if the building envelope is breached.

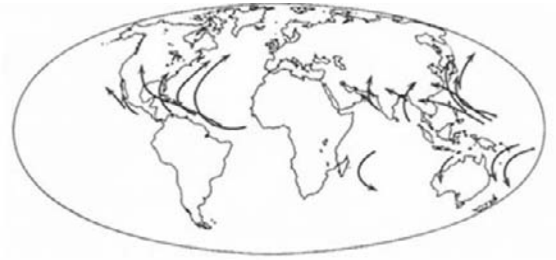


Fig. 2.9 Location of tropical cyclone formation and typical storm paths.

History

The deadliest tropical cyclone on record was the Bangladesh Cyclone of 1970, where an estimated 300,000 people perished. They died in a massive storm surge that inundated much of the low-lying coastal region of that nation. Storm surge flooding is historically the largest cause of fatalities, followed by rain-induced (inland) flooding. More recently, rain-induced flooding and landslides from Hurricane Mitch caused over 10,000 deaths in Honduras and Nicaragua in 1998, and storm surge flooding killed over 10,000 people in southwest India in a 1999 cyclone.

The largest death toll in U.S. history occurred in the Galveston Hurricane of 1900, causing an estimated 6,000-10,000 casualties. Residents of this prosperous barrier island on the southeast Texas coast did not evacuate due to inadequate warnings, and many were lost to the storm surge. As tragic as this storm was, it served to bring national attention to the need for improved hurricane warning and response systems. The introduction of maritime radios in 1909 provided a major improvement in storm tracking capabilities, as ships could send in hurricane reports while out at sea. Tracking and prediction capabilities increased significantly in the 1940s and again in the 1960s, with the advent of weather reconnaissance aircraft and weather observation satellites, respectively. Today, computers combine data from surface, aircraft, and satellite-based sensors with complex atmospheric models to generate ever-improving forecasts. Over the past 30 years, inland rainfall flooding has replaced storm surge flooding in the U.S. as the number one killer in hurricanes, due to improved hurricane tracking and predictions. A major loss of life in storm surge was during Hurricane Camille in 1969, causing 256 fatalities in southeast Louisiana and Mississippi. This Category 5 storm (see next section) had sustained winds of 85 m/s (190 mph), a maximum storm surge of 8 to 9 m and a central pressure of 909 hPa.

Although warning times have increased significantly in the past 40 years, so have coastal populations in the southeastern United States. During that same time, there has been almost no increase in major transportation infrastructure. Lead times required to evacuate major coastal cities like New Orleans and Miami have increased rapidly as well. In some locations they now exceed 72 hours, which is in excess of the predictive capability of today’s computer models. In these areas, the potential still exists for a catastrophic disaster with thousands of casualties from storm surge flooding.

While extreme winds and wind-borne debris are not usually the biggest killers, they are often the largest cause of property damage. Hurricane Andrew, which struck south Florida and south-central Louisiana in August 1992, was the most expensive wind event in U.S. history, causing $30 billion in damage. The storm was a strong Category 4 storm (922 hPa) when it made landfall just south of Miami, devastating the entire area. Analysis of the meteorological data fifteen years later has caused some to view Hurricane Andrew as a Category 5 event, and the actual designation remains somewhat controversial. Andrew destroyed over 28,000 homes and damaged another 107,000 homes, and damaged or destroyed over 82,000 businesses in Florida alone. The storm proceeded to cross the Gulf of Mexico, where it re-intensified before striking Louisiana as a weakening Category 3 storm. Fortunately it struck a relatively unpopulated area of the coast between New Orleans and Lafayette, but nevertheless damaged and destroyed thousands of homes and businesses. The overall extent of the damage was such that it bankrupted numerous insurers in both Florida and Louisiana. The ensuing rebuilding efforts led to construction materials shortages that impacted prices and availability nationwide.

Several other notable Atlantic Basin storms are briefly described below. The Labor Day Hurricane of 1935 was the most intense (892 hPa) land-falling hurricane in US history (Florida, 408 fatalities). This storm and Hurricane Camille in 1969 are the only two Category 5 storms to strike the U.S. mainland in the past hundred and twenty years (as far back as reliable records go). Some researchers believe that Hurricane Andrew should be re-categorized as a Category 5 storm at landfall in Florida, but this revision of history remains a topic of vigorous debate. Hurricane Gilbert, which ravaged Jamaica and the Yucatan peninsula of Mexico in 1988, had the lowest central pressure ever recorded in the western hemisphere, at 888 hPa and winds of 296 km/h (184 mph). Category 4 Hurricane Hugo, which devastated South Carolina in 1989, was the most expensive storm at that time causing an estimated $6 billion in damage due to both winds and surge. Hugo was also unusual in that it decayed very slowly after landfall; hurricane force winds extended over 320 km (200 miles) inland. In 1999 Hurricane Floyd grazed the southeast Atlantic coast from southern Florida to South Carolina, before coming ashore in North Carolina. The storm caused massive rainfall flooding and $4.5 billion in damage. This storm was unique in that it caused the largest peacetime evacuation in U.S. history. Before Floyd's floodwaters had completely disappeared Hurricane Irene struck the same region again, adding to the devastation. Lastly, while Hurricane Katrina on the Gulf Coast caused substantial flooding it was not a very strong wind event.

Saffir-Simpson Scale

Storms are classified according to the maximum sustained surface wind speeds, defined as one-minute average speeds at 10 m height over open water. A tropical cyclone with sustained wind speeds less than 17 m/s (39 mph) is referred to as a tropical depression. Once the wind speeds exceed 17 m/s (39 mph), it becomes a tropical storm. If the storm continues to intensify and the maximum sustained winds exceed 33 m/s (74 mph), the storm is then classified as a hurricane.

Hurricane intensity is characterized using the Saffir-Simpson scale (Table 2.3). This scale was developed in 1970 by wind engineer H. Saffir and meteorologist R. Simpson. Hurricane categories are based on maximum sustained surface wind speeds. The other columns provide values of minimum atmospheric pressure and maximum storm surge typically associated with each storm category. Category 3, 4, and 5 storms are often referred to as major hurricanes. Descriptions of typical damage are given in Table 2.4.

Table 2.3 Saffir-Simpson Hurricane Scale

Category	Description	Wind Speed		Central Pressure		Storm Surge	
		m/s	mph	hPa	inches Hg	m	ft
1	Minimal	33-42	74-95	980	28.94	1.0-1.7	4-5
2	Moderate	43-49	96-110	965-979	28.50-28.91	1.8-2.6	6-8
3	Extensive	50-58	111-130	945-964	27.91-28.47	2.7-3.8	9-12
4	Extreme	59-69	131-155	920-944	27.17-27.88	3.9-5.6	13-18
5	Catastrophic	>69	>155	< 920	< 27.17	>5.6	>18

Table 2.4: Typical Damage by Hurricane Category

Category	*Description*
1	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also, some coastal road flooding and minor pier damage.
2	Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.
3	Some structural damage to small residences and utility buildings with a minor amount of curtain wall failures. Damage to shrubbery and trees with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water 3 to 5 hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures with larger structures damaged by battering of floating debris. Terrain continuously lower than 5 ft. (1.5 m) above mean sea level may be flooded inland 8 miles (13 km) or more. Evacuation of low-lying residences with several blocks of the shoreline may be required.
4	More extensive curtain wall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 10 ft. (3.0 m) above sea level may be flooded requiring massive evacuation of residential areas as far inland as 6 miles (10 km).
5	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 15 ft. (4.6 m) above sea level and within 500 yards (460 m) of the shoreline. Massive evacuation of residential areas on low ground within 5 to10 miles (8 to16 km) of the shoreline may be required.

Source: National Hurricane Center, 2002

Future Trends

Reliable records of storm tracks and intensities in the Atlantic Basin only go back about a hundred years. Over that period, the average number of named storms (tropical storms and hurricanes) per year is typically nine or 10, while the number reaching hurricane strength averages between five or six. Storm activity can vary significantly from those averages in a given year. Over the past century, the minimum number of named storms was four (in 1983) and the maximum was 28 (in 2005).

Besides annual variation, there appears to be a significant pattern of storm activity on a multi-decadal scale (Gray Schaeffer and Landsea, 1996). The Atlantic Basin experiences runs of 20-40 years of higher than normal activity, followed by a similar pattern of lower than average activity. The first few decades of the twentieth century were relatively calm. Then the basin heated up from the late 1920s to late 1960s, with higher than normal activity. This was followed by 25 years of lower than normal activity during the 1970s, 1980s, and early 1990s. The year 1995 marked a return to a more active cycle of storm activity, which has continued to date. If past trends hold, the Atlantic Basin is likely to continue to experience higher than normal levels of tropical storm activity for the next two to three decades.

It has been proposed that global climate change may significantly impact storm activity. According to some climate scientists, warmer ocean temperatures could lead to increased storm activity, both in numbers and intensity. The entire topic of global climate change and its possible effects on tropical weather patterns is the subject of ongoing and vigorous scientific debate, and is by no means a proven theory. However, if observational evidence of global climate change builds (natural or anthropogenic) then design codes may need to account for increases in storm frequency and intensity.

Thunderstorms

Figure 2.10 shows the life cycle of a thunderstorm in three stages as proposed by Battan in 1961: Cumulus Stage, Mature Stage, and Dissipating Stage. During the cumulus stage, several smaller cumuli clouds combine to form a single cell, which is a region of relatively strong updrafts containing suspended precipitation. Air converges into the cell at all levels of penetration. The temperature in the cell at this stage is greater than the ambient temperature and condensation, and freezing of precipitation produces the first radar echo. The first descent of rain from the base of the system marks the mature stage. The presence of rain indicates that the precipitation particles have grown past the stage where the updraft is sufficient to keep them suspended, resulting in the formation of downdrafts. The dissipating stage is the end of a cell's life cycle. At this point updrafting has stopped and the downdraft has spread over the entire cell. The cell remains colder than its local environment while there is still some downdraft and rain, but it is effectively "draining". It is to be noted that this three-step life cycle is a major simplification of a real storm, which may contain many cells at different stages of evolution.

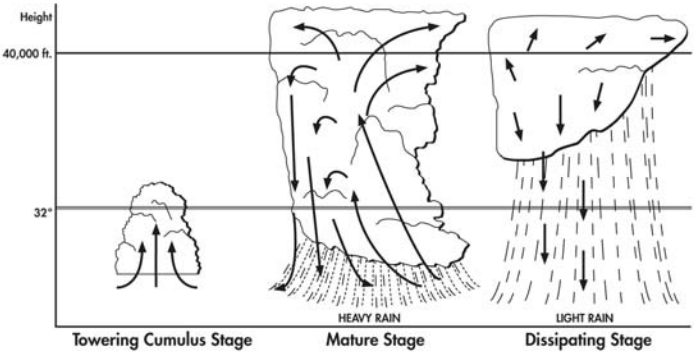


Fig. 2.10: The life cycle of a thunderstorm, consisting of the Cumulus (left), Mature (middle) and Dissipating (right) stages. Based on information from NOAA.

Convection is the primary mechanism that produces updrafts. Convection starts when air close to the ground is heated. The temperature increase causes near ground-level air parcels to expand. An expanded air parcel is less dense than its surrounding environment, and rises due to buoyancy. As the parcel rises, it continues to expand in the new lower pressure environment and cools adiabatically. In an unstable atmosphere, the air temperature decrease with altitude (lapse rate) is greater than the adiabatic lapse rate. Under such conditions, the rising air remains warmer than its surrounding environment, therefore, maintaining a lower density and continues to ascend. If the updraft develops rotation then a tornado may form (see the following section).

Evaporation and water loading are two of the factors responsible for the formation of a strong downdraft, Srivastava (1987). As the parcel of air ascends, moisture within the parcel condenses to form precipitation particles. As these particles continue to grow, the updraft is less able to sustain their weight. Upon reaching a critical size, the precipitation particles begin to descend again. They may fall through the parent updraft or some other location within the cell. Precipitation melts and evaporates as it descends, cooling and increasing the density of air in the immediate vicinity of the downdraft. The cooled air mass containing the precipitation becomes negatively buoyant, and accelerates towards the ground. As the downdraft proceeds, the precipitation continues to cool, while the descending air mass undergoes compression warming.

In 1982 Wakimoto proposed four stages of thunderstorm outflow, commencing as the parent downdraft descends beneath the base of the clouds (Fig. 2.11). These are: Formative Stage, Early Mature Stage, Late Mature Stage, and Dissipating Stage.

Rain and cold air first penetrate the base of the cell during the formative stage of the outflow. This stage of the outflow coincides with the mature stage of the storm. Flow begins to diverge and a horizontal vortex containing embedded precipitation, known as a precipitation roll, forms during the early mature stage of the outflow. This stage of the outflow occurs as the thunderstorm begins to dissipate. Flow is advancing away from the storm and is similar to a developed density current by the late mature stage of the outflow (Fig. 2.12). The descending air source is almost depleted at this stage. The descending air source has been exhausted when the outflow reaches the dissipating (final) stage. Flow has now traveled a long distance from the point of origin. The depth of the gust front shrinks and its structure weakens during this stage.

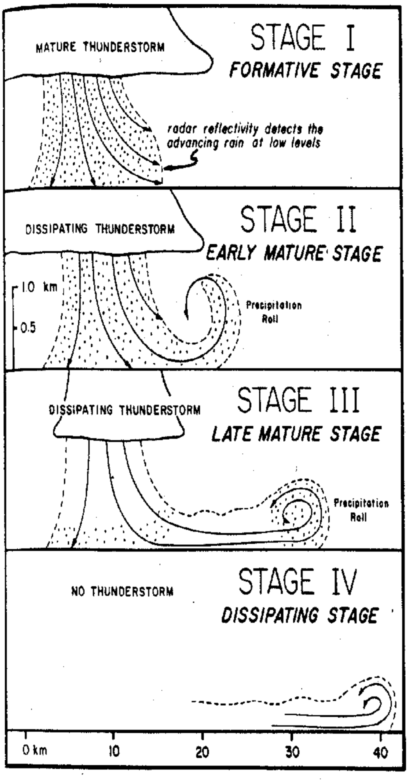


Fig. 2.11: The four stages of thunderstorm outflow.
Courtesy of NOAA, National Severe Storms Laboratory.

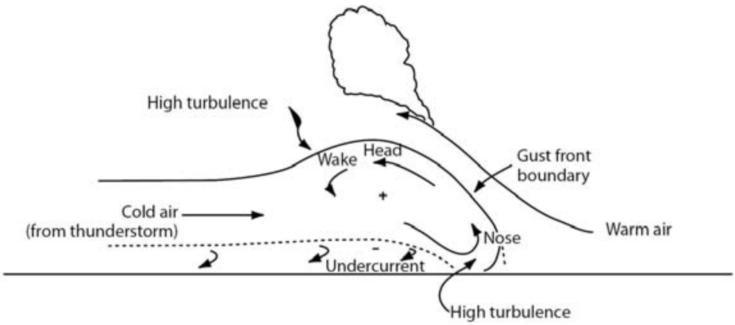


Fig. 2.12: The structure of the front of the diverging flow. From Wakimoto 1982, © American Meteorological Society. Reprinted with permission.

Tornadoes

Tornadoes, such as that shown in Figure 2.13 are the strongest of atmospheric storms. They are spawned from convective storms such as severe thunderstorms and from rainbands in landfalling hurricanes. Tornadoes are rotating columns of air that are visible as the result of condensation around the funnel and from dust and debris picked up from the ground. They occur worldwide but are most common in the Great Plains of the United States and in northeast India-Bangladesh. The portion of the Great Plains from northern Texas to western Iowa is often called tornado alley due to the high frequency of tornadoes in the region (Davies-Jones Trapp and Bluestein, 2001).

Fig. 2.13: Tornado spawned from super cell thunderstorm on May 15, 2003 in the panhandle of Texas.

Fig. 2.14: Residential neighborhood destroyed in the Moore, Oklahoma tornado of 1999.

As shown in Figure 2.14, tornadoes are capable of wreaking severe damage to buildings and other structures. Figure 2.15 shows a damage path in the Oklahoma City metroplex from the tornadoes in May of 1999. Close inspection of Figure 2.15 indicates that the damage (and the wind speeds) varies both along and across the tornado path. The maximum wind speed in a tornado can range from less than 70 mph to over 200 mph. Contrary to a commonly held belief that structures explode as a result of the reduced (below atmospheric) pressure at the core of the tornado, post disaster investigations have revealed that the damage is principally caused by wind-induced pressures and windborne debris (Mehta McDonald Minor and Sangar, 1971; Mehta Minor and McDonald, 1976; Minor and Mehta, 1979).

Fig. 2.15: Damage path in a residential area of Oklahoma City, OK, from one of the May 1999 tornadoes.

Fig. 2.16: Midrise building struck by the Fort Worth tornado in March 2000.

Tornadoes are low probability events, thus very few structures are explicitly designed for tornadic wind speeds due to the additional costs involved. Examples of structures that are designed for tornadoes include nuclear power plant facilities, corporate data processing centers and shelter areas in schools and homes. Even though most ordinary engineered construction is not designed to resist the strongest tornadoes, they often perform well structurally. Figure 2.16 shows a mid-rise building hit by the Fort Worth, Texas, tornado in March 2000. The building sustained cladding damage but withstood the storm structurally. Envelope damage, which opens the building to the wind environment, can result in extensive damage to the building interior due to wind circulation inside the building. In general, post disaster investigations have revealed that engineered construction fares much better in tornadoes than non-engineered construction.

History

Tornado wind speeds and the atmospheric pressure change at the core of the tornado are difficult to measure directly. Around the turn of the last century, tornado wind speeds were believed to be as high as 179 to 224 m/s (400 to 500 mph). Photogrammetric analysis of entrained debris and cloud tags in tornadoes indicated that wind speeds are significantly less than 156 m/s (350 mph) (Golden, 1976). These wind speeds are typically established significantly above the ground and thus the built environment. Wind speeds near the ground are best established using forensic engineering of damaged structures. This work has revealed that the most intense tornadoes have wind speeds less than 112 m/s (250 mph) (Mehta Minor and McDonald, 1976).

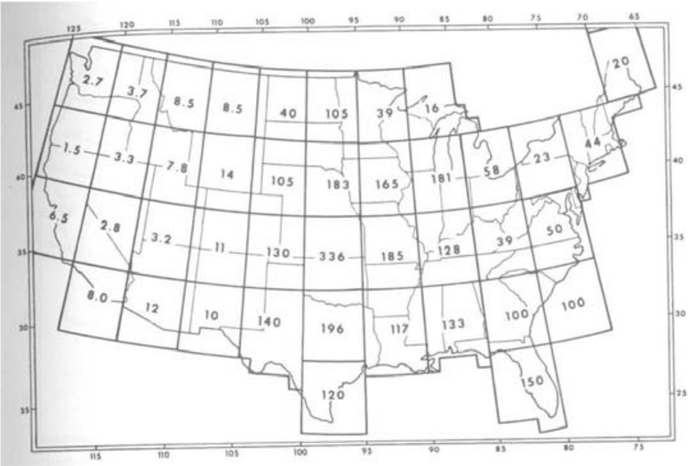


Fig. 2.17: Tornado strike probability within 5-degree squares in the contiguous United States. Units are 10^{-5} probability per year. From Markee, Beckerley, and Saunders 1974.

Fujita Scale

Until Fujita's pioneering work (Fujita, 1971), there was no systematic procedure to categorize tornado intensity. Fujita proposed a scale to classify tornado wind speeds based on appearance of damage (Table 2.5). His scale ranges from F0 (weak tornadoes) that have wind speeds less than 32 m/s (72 mph) to the most intense (F6) with inconceivable damage. His scale continues to F12 with sonic wind speeds, but these ratings are of little practical use. An F-Scale rating for a tornado is established based on the worst damage along the tornado path. The wind speeds assigned to each F-Scale were not rigorously established. Assignment of a wind speed to an appearance of damage inherently assumes that all buildings have roughly equal strength and quality of construction. This is not a valid assumption and Fujita later modified his scale to try and adjust for the construction type. Wind engineers commonly believe that the wind speeds associated with F-Scales F0 through F2 are probably reasonable; however, the speeds associated with F3 through F5 tornadoes are overestimates.

To more accurately tie the wind speeds associated with each F-Scale description of damage, researchers at Texas Tech University (McDonald and Mehta, 2004) undertook a project to refine the wind speeds associated with each F-Scale. The result of the project was an enhanced Fujita scale. Expert elicitation was used to establish mean, upper, and lower bound wind speeds for varying degrees of damage to a wide variety of structures types. The Enhanced Fujita (EF) scale has been accepted by the National Weather Service (Table 2.6).

Table 2.5: Fujita Scale

Scale	*Wind speed, mph*	*Qualitative Description*
F0	<73	**Light damage.** Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
F1	73–112	**Moderate damage.** Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads.
F2	113–157	**Considerable damage**. Roofs torn off frame homes; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	158–206	**Severe damage.** Roofs and some walls torn off well-constructed houses; trains overturned; most trees in a forest uprooted; heavy cars lifted off the ground and thrown.
F4	207–260	**Devastating damage.** Well-constructed houses leveled;structures with weak foundations blown away some distance; cars thrown; large missiles generated.
F5	261–318	**Incredible damage**. Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 m (109 yds); trees debarked; incredible phenomena will occur.

Source: Fujita Tornado Damage Scale, Storm Prediction Center, National Oceanic and Atmospheric Administration (http://www.spc.noaa.gov/faq/tornado/f-scale.html, accessed Feb. 15, 2012).

Tornado records, based on the original F-Scale, are maintained in a database by the Storm Prediction Center (formerly known as the National Severe Storm Forecasting Center). The National Weather Service has assigned Fujita Scales to tornadoes since 1971. F-Scale classifications for tornadoes prior to 1971 were assigned based on damage descriptions from official records, newspapers, and technical publications.

Distribution of Intensity

Approximately 1,200 tornadoes are reported annually (Davies-Jones Trapp and Bluestein, 2001). The distribution of the tornado intensities indicates that the vast majority of the tornadoes are weak tornadoes. Table 2.7 gives the tornado frequencies by F-Scale and shows that 90 percent of the tornadoes are rated F2 of lower. Only 0.3 percent of the tornadoes are categorized as F5, the most intense storm.

Table 2.6: Recommended EF-Scale Wind Speed Ranges

Enhanced Fujita Scale Classification	*Speed of 3-Second Gust (mph)*
EF0	65–85
EF1	86–110
EF2	111–135
EF3	136–165
EF4	166–200
EF5	>200

Source: Storm Prediction Center, National Weather Service, National Oceanic and Atmospheric Administration (http://www.spc.noaa.gov/efscale/ef-scale.html; accessed February 16, 2012)

Table 2.7: Tornado Frequencies and Classifications from 1950 to 1994.

F-Scale (Wind Speed Range)	*Number of Tornadoes*	*Percentage of Total Number*	*Cumulative Percentage*
F0 (40–72 mph)	11,046	31.3	31.3
F1 (73–112 mph)	12,947	36.7	68.0
F2 (113–157 mph)	7,717	21.9	89.9
F3 (158–206 mph)	2,523	7.2	97.1
F4 (207–260 mph)	898	2.6	99.7
F5 (261–318 mph)	121	0.3	100
Total	35,252	100	

Source: Storm Prediction Center, 1994

Chapter 3

Cladding Pressures

Cladding pressures on buildings are comprised of combinations of external pressures and internal pressures. The magnitudes of external pressures that can combine with significant internal pressures to establish design loads are discussed below. For design purposes, internal pressures may come from façade leakage, air-conditioning overpressure, or even windows and doors left open during a strong wind event. In hurricane-prone regions, modern codes and standards also require consideration of debris impacts on cladding. In some cases this may involve the use of well-designed hurricane storm shutters to ensure that the building envelope is not breached by flying debris (Fig. 3.2). Once the design pressure is established, the builder may use a previously tested and known product or have a new façade design tested for strength and water infiltration via some established full-scale testing procedure such as the pressure box. When pressures are referred to as negative it means the action is attempting to pull the cladding off the wall, and when they are called positive the wind is pushing on to the wall. Negative pressures are frequently the largest magnitudes in the cladding design load.

Fig. 3.1: Accurate design pressures are needed for glazed curtainwalls.

Fig. 3.2: Balcony-edge storm shutters may be used to protect the glazing. from flying debris.

External Pressure

Knowledge of external pressures is necessary to evaluate wind loads on components of the curtainwall and cladding systems. These wind pressures can be calculated directly from the basic 3-second gust wind speed (V) measured at 10 m above grade in open terrain (usually airports), by using the velocity pressure from the Bernoulli Equation $q = 0.5\ \rho\ V^2$, in which ρ is the air density; an exposure factor (K_z) to take into account the variation of the upstream velocity by the terrain roughness and height; and an aerodynamic pressure coefficient (GC_p) to take into account the variation of pressures at the various locations of the building envelope due to the building shape and its interaction with the wind flow and direction.

There may also be topographic (K_{zt}), directional (K_d), and importance factors (I) included in this calculation; but, in short, the external cladding pressure p is given by an equation similar to,

$$p = q\, K_z\, (GC_p)$$

and Fig. 3.3 shows a *simplified* wind pressure distribution on the envelope of a tall building in a diagrammatic way.

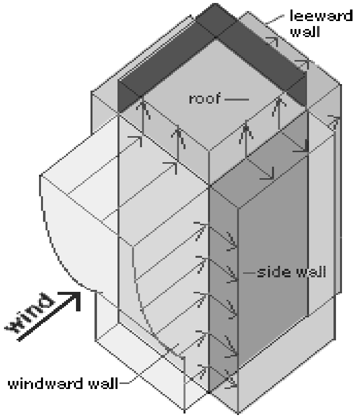


Fig. 3.3: Simplified wind pressure distribution on the building envelope.

Note that only on the windward wall of the slim building does the wind pressure vary with height above ground. A broad-faced, ocean-side condominium does not see such a strong variation in peak positive pressure with height. Both these are consistent with the results of wind-tunnel tests, which show a much greater variability (related to height) on the windward wall of slim buildings than on any other surface. However, in reality, a variety of turbulent effects occur, especially at building corners, edges, roof eaves, cornices, and ridges. Some of these effects are accounted for by the aerodynamic pressure coefficient (GC_p) in the building code calculation, which effectively increases the magnitude of the wind pressure at critical regions of the building envelope. Specific attention should also be given to localized areas of extremely high pressure, which are averaged into the total design pressures used when considering a structure's *"main wind force resisting system."* These high pressures need to be considered explicitly when examining the forces acting on relatively small surface areas, such as mullions and glazing, plywood sheathing panels, or roofing shingles. Building codes either stipulate higher wind pressures for small surface elements like glass and wall panels, or provide separate *component and cladding* values for the external pressure coefficients and gust factors.

Internal Pressures

Wind-generated pressures inside buildings can play a significant role in the overall loading of the building envelope. Internal pressures either combine with, or counteract, external building pressures to produce net pressures across the building envelope. Consistent with the sign convention for wind pressures noted earlier, positive internal pressures are directed toward a surface (tending to push the exterior walls outward), and negative internal pressures act away from a surface (tending to pull the exterior walls inward).

If the building envelope remains intact during a strong wind event then the internal pressure influencing the façade is relatively modest. The leaks and cracks around the whole external surface of the building will allow some area-averaged external pressure to infiltrate into the internal building volume. This is referred to as façade leakage, and when combined with a small air-conditioning overpressure, the typical internal pressure that is added to the external pressure yields a net design pressure for the building envelope in a range from about ±5 to ±15 psf (±200 to ±700 Pa). If there is a breach in the building envelope (Fig. 3.4), then the internal pressure will be substantially larger and is likely to initiate further catastrophic failure of the structure and/or envelope. Thus, the focus of most modern building codes is to protect the building envelope from either debris-induced breach or pressure-induced failure.

Fig. 3.4: Increased internal pressure, caused by a windward window failure (not shown to the left), overloaded the leeward unreinforced blockwork wall (Hurricane Andrew). The critical wind was from left to right.

Façade Leakage and HVAC Contribution

The magnitude of pressures inside a building is governed by the distribution of external building pressure, leakage through the building envelope (or porosity), HVAC systems and the presence and location of significant (or dominant) openings in the building envelope. Unless very specific and expensive precautions are taken to eliminate air leakage (such as for the containment of radioactive or harmful biological agents), all buildings will have some amount of leakage and will therefore enable outside air (and thus external wind pressures) to come inside the building. In the absence of large external openings such as windows and doors, external pressures are generally admitted to the building's interior via HVAC systems (exchanging air with the outside environment) and via tiny cracks between cladding and roof elements, around doors, windows, and electrical outlets. Conceptually, internal pressure can be thought of as a weighted average of the instantaneous external pressures at all the different leak locations and HVAC intakes and exhausts. These external pressures vary greatly over the outside surfaces, and will be positive on some surfaces and negative on others at the same instant in time.

Enclosed buildings are those in which air leakage through the building envelope is attributed only to porosity and HVAC systems. These buildings are not considered to have distinct openings in the curtain wall, such as operable doors or windows. For buildings with common construction on all exterior surfaces, porosity will be distributed approximately uniformly around all outside wall surfaces. At any given instant, more external surface areas are subjected to negative pressures than positive pressures. For enclosed buildings with an approximately uniform distribution of porosity, the internal pressure will be slightly negative, due to the transmission of external pressures from the majority of negative pressure surfaces. Combined with positive (inward-acting) external pressures, this small negative internal pressure will make only small increases in the net inward loads on windward surfaces; these net positive pressures should be considered in design but often will not control over negative pressures. Negative internal pressures serve to counteract negative external pressures. This counteraction, however, cannot be relied upon for design purposes, due to uncertainties in the exact value of external pressure for any particular building.

Breaches in the Façade

Partially enclosed buildings have distinct (or dominant) openings in addition to the porosity discussed above. Such distinct openings may be caused by doors or windows being left open during a windstorm, or they may be created accidentally by flying debris breaking doors and windows or breaching sections of the building envelope. The internal pressure in partially enclosed buildings is governed by the external pressure at the dominant opening(s).

The largest positive or negative internal pressures are found to occur with a single dominant opening and low building porosity. In this case, internal pressures will be very similar to the external pressure in the region of the single dominant opening (actually, the internal pressure will be slightly smaller than this external pressure, depending on additional porosity in the building serving to relieve the external pressure, and also depending on the internal volume of the building and complex mechanisms of transmission of the dominant-opening pressure throughout the building). For design purposes, a conservative estimate of internal pressure can be achieved by equating the internal pressure to the largest external pressure at a potential dominant-opening location (in some cases, this estimate may be overly conservative).

The worst-case scenario for internal pressures is a building with a single, windward opening. In this case, the building will experience a relatively large positive pressure, which will enhance negative external pressures to produce larger outward-acting pressures on leeward and sidewalls and on most roof surfaces (Fig. 3.5). Because negative pressures generally control the design of cladding elements, the effect of a large positive internal pressure can be quite significant.

Buildings with two or more dominant openings are found to have smaller internal pressures than buildings with a single dominant opening. Similarly, buildings with large porosities will have smaller internal pressures than more tightly sealed buildings. Because the possibilities of having more than one dominant opening and/or a leaky building (usually frowned upon by building tenants!) is uncertain, this scenario cannot be relied upon for building design. The classic design case remains that of a single dominant opening with low building porosity.

For overall frame shears (main wind force resisting systems), internal pressures will cancel mathematically, and as such are of little concern for the overall horizontal shear. It should be noted, however, that the potential loss of local cladding elements (such as plywood shear panels near building corners) due to internal pressure contributions can still compromise the reliability of the overall structural frame and should be considered in design.

Fig. 3.5: Windward leaky hanger doors during Hurricane Andrew increased the net leading-edge roof pressures, via larger internal pressures.

Windborne Debris

A common experience during severe windstorms such as tornadoes, hurricanes, and severe thunderstorms is the occurrence of flying debris of all types. If these objects are able to remain airborne long enough, they can impact downwind buildings, sometimes causing injury or loss of life, as well as increasing the property damage beyond that produced by direct wind forces (Fig. 3.6). A common occurrence is the breaching of building envelopes, following which high internal wind velocities and pressures are created. A well-documented "chain reaction" effect can occur, in which debris from upwind buildings breach the windward walls of downwind buildings during a hurricane; high internal pressures occur followed by failure of roof and sidewall elements, thus generating more debris, and the process continues downwind.

Debris Sources and Flight Speeds

Since the force of gravity always acts and will eventually cause an item of debris to strike the ground, the most common flying objects are those removed from the upper parts of buildings, especially roofs of buildings. These include roof cladding such as shingles or tiles, roofing components such as the classic "2 by 4" (actually about 40 by 90 mm or 1.5 in. by 3.5 in.) wooden members, and gravel from the roofs of high-rise buildings (this system is not recommended in high wind areas).

Fig. 3.6: Windborne debris can often generate dangerous missiles.

Smaller, lighter objects will start to fly at lower wind speeds and travel faster and farther than larger, heavy objects. Figure 3.7 shows three types of debris shapes, with different flying characteristics. The 'compact' types (perhaps represented by a piece of roof gravel), generally do not experience any lifting forces from the wind, and tend to fall downwards while being projected forward by wind forces. The plate type, representative of a roof shingle, for example, can experience lifting forces and will often fly faster and for longer than compact objects. The flight trajectories of plates are quite dependent on their angle to the wind at the start of their flight. Rod objects, represented by roofing members, for example, will usually have complicated flights with rolling and tumbling being present.

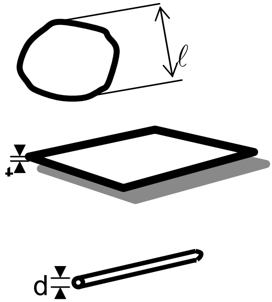


Fig. 3.7: Types of windborne debris (top to bottom): compact; plate; rod. From Holmes 2007, page 20; reproduced with permission from Taylor and Francis.

The horizontal flight speed of windborne debris should not exceed the wind speed, although this can be approached if the object is allowed to fly for long enough.

Debris Impact

Modern building codes and standards recognize windborne debris as an additional cladding load. ASCE 7 and the International Building Code (IBC 2003) define regions wherein designs for windborne debris are required. Generally, these regions are areas susceptible to hurricanes. Windborne debris loads are divided into large missiles and small missiles. Large missiles are specified for the lower 9 m (30 ft.) of a building façade, while small missiles apply up to a specified height (60 ft. or 18 m in ASCE 7) or for the full height of a building. The most common large missile is the classic "2 by 4" (actually about 40 mm by 90 mm or 1.5 in. by 3.5 in.) timber weighing 9 lbs. or 4 kg (representing a class of large objects) impacting at 15 m/s (50 ft./sec.). The most common small missile is a 2 g steel ball (representing roof gravel) impacting at 40 m/s (130 ft./sec.). ASTM E 1996 is a commonly referenced specification for windborne debris loads on high-rise buildings.

Fig. 3.8: A failed beachside deck canopy and adjacent roof segment becomes a source of many sizes of debris for downwind buildings.

Chapter 4

Structural Loads

Wind pressures primarily act at right angles to the surface exposed to the airflow, so that for vertical walls on high and low-rise buildings, the forces are horizontal. On a flat roof, the wind forces act vertically. For a roof pitched at say 30 degrees to the horizontal, the wind force acts at 30 degrees to the vertical (Fig. 4.1).

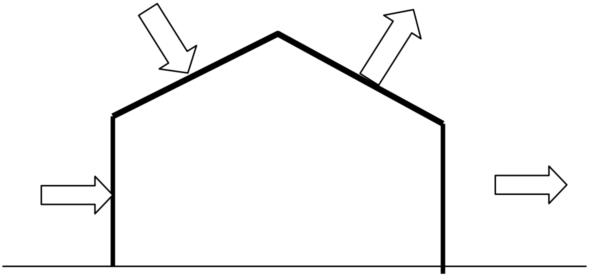


Fig. 4.1: Directions of wind forces.

When a tall building experiences vibration due to the wind loads, the structure sees apparent forces due to the mass times the acceleration of the structure at each floor level, for that part of its response. These apparent forces are known as inertial forces and are similar to those acting on a building responding to earthquakes. For the sway and torsional motions of a tall building, these forces act horizontally.

Building Response

From a structural design perspective, the most important aspects of building responses to wind are wind-induced loads and wind-induced building motions. The former are normally considered for the structural safety and the latter normally for the structural serviceability.

For a typical building the important wind loads are applied in horizontal directions and include alongwind loads, crosswind loads and torsional loads, which cause responses as shown in Figure 4.2. For structures with large roofs, such as arenas or stadiums, the important wind loads should include lift or down-force which is applied in the vertical direction on the roofs, as shown in Figure 4.3. Each of these loads consists of a static component (i.e., mean component) and a dynamic component (i.e., time-varying component). The classification of the wind loads is illustrated in Figure 4.4.

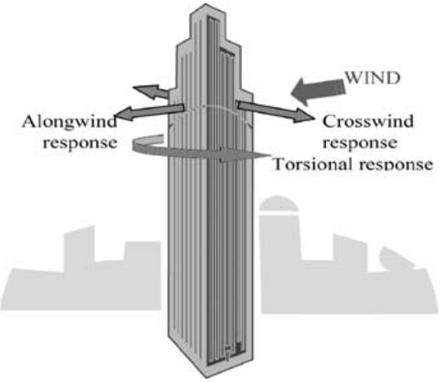


Figure 4.2: Alongwind, crosswind and torsional responses of a typical tall building.

Figure 4.3: Stadium roofs have other wind concerns.

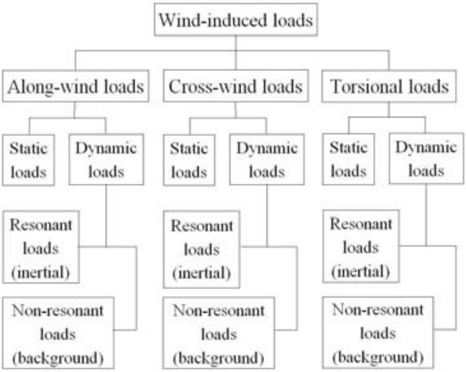


Figure 4.4: Classification of wind loads on a building.

The static wind loads are the results of mean wind pressure and are sensitive to the building geometry. For tall buildings, static wind loads are often dominant in alongwind direction. Crosswind static loads can be significant for some buildings with special shapes. Examples of these shapes include triangles and some unsymmetric curved sections. If the resultant force of the static wind pressures (including alongwind and crosswind) is away from the center of stiffness, a static torsional loading will be created. A typical example is the building with an "L" shape floor plan, where the torsional arm can be about 30% of the building width (Xie and Irwin, 2000). Buildings with unsymmetric step elevations can also cause high torsional loads.

Various types of wind excitation can induce the dynamic loads. The basic dynamic loads are due to unsteady wind pressures. These unsteady wind pressures can be caused by wind turbulence in the approaching wind, or by flow separations off the building surface. If the building motions are not significant, these dynamic loads can be assumed to be independent of the building's dynamic properties (quasi-static theory). These dynamic loads are called "background loads" or "non-resonant loads" and due directly to the wind pressures on the building surfaces. For a tall building or a large flexible structure, the background loads by themselves may not be very large because the unsteady wind pressures are not well correlated over the entire building surface. However, for these flexible structures the unsteady wind pressures can also excite the building structure into motion and this causes inertial loads, as the building mass accelerates during the motion. These inertial loads are generally called resonant loads because they occur at the building's natural frequencies only, and they are greatly magnified relative to the direct pressure loads coming from the wind at those frequencies.

Buffeting response causes the most common inertial loads. Buffeting is a random vibration of the structure excited by a broadband unsteady wind loading caused by wind turbulence. Buffeting will excite a building's sway and torsional modes of vibration and cause horizontal loads as well as torsional moments. Buffeting-induced dynamic loads increase with increases of wind speed and wind turbulence level. All buildings will experience some degree of buffeting responses. A typical spectrum of wind-induced base overturning moment is illustrated in Figure 4.5, which shows the background loads and the resonant loads caused by the buffeting response.

Some buildings or structures may experience vortex-induced oscillations. Vortex-induced oscillation originates from the alternate and regular shedding of vortices from both sides of the structure. This shedding of vortices generates rhythmic fluctuating forces on the structure in the crosswind direction. The frequency of the vortex shedding increases with increasing wind speed. If the frequency of the vortex shedding is close to one of the structure's natural frequencies at certain wind speed, large oscillations may occur due to resonance effects. Once vortex-induced oscillations are established, the vortex shedding frequency can become locked onto the structure's natural frequency even if the wind speed varies slightly from the original speed that initiated the motion. Wind turbulence tends to break up the regular shedding of vortices. Therefore, vortex-induced oscillations are most critical when structures are exposed to an open terrain where the turbulence level is relatively low. A structure by a lake or estuary may experience even lower turbulence levels due to the thermal stability effects of warm air flowing over cool water. Vortex-induced oscillations may cause large dynamic loads and severe building motions at a relatively low wind speed. Therefore, not only structural strength, but also serviceability and structural fatigue need to be carefully examined if there are potential vortex oscillation problems. Generally, vortex-induced oscillations should be minimized.

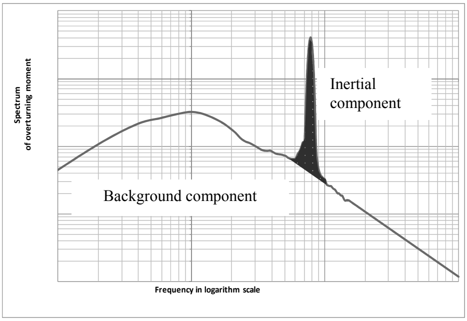


Figure 4.5: Typical tall building base moment response spectrum.

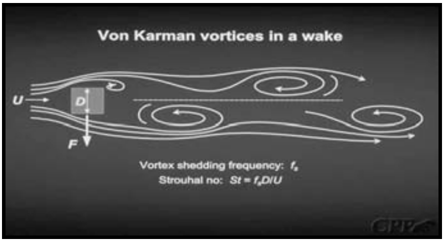


Figure 4.6: The alternate shedding of vortices off the side of a building creates forces that act perpendicular to the wind flow - a crosswind response.

If a building is located downstream of another tall building or a large structure, it is possible that the study building will be excited by the wake of the upwind building. Different from the buffeting case, the wake turbulence normally has a narrow band spectrum (i.e., the energy of the wake turbulence is concentrated over a narrow range of frequencies). If the outstanding frequency of the wake turbulence is close to one of the study building's natural frequencies, the study building may experience large resonance loads as well as motions. Upwind structures or topographic features may also cause localized accelerated flow acting on the study building and result in high response. This phenomenon is often referred as a "channeling effect."

Although divergent aerodynamic instability, such as galloping or flutter, has not been recorded for buildings, it has occurred on some lightweight structures such as sign structures, roof top spires and bridges. Galloping and flutter are self-excited aerodynamic instabilities that can grow to very large amplitudes and cause structural failure. The onset of galloping instability can be regarded as the wind speed at which aerodynamic forces cause the total system damping value, comprising structural damping and aerodynamic damping (which may be negative in unstable cases), to be less than zero. The higher the wind speed is above this critical speed, the more quickly the oscillations will grow to failure. Many readers will have seen the film sequence of the Tacoma Narrows bridge failure in the 1940s as an example of this mechanism (Tacoma Fire Department 1940). Therefore, it needs to be confirmed that the critical wind speed is much higher than the wind speeds expected at the site during the life of the structure.

The key parameters that affect wind-induced building response include:

1. The building's geometry and dimensions. Generally, a streamlined shape tends to experience lower wind loads. Open balconies, especially those around building corners, may be helpful in reducing wind-induced building response.
2. The building's mass and stiffness. Generally, heavier and stiffer buildings tend to be less sensitive to wind excitation than lighter and more flexible buildings.
3. The building's structural damping level. The wind-induced dynamic response of buildings will be decreased with increased structural damping level. In practice the damping inherent in the building's structural system is not readily controlled and estimates of the damping can only be made approximately based on empirical data. However, supplementary damping devices, such as tuned mass dampers (TMD), tuned liquid dampers (TLD), viscous dampers and active damping systems, can be effective and economic ways to reduce the wind-induced structural response.
4. The building's exposure to wind. Generally, a building will experience higher wind-induced response in an open terrain than in a built-up terrain. Problems with vortex-induced oscillations are mostly associated with open terrains. However, exceptions may exist if the surrounding buildings in a built-up area cause channeling effects and create accelerated flow, or induce wake buffeting loading on the study building.
5. The building's orientation. If a building's orientation is so designed that its most sensitive direction to wind excitation is away from the prevailing strong wind direction at the site, the probability of large wind-induced response will be reduced.

Strategies to Resist Wind

The following sections describe various design strategies for resisting or minimizing wind forces and response. The first of these describes aerodynamic strategies, which range from choosing a favorable roof such as a hipped or conical roof, to the use of desirable cross-section or corner chamfers on a tall building to reduce the wind forces to the vibration response produced by wind forces.

Other sections discuss structural strategies to resist wind forces and the directions in which the forces on a building act in strong winds. For a tall building, these forces are primarily horizontal, and the structural resistance is provided by systems such as cross bracing and shear walls.

On an inclined roof, the forces act at right angles to the roof surface, and thus have a strong component acting vertically. On a low-rise building, it is important to resist the vertical 'uplift' forces applied by the wind with a continuous load path down to the foundation. The roof is often the part of a low building that fails first in severe windstorms.

When the vibrations of tall buildings produced by wind are over the limits regarded as acceptable for human comfort (Chapter 5), they can be reduced by the use of special damping systems, such as tuned mass dampers or viscoelastic dampers. Devices like these, which have been installed in buildings, are described under structural strategies.

Section on storm shelters describes a social strategy to combat the effects of severe wind storms—namely the use of in-house or community storm shelters. This strategy assumes that many existing building structures will fail in severe windstorms, but the safety of residents can be assured by the use of storm shelters of high structural strength and resistance. This section describes the special design requirements of these structures.

Aerodynamic Strategies

Whether for a super-tall building or a domestic home, wind loads are greatly influenced by the shape of the design—the architecture. Good aerodynamic choices will result in reduced wind loads. For example, hips roofs on a home generally experience lower uplift pressures during an extreme wind event than gable roofs. They are simply more aerodynamically friendly.

The application of aerodynamics to architectural shape becomes even more important as a building becomes taller. The wind loads typically control tall building design. Varying the shape of the building with height will decorrelate the vortex shedding and so the crosswind response of a tall building. A residential building with protruding corner balconies will have a similar effect, and also reduce local cladding loads. Some taller buildings have open "refuge floors" (Fig. 4.7) for fire-safety reasons, but the aerodynamic impact is to allow flow through the building to reduce the magnitude of the negative pressure behind it. Dynamic loads on tall chimneys are often countered by installing helical strakes on the chimney. Even long suspension bridge decks commonly have fairings (triangular leading edges along both sides of the bridge deck) along their length to improve aerodynamic performance. In summary, using aerodynamic building shapes with strategic corner details, varying the shape with height, or using refuge floors to diminish the wind-induced structural loads will result in a better tall building design.

Cladding pressures may also be ameliorated with strategic design features. Corner balconies, as noted above, will reduce the design cladding pressures. Roof pressures may be reduced by the use of porous parapets or perimeter spoilers as shown in Figure 4.8. Even placing a new building within a complex cityscape of similar structures will be aerodynamically advantageous.

Fig. 4.7: Tall buildings resist the wind by architectural shape and structural system – Two International Finance Centre, or 2IFC, (420 m) in Hong Kong, China.

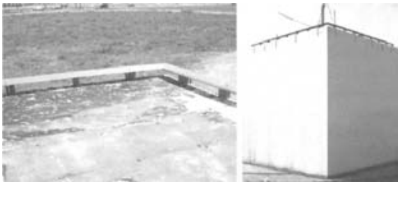


Fig. 4.8: Roof-corner vortex formation and roof-edge flow separation may be controlled by roof-edge spoilers. The diminshed roof pressures are substantially smaller.

Structural Strategies

While all structures in the wind must be designed to resist both lateral forces and uplift forces, which of these requirements is more important for a particular building is generally a function of the structure's aspect ratio, or relative height to width, as well as its shape. The design of a broad, low building with a relatively large roof area in proportion to its height, must give attention to resisting the uplift forces on the roof surface, with careful detailing of the connections to create a continuous load path to anchor the structure to the foundation. In contrast, a tall structure on a relatively narrow base must be designed with primary concern for lateral force resistance and overturning.

The use of shear walls is a time-honored, traditional way of resisting lateral wind loads on buildings. Solid masonry bearing walls provided resistance to lateral shear forces in times predating the development of the modern building materials steel and concrete. Shear walls in today's multi-story office and apartment buildings are typically created by forming one or more tall, rigid structural "boxes" wrapped around centrally-located elevators, stairs and/or lobbies. Such a structure is called a central core, and its action is to resist the tendency under the lateral force of the wind for a floor to shear or slide relative to the one below. For shear walls to be most effective they should be continuous throughout the height of the building and have as few openings as possible. A minimum of two shear walls orthogonal to one another is necessary to provide resistance to lateral wind forces, since the wind may come from any direction. Shear walls may be staggered within a vertical plane when required for interior spatial arrangements, but this is not ideal.

Reinforced concrete or braced or rigid steel framing may be used to form shear walls in multi-story buildings. Braced steel frames have diagonal members in the vertical shear walls which act in tension or compression to resist the tendency for side-to-side lateral movement of one floor relative to another. Rigid steel frames use moment-resistant connections instead of diagonals to withstand lateral forces. Moment connections are generally less efficient than diagonal members in resisting shear, but they create less difficulty when it comes to placing doors, windows or other openings in shear walls. Buildings may be designed with a combination system, using braced frames in one direction and moment frames in the perpendicular direction.

As tall buildings reach greater heights, they require structural systems with greater stiffness to increase their resistance to wind-induced lateral motion. In "tube" structures, the major wind-resisting structural system is located in or near the perimeter walls of a tall building, rather than around an internal core. As such, the wind-resisting structure becomes a factor in the architectural expression of the building. Tube structures, while inherently very efficient in use of material, must accommodate the competing demands of rigidity and continuity of structure on the one hand, and the occupants' need for multiple entrances at ground level and desire for large windows, on the other. Among the best-known expressions of tube structures in tall buildings are the closely-spaced columns of the former New York World Trade Center towers, the diagonally-braced façade of Chicago's John Hancock Building and the nine bundled tubes of Chicago's Sears Tower. The appeal of a tube structure's inherent stiffness and structural efficiency has led to many variations on this theme, among them the tube-within-a-tube, tube of stacked multi-floor modules, internal tube with extensions to exterior columns and buttressed tube or tubes.

Tall building structures must satisfy criteria for both strength (safety) and serviceability (human comfort). Wind-induced motion can cause discomfort to building occupants and, thus, in today's very tall buildings it is usually the serviceability criteria that control the design. If it is determined during the design process that top-floor accelerations could exceed acceptable limits (or it is found to be the case in a post-occupancy assessment), either the stiffness or the damping of the structure must be increased.

It has become common practice in very tall buildings to reduce top-floor accelerations by providing the structure with energy-dissipating damping devices, of which there are three basic types: (1) viscoelastic dampers, (2) tuned mass dampers and (3) tuned liquid dampers.

Viscoelastic dampers were first used in the former World Trade Center towers, 10,000 dampers installed in each tower at the joist-column joints. The dampers were attached in a diagonal configuration somewhat like small shock-absorber knee braces, each damper connecting the bottom flange of a long-span floor joist to the inner surface of an exterior column. Inside the damper casing, neoprene pads layered between sliding metal plates served to absorb, or damp, the relative movement between the joist and column as the building swayed, reducing its motion in the wind.

Tuned mass dampers are large, multi-ton blocks of lead, steel or concrete placed on a near-frictionless surface on an upper floor of a tall building. Figure 4.9 shows an alternative, which is a 700-t (620-ton) steel-sphere, pendulum design. The activation in a strong wind allows the mass to move in a motion that counteracts the wind-induced motion of the swaying building. A pair of tuned mass dampers was retroactively added to Boston's Hancock Tower to control the building's excessive wind-induced lateral and torsional movement. The tuned mass damper installed in the Citicorp Tower in New York was designed as an original part of the building's wind-resisting structural solution.

The tuned liquid sloshing damper is the most recently developed of the three types of supplemental damping devices. It consists of a large tank or tube containing a liquid (often water) of a specific viscosity. Paddles or fins in the tank impede the movement of the liquid as the wind-induced motion of the building causes the liquid to slosh back and forth, which in turn damps the building motion. Some of the most recently constructed very tall buildings and suspension bridge piers contain liquid sloshing dampers designed to reduce wind-induced accelerations to acceptable levels.

Figure 4.9: A pendulum-style tuned mass damper used in the recently completed Taipei 101, Taiwan. Photograph courtesy of Rowan Williams Davies and Irwin Inc. and Motioneering Inc.

Storm Shelters

Storm shelters are buildings (large or small) or portions of buildings designed specifically for the protection of life and safety during extreme wind events such as tornadoes and hurricanes. The design wind speed can be determined for a specific event (such as, a category 4 hurricane) or by selecting a wind with an appropriately low risk of occurrence (0.01% ~ 0.0001% probability per year), depending on the level of protection desired. Combined wind and flood loads must also be considered for all types of shelters at risk from rainfall flooding. Hurricane shelters may additionally be subject to storm surge flooding, which could occur simultaneously with the wind loads.

There are several types of debris that must be considered: windborne missiles, lay-down hazards, rollover hazards, and collapse hazards. The primary hazard presented by windborne missiles is penetration of the building envelope. While the large missile criteria used for normal design in hurricane regions (wood member as described in Chapter 3) is still relevant if used with a larger missile speed, consideration should also be given to more significant missiles with greater penetration capacity such as steel roof joists or purlins.

The other three types of wind-generated debris can impact the building envelope and/or main structural system. Lay-down hazards are structures or other objects (such as, buildings, communications towers, or large trees) located close enough to the shelter such that they might fall onto it. Shelters should preferably be sited to avoid lay-down hazards. Alternatively, they should be designed to sustain the impact load from the lay-down hazard. Rollover hazards are large objects tumbling along the ground, such as vehicles or large trash dumpsters. Collapse hazards are loads due to falling debris from unreinforced portions of the shelter building or adjacent/connected buildings. Loads due to rollover and collapse hazards should be considered.

Debris-impact resistant doors and windows should be used in all shelter spaces. However, due to the large uncertainty in debris size and impact speeds, these areas should be treated as openings for purposes of determining internal pressures.

Sometimes only a portion of a building will be used for the shelter and designed for extreme wind loads. For example, residential shelters are often located in a large walk-in closet. A community shelter at a school may consist of one hardened wing or floor of a classroom building. The shelter portion of the building should preferably be structurally separate from the remainder of the building. Alternatively, the shelter space should be designed to withstand the loads imposed on it due to failure of connected portions of the building that were not designed to withstand the extreme loads.

Federal Emergency Management Agency (FEMA) publication FEMA 320 provides guidelines for the design and construction of in-residence shelters. FEMA 361 provides similar guidelines for community shelters. The International Code Council is currently in the process of developing a national standard for storm shelter design and construction that addresses both residential and community shelters for hurricanes and tornadoes.

Figure 4.10: Public storm shelters are needed in many hurricane areas. Mobile homes should not be used for refuge. This rollover failure offers only risk, not protection.

“Red Flag” Issues

There are several wind-related issues that are worth highlighting individually to the architect and engineer. These items not generally addressed well, or at all, in codes and standards and yet they can be very important to the success of a new building. Over the four decades of wind-tunnel testing of various shapes, researchers have noted the geometries that work better than others from an aerodynamic sense. The same exploration of new architectural shapes has also generated knowledge about the crosswind response of tall buildings – an important area not effectively covered in most codes and standards (there is some information in the Standards Australia AS1170.2 (2002) for tall rectangular buildings and some guidance in the Architectural Institute of Japan (1996) Recommendations).

Nearby buildings may shelter a new building and reduce wind loads, or they may shed vortices and increase the turbulence impinging on the new building to increase the loads on whatever is in their wake. These phenomena are not addressed in the modern codes and standards. Another issue is the effect of torsion on the response about the vertical axis of a building due to the wind. The lack of coherent research in this area, and the multitude of building shapes, means that any guidance given (ASCE 7, AS1170, AIJ, and the Euro code) is commonly deficient. These, and other issues, are discussed in the following sections.

Building Shape and Wind Loads

The starting point to the understanding of wind loading on buildings and structures is an understanding of bluff body aerodynamics. This understanding can then lead to a description of the way aerodynamic pressures and forces are developed on structures. This description then leads to the way integrated pressures can act effectively as an instantaneous load on small structures and components of structures through to the resonant process that loads tall or slender structures in both along-wind and crosswind directions. This section will explain the wind loading process that is used to calculate the design loads presented in codes.

Most structures encountered in wind loading problems such as buildings, and towers constitute what are termed 'bluff bodies'; in contrast to streamline bodies such as aircraft wings. The term 'bluff' in aerodynamics is used to describe blunt obstacles that cause the formation of broad wakes due to the flow separating from their boundaries. In an ideal fluid, that is one in which there is no viscosity, such distinctions are unnecessary since there is no wake formation; the flow patterns can be described fully by streamlines and the pressure in the flow can be determined by the Bernoulli equation. In a flow of air such as the wind, however, the influence of viscosity is significant and the flow patterns are drastically altered. This is illustrated by the time-averaged flow pattern past a two dimensional square cylinder shown in Figure 4.11. In this instance a layer of intense shear or vorticity separates from the body at the two upstream corners and divides the flow into two distinct regions, specifically an outer region where the flow is essentially unaffected by the viscosity and a wake region. Separating these regions is the so-called 'shear layer' (curved rotational arrows in Figure 4.11).

The time averaged aerodynamic forces resulting from the surface pressure distributions on structures are conventionally resolved along directions parallel to and perpendicular to the direction of the undisturbed free stream flow; these forces are referred to as the drag (alongwind) and the lift (crosswind), respectively.

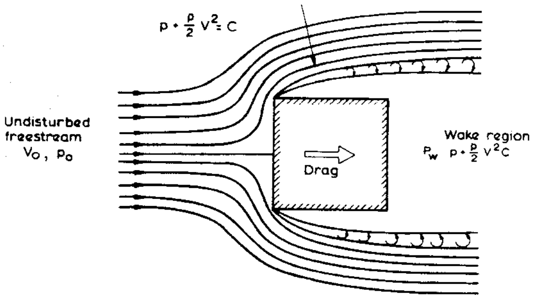


Figure 4.11: Time-average pattern of flow past a two-dimensional square cylinder. In the outer region the time average flow is relatively unaffected by the viscosity of the fluid except for the very thin layer close to the front face of the bluff square cylinder.

A drag force also results from the action of surface friction, or shear stress. While the shear stress contributes significantly to the drag of streamlined shapes, it is a low-order term compared with the pressure drag for bluff bodies. The aerodynamic drag forces on bluff bodies are usually larger than the lift forces, where again the opposite is true for streamline shapes at low angles of attack.

The wake region in Figure 4.11 is characterized by the energy dissipation that takes place due to the action of viscosity following the 'cascade' of energy of turbulent motion to smaller and smaller scales. It is a region in which the velocities and pressure gradients are relatively small and in view of the energy loss due to viscosity, it is no longer possible to use the Bernoulli equation directly to relate pressure and velocity. The pressure in the wake is related to the pressure existing at the freestream just outside the shear layer that is dependent on velocity (the Bernoulli equation) and hence is dependent on the geometry of the wake as defined by the shear layer. In particular, the position of the separation points and the radius of curvature of the shear layer are significant.

Two new factors that were not involved in the preceding discussion on two-dimensional bluff bodies are now introduced. The building bluff body is three dimensional, permitting flows around a free end, and the incident freestream flow is a turbulent shear layer with mean velocity increasing with height and turbulence intensity decreasing with height (Holmes, 2007).

There are two quite separate flow fields, which will be described with reference to Figure 4.12 to relate to the cause of high ground-level wind speeds near the base of buildings.

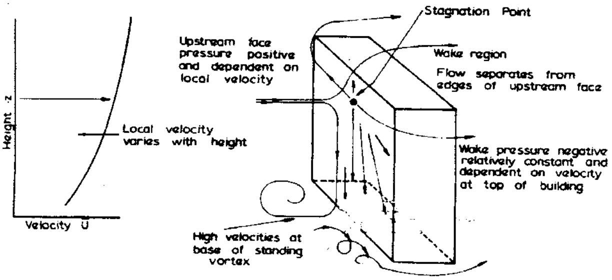


Figure 4.12: Features of the flow field around a large, three-dimensional, bluff building in an atmospheric boundary layer.

The first type of flow is caused by the pressure distribution on the windward face of a building that tends to be directly related to the local wind, dynamic pressure that increases with height. This pressure gradient induces flow vertically down the face (often called "downwash") below the stagnation point (which can be as high as 80% of the building height). This flow rolls up into a standing vortex system at the base of the building causing high wind velocities in this region. Buildings of near circular footprint, which promote lateral flow, do not produce strong vertical flows. Conversely, rectangular and concave buildings do produce strong vertical flows with consequent high wind conditions in the standing vortex system. The configuration of upstream buildings can be critical for this flow because under certain conditions the vortex flow behind a lower upstream building can augment the vortex in front of the larger building, further increasing the high wind velocities at the base.

The second type of flow is caused by the pressure difference between the low-pressure wake regions (leeward and side faces) and the relatively high-pressure regions at the base on the windward face. Flow directly between these two regions through arcades or around corners can cause very high local wind velocities. The low wake pressure tends to be dependent on the velocity along the top free boundary, that is, the freestream velocity at the top of the building. Hence, the taller the building the lower is the wake pressure and the higher the velocities that are induced around corners for a given aspect ratio. In general this problem is much harder to control because the wake pressure cannot easily be modified.

The mean surface pressure on buildings falls into two regions: (1) the positive pressures (on the upstream face), which are dependent on the mean dynamic pressure of the incident natural wind boundary layer and (2) the negative pressures (in the wake region, which is defined as all that region downstream of the separated shear layers), which are dependent on velocity just outside the shear layer. For buildings where the shear layers do not re-attach, the wake and, hence, the mean surface pressures generally tend to be dependent on the dynamic pressure at the top of the building.

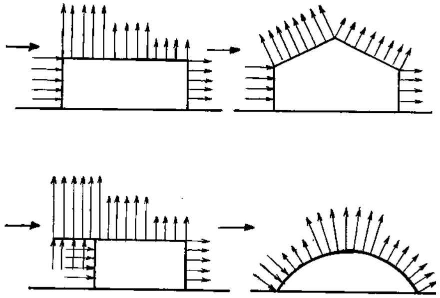


Figure 4.13: Typical code pressure distributions around buildings.

Mean pressure distributions on buildings are illustrated in Figure 4.13. These are the distributions that are typically developed in wind loading codes, based on quasi-steady concepts, to determine design wind loads or relatively small (domestic) structures.

The description of the aerodynamics of bluff bodies has so far been mainly restricted to mean flows, pressures and forces. However, to determine loading on cladding and glazing it is also necessary to consider the local fluctuating pressures. There are three very distinct pressure areas on a bluff body shown diagrammatically in Figure 4.13.

a) The upstream face where pressures are positive. The standard deviation fluctuations relate to the incident turbulence with an approximately normal distribution.

b) The streamwise faces (including roofs) near an upstream corner under the re-attaching shear layer are where the highest negative pressures occur. The standard deviation fluctuations relate to wake pressure fluctuations, but the distribution is far from normal due to intermittency, which it is related to the curvature of the shear layer, which in turn is dependent on the fluctuating re-attachment point.

c) The rear faces well downstream of any re-attachment in the wake where the pressures are negative. The standard deviation fluctuations relate to wake pressures and are relatively low with distributions showing moderate intermittency. The pressures in these areas are not normally critical for cladding design.

As it is the high negative pressure areas under re-attaching shear layers that tend to determine cladding design, the turbulence characteristics, leading edge shape and corner angle are very significant. For this reason modelling of this phenomenon has been difficult and some wildly differing pressures are offered throughout the general literature and wind loading codes that need very careful interpretation.

Alongwind and Crosswind Dynamic Response

The previous section dealt with the development of mean, quasi-steady and fluctuating pressures on buildings and structures. This section will deal with tall or slender structures where the effective wind loading is developed by the dynamic response to energy fed into the structure from fluctuating pressures via the resonant response process. The dynamic response in this context is in a natural mode of oscillation and the loads (base moments for example) are a result of resistance to inertial loading (mass times acceleration) resulting from the motion.

It has proved convenient to divide the response of structures to wind action into those motions that are alongwind and those that are crosswind. This distinction of convenience really relates to the forcing mechanisms rather than the response, because in many cases the alongwind and crosswind motions are of similar magnitude resulting in a response along an elliptical path, which is more circular than would occur if one were dominant.

Since the early 1960s it has been known that the alongwind response of most structures originates almost entirely from the action of the incident turbulence of the longitudinal component of the wind velocity (superimposed on a mean displacement due to the mean drag). Analytical methods, using spectral and spatial correlation considerations to predict the alongwind response of many structures have become highly developed, to the point where a gust factor approach is included in a number of wind-loading codes.

By comparison, the crosswind forcing mechanisms have proved to be so complex that as yet there is no generalized analytical method available to calculate crosswind response of structures. In many cases the major criterion for the design of structures, including tall buildings, is the crosswind response. This has meant that the only recourse left has been to determine this response from aeroelastic and/or aerodynamic model tests conducted in a wind-tunnel model of the natural wind.

In order to predict the response of a structure to a gusting wind it is necessary to define the spectrum of the loads induced by gusts. In order to appreciate the relationship between the spectrum of the overall loads on a building and the spectrum of velocity fluctuations, it is convenient to think in terms of wavelengths (or the inverse-wave numbers) rather than frequencies. If the mean wind speed at a given height is $\bar{U}(z)$ then we can associate a wavelength $\lambda = \bar{U}(z)/f$ with a frequency component f. λ is then a linear measure of the size of gusts or eddies producing load fluctuations at frequency f.

The effectiveness of a gust in terms of producing a load on a large structure will depend largely on the gust size in relation to the size of the structure, i.e. the ratio λ/H or $\bar{U}/fH$. In the case of high frequency components, the ratio $\lambda/H \ll 1$ and the pressures produced are well organized or correlated over quite small areas of the building. Their total effect is small since in some areas they will tend to produce increased loads while simultaneously, at other parts of the structure, there will be a decrease in load. The pressures due to the high frequency components of the wind spectrum are poorly correlated over the building as a whole. The very low frequency components of gustiness are associated with values of $\lambda/H >> 1$ and in this case their influence is felt over the whole, or at least large areas, of the building simultaneously.

The development of a gust factor approach is beyond the scope of this document, but a number of wind loading codes do incorporate such an approach based on spectral mechanics and resonant structural response for alongwind loading.

Probably the main reason why theoretical methods for predicting cross-wind response of structures have proved so intractable is that there are a number of quite separately identifiable excitation mechanisms that are frequently superimposed. In this discussion the excitation mechanisms will be identified as associated with:

a. the wake,
b. the incident turbulence, and
c. the crosswind displacement.

The main aerodynamic variables on which all three mechanisms depend arise from the characteristics of the incident free-stream turbulence structure and the mean wind speed. Wake induced excitation of structures was probably first identified in terms of cross-wind response of a structure when at certain critical wind speeds resonance occurred between a structural frequency and the shedding frequency of the von Kármán vortex street. One of the best examples is that of a lightly damped chimneystack oscillating at critical wind speeds in its fundamental mode.

The use of the term 'vortex excitation' has been deliberately avoided in favor of the term 'wake excitation' in this section so as to include all wake induced excitations and not just those associated with critical velocities. It is important to appreciate that the wake in this context is not just a base flow, but originates at the shear layer shed from the leading edge of a bluff body. This is particularly relevant to part of the excitation mechanism of low pitched roofs in general, cantilevered grandstand roofs in particular, and bridge decks.

With the exception of lightly damped slender structures it would appear that most realistic structures in turbulent wind flow having significant wake excitation, have crosswind response characteristics that increase regularly with mean speed to the power of between 2 and 3 and do not exhibit strong critical velocity effects.

It has proved difficult to isolate a measurable parameter that defines wake energy in terms of energy available to cause crosswind excitation. A diagrammatic representation of the forces originating from the wake available to cause crosswind excitation of various structures as a function of reduced frequency ($nb/\bar{u}$) is given in Figure 4.14 (b is the body width and $\bar{u}$ is the local mean velocity). The implication of this figure is that all bluff bodied structures get some crosswind excitation originating from the wake. In practice it seems that for a majority of structures the wake excitation is dominant. It is only when the afterbody becomes long enough to cause significant flow re-attachment (i.e. becomes a more efficient lifting body) that the incident turbulence excitation becomes first significant and then dominant, or at very low values of reduced frequency for certain sections when the rate of displacement (galloping) excitation becomes dominant.

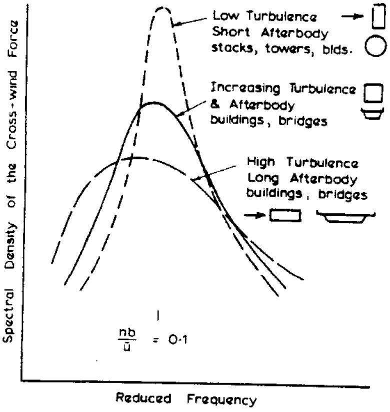


Figure 4.14: Trend of frequency distribution of forces originating from the wake, which are available to excite cross-wind motions for various structures and freestream turbulence.

Also included under wake excitation is the interference effect of the wake shed by an upstream structure, which could equally well be described as excitation due to incident turbulence for the structure affected.

The turbulent properties of the natural wind give rise to changing wind speeds and directions that directly induce varying lift and drag forces and pitching moments on the structure over a wide band of frequencies. The ability of incident turbulence to produce significant contributions to crosswind response depends very much on the ability to generate a crosswind (lift) force on the structure as a function of longitudinal wind velocity and angle of attack (α). In general this means a section with a high lift curve slope ($dC_L/d\alpha$) or pitching moment curve slope ($dC_m/d\alpha$) such as a streamline bridge deck section or flat deck roof. The mechanism of structural response to excitation from incident turbulence is either via the process of resonant excitation of one or more of the natural structural modes or by a single response to a well-correlated discrete gust.

Several crosswind excitation mechanisms are recognized under this heading, which more explicitly should read “excitation due to crosswind displacement and higher derivatives of displacement, and rotation.” There are three commonly recognized displacement dependent excitations, galloping, flutter and lock-in, all of which are also dependent on the effects of turbulence inasmuch as turbulence affects the wake development and hence the aerodynamic derivatives.

Galloping excitation results in a single degree of freedom motion that depends on the sectional aerodynamic force characteristics and on the rate of cross-wind displacement to produce a force in phase with the displacement. It is mostly two-dimensional structures such as electrical conductors that are prone to this form of excitation in practice. Flutter as a name is usually used to cover instabilities and excitations using more than one degree of freedom. In the civil engineering field the bridge deck has suffered, and is the one most likely to suffer, forms of flutter excitation.

Lock-in is a term used to describe a phenomenon whereby the crosswind displacement of a structure causes an increase in the wake energy, which in turn increases the crosswind response of the structure. In practice, this only seems to happen in turbulent flows when the structure is operating near the peak of the wake energy spectrum, which is near the wind speed at which the dominant vortex shedding frequency is the same as that of the structure. This can be referred to as a critical wind speed, as in a limiting form lock-in can cause rapid oscillatory divergence. The occurrence of galloping and lock-in with respect to towers can be regarded as displacement-dependent sources of excitation, which are superimposed on the wake excitation and are diagrammatically described as such in Figure 4.15.

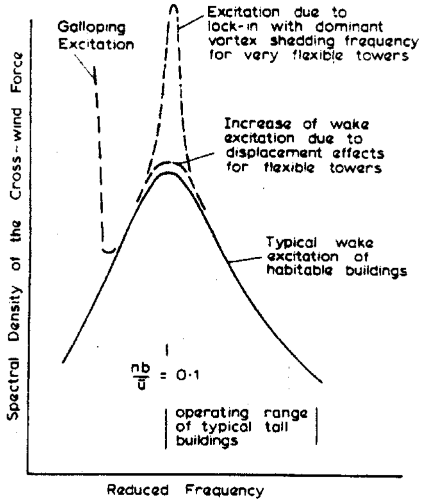


Figure 4.15: Superimposed displacement dependent effects on the distribution of forces originating from the wake, which are available to excite cross-wind motions on structures.

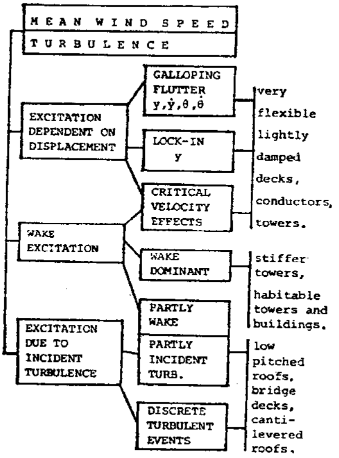


Figure 4.16: Variables and mechanisms associated with the cross-wind response of structures.

Turbulence plays a very significant role in the crosswind response of structures and there are two quite separate effects of the magnitude of freestream turbulence on the response of structures to wind action. The first is the direct effect on the response of a structure under the mechanism of excitation due to incident turbulence. The second and less well known effect of freestream turbulence on the mean and oscillatory response of a structure stems from the modification of the shear layer which in turn controls the development of the wake and hence the mean aerodynamic forces and the wake excitation. This effect is shown diagrammatically in Figure 4.14.

A diagrammatic summary of the main variables and mechanisms associated with the crosswind response of a range of structures is given in Figure 4.16.

Interference Effects

"Interference" is the phenomenon where the wind flow around one or more structures affects the wind loads on a nearby structure (Figure 4.17). "Shielding" and "buffeting" are other terms used to describe aerodynamic interactions between or among structures. Shielding usually refers to situations where the presence of an upwind building or buildings reduces the wind load on a downwind building, due to the downwind building's location in the wake of the upwind building. Buffeting is a term used to describe the random excitation of a downwind building due to the side-to-side alternation of vortices shed from the wind flow around an upwind structure. The term interference is used when there is an alteration in the load on a structure due to the presence of another. It is also an all-encompassing term that includes increased and decreased loads as well as crosswind effects that occur due to the upwind proximity of another structure.

Figure 4.17: Buildings in close proximity to one another may reduce wind loads (shielding) or increase wind loads (turbulent energy shedding) on their neighbors.

The complexity of architectural aerodynamics and the large number of variables needed for a full description of interference-causing configurations have made the codification of interference effects elusive, despite the fact that interference can cause both significant reductions and dangerous increases in the wind loads on structures. The only standard that explicitly attempts to codify shielding effects is the Australian/New Zealand Standard AS/NZS1170.2. This document specifies a 'Shielding Multiplier', M_s, applicable to design gust velocities that can take values less than 1.0 but no less than 0.7. There is some mention of interference interaction in the draft Eurocode, but it is limited to pairs and arrays of cylinders and a discussion of wake buffeting. Increasing the wind load is recommended for a low building adjacent to a tall building surrounded by low buildings. Other codes and standards, although not specifically using reduction factors for shielding effects, often incorporate reduced velocity or pressure multipliers near the ground in urban or suburban terrain.

Increased wind loads tend to occur when the presence of the upwind structure causes an increase in the velocity of the wind impinging on the downwind structure. This phenomenon can occur when the wind flow is channeled between two buildings or when the interfering building is shifted to one side rather than being located directly upwind of the affected building. Also, depending on the relative angles of orientation in the wind and to one another, and the proportions of the buildings, interference can cause significant increases in the peak torsional response of a downwind building.

Torsional Response

Torsional loading—causing a building to twist about its vertical axis—has long been ignored by building codes because of the lack of a theoretical basis on which to establish even simplified loads on an elementary rectangular shape. This lack of attention for many years has, unfortunately, resulted in an industry where most architects and design engineers are oblivious to the effects of wind-induced torsion, when it is likely to be of concern, and how to guard against it. Yet excessive torsional response is often the cause of poor curtainwall performance due to racking deformations, cracking of interior concrete and masonry walls, and increased perception of motion by the building occupants.

In real world situations, torsion can arise from a variety of sources. Mean torsional loads can occur in buildings whose cross-sectional shape is not symmetric (for example, the architecturally popular parallelogram in plan has one of the highest known torque coefficients), in a broad building that is partially shielded by a building offset from its centerline in very close proximity (Figure 4.18), or in a building which is structurally unsymmetric—one whose elastic axis is offset from its centroid axis (i.e. center of rigidity versus center of mass). This could occur, for example, in a building having an elevator core at one end, around which are the only significant lateral-resisting shear walls. Dynamic torsional loading due to gust buffeting can occur in all of these cases, as well as in a broad but totally symmetric building, because the gust wave fronts will not be totally correlated across the width. Dynamic torque, even if small, can be amplified in resonance to significant levels depending on the dynamic characteristics of the structural frame.

Figure 4.18: Partially shielded long slim condominium can produce substantial torsional mean and peak moments.

The most significant sources of torsion—building shape and environment exposure—are generally beyond the control of the structural engineer. However, the means by which the torque can be resisted are fully the engineer's responsibility. As a general rule, the most effective way of resisting torque is to provide adequate lateral stiffness in the form of, say, shear walls or braced or rigid frames, located as close to the outside or ends of the building as possible. This will have two effects: first, a given torque will produce lower stresses when resisted by elements spaced far apart; second, a wide spacing will result in higher torsional stiffness, and thus a higher natural frequency in torsion, which in turn reduces the dynamic amplification. Effort should also be made to keep the structure as dynamically symmetrical as possible, with minimum eccentricity between the inertial and elastic axes—i.e., the center of resistance at each floor should be as close as possible to the center of mass.

What magnitude of torsion should be assumed for design load? ASCE 7-95 was the first U.S. standard to require a torsional load, but it was very small, amounting to an eccentricity of 3.5 percent of the building width on the full design shear. This was significantly increased in ASCE 7-02, which requires that three quarters of the design shear be applied at an eccentricity of 15 percent. In addition, a dynamic gust factor must be applied if the building is "flexible" (defined by the standard as having a natural frequency of vibration less than 1 Hz), computed while taking account of the eccentricity between the inertial and elastic axes. The draft Eurocode requires that the full design shear forces be applied at an eccentricity of 10 percent. This requirement may be conservative for an elementary rectangular building, but may be quite unrealistic for other shapes, and even unconservative for certain less common shapes. The ASCE 7 standard, which is incorporated by reference into most other U.S. codes including IBC, is not intended to apply to buildings of "unusual cross-sectional shapes" or a "site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special consideration." For such conditions, buildings "shall be designed using recognized literature documenting such wind load effects or shall use the wind-tunnel procedure."

Building Appurtenances

Wind loads on buildings are recognized as a hazard that requires continuous acquisition of knowledge for effective mitigation. The current U.S. standard, ASCE 7-05, provides detailed wind design loads for structural systems as a whole, and for structural components such as roofs and walls including local cladding pressures. Wind loads on rooftop appurtenances, on the other hand, are only addressed in a cursory fashion (ASCE-7 clause 6.5.15.1) due mainly to limited availability of quantitative studies performed in field or wind tunnels to assess an appropriate gust effect factor.

Failures of rooftop equipment by winds have been well documented by field observers dispatched for damage assessment following major hurricanes and typhoons. It is common that equipments such as fans, HVAC units, and relief air hoods, are blown off their pedestals or support stands by excessive overturning moment (Fig. 4.19). On smaller pieces of equipment, fasteners (typically screws) used to attach the equipment to the pedestal/stand fail either by pullout or shear-off. On larger pieces of equipment (for example, a few hundred to more than a thousand pounds), it is common for the equipment to have no provision for uplift resistance other than the self-weight of the equipment itself. In very high winds, even extremely large and heavy units can be thrown from their kerb supports

In many cases, access panels (doors) on the HVAC units are blown off by high local negative pressures. Most failures are typically attributed to weak fasteners or to light metal through which the fastener is placed. Loose mechanical debris can cut the roof membrane, break glass, and injure people.

For codification into the ASCE Standards, for example, some wind-tunnel tests suggest a higher gust effect factor for rooftop appurtenances than for the base buildings. Use of a higher gust effect factor can be justified because the most typical rooftop equipment is relatively small in size to promote occurrence of high area-averaged, well-correlated, peak pressures. In addition, the equipment may be located in an accelerated flow zone near a roof edge or elevator overrun, thus warranting a higher gust effect factor. It is also reported that the peak horizontal and vertical forces acting on cubic rooftop equipment are highly correlated, and jointly cause large overturning moment. The current ASCE-7 value for a gust effect factor ranges up to 1.9.

Figure 4.19: Toppled rooftop HVAC equipment during Hurricane Andrew (1992).

Chapter 5

The Wind Tunnel and Physical Modeling of the Wind

The design wind loads to be used in the development of a new building may be estimated by using a code or standard, such as ASCE 7, or by physically modeling the new building in a well-conducted wind-tunnel test. The wind engineer is responsible for ensuring that the wind-tunnel test, typically at scales ranging from 1:200 to 1:500, is performed with the correct approach flow and that an adequate expanse of model surrounding the subject building is built. Figure 5.1 shows an example of a 1:300 model at the downwind end of a boundary-layer wind tunnel. The flow approaching the model first passes over some spires and a trip that spans the wind tunnel's entrance section (to generate some initial turbulence) and then travels over a long length of roughness elements on the wind-tunnel floor (wooden cubes in the example shown). The suburban approach flow in this case (Exposure Category B in ASCE 7) is generated by many upwind cubic elements that may be thought of as representing the suburbia surrounding the city center. The resulting flow profile arriving at the turntable model has the desired vertical mean velocity profile and vertical turbulence intensity profile (gustiness) for the scale chosen. Data are then typically taken with special instrumentation at 10-degree increments (36 wind azimuths) by rotating the model on the turntable. Details of the techniques to be used and parameters to be satisfied in this physical modeling process may be obtained from technical documents such as ASCE Manual of Practice Number 67 (1999) or Australasian Wind Engineering Society Quality Assurance Manual (2001). The discussion that follows here illustrates what can be done for clients with this need, and the reader is directed to technical manuals like ASCE 67 or AWES QAM-1 for the detailed advice on how to generate the required data or to assess its correctness.

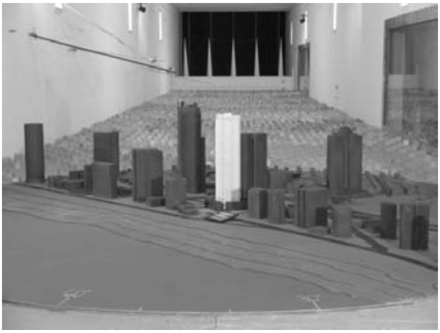


Figure 5.1: A new building being tested in a boundary-layer wind tunnel with the surrounding cityscape on the turntable.

Structural Load Studies

Wind-tunnel model tests to determine loading on a building's structural frame are performed by a variety of methods. These depend on the nature of the expected loading and dynamic response of the structure. They have also evolved substantially over the last 30 years or so, and continue to evolve further.

It is very common to describe the nature of the expected loading and response by distinguishing the various components as follows:

Mean: The spatially integrated effects of the external pressure distribution, averaged over a period of time of say 20 to 60 minutes.

Background: The fluctuating portion of the external aerodynamic loading, typically described as the peak value of a load effect—base moment, shear at a particular floor level, etc—in excess of its mean value. Background fluctuations typically occur primarily at frequencies that are lower than the structure's lowest natural frequencies of vibration.

Resonance: The additional amplification of background aerodynamic effects, when there is significant aerodynamic loading at frequencies that are close to the natural frequencies of vibration.

Aeroelastic: The modification of external aerodynamic flow patterns and associated pressure distributions that sometimes occurs when the dynamic motions of a structure—usually induced by resonance—are unusually large.

Prior to the 1980s, model tests were usually conducted only on very tall buildings, for which all of the above effects can be significant. The largest loads were expected to be dominated by resonance, with possible aeroelastic effects included. Tests were performed using an aeroelastic model, in which a rigid model of the building is supported on a flexible mechanism and placed in a boundary-layer wind tunnel capable of modeling the atmospheric boundary layer. Such a test may be viewed as a physical analog of the governing equation of motion, which in a simplified form is

$$m\ddot{y} + c\dot{y} + ky = f(t, y, \dot{y}, \ddot{y})$$

The aeroelastic model is scaled to the prototype geometry and "tuned" to the proper values of the mass *m*, damping coefficient *c*, and stiffness *k*. The wind-tunnel environment is configured to provide a properly scaled external loading, *f*. This loading is a combination of the turbulent wind velocity and its interaction with the model. It exists in the model test, but cannot be measured explicitly. The response of the model structure, *y*, is monitored directly through the overall displacement, acceleration, or equivalent forces (moments) at the base of the building. No direct information is available regarding the distribution of forces over the height of the structure. However, the fluctuating portion of the response is dominated by resonance, and therefore assumed to be the dynamic response of the fundamental mode of vibration, for which the mass distribution and mode shape is known. Within reasonable accuracy, then, the dynamic portion of the response load can be distributed to each floor in proportion to the mass and modal displacement at that floor. The data determined in this manner are static-equivalent loads, which the engineer can apply to the structure, and perform a simple static analysis to check design.

Aeroelastic models are relatively expensive to design and build, time consuming to test, and somewhat difficult to interpret in view of uncertainty or changes in the building's dynamic properties. In many cases, redesign of the building structure could require that the model be retuned and retested, entailing additional time and expense.

In the 1980s it was realized that in most cases, the excitation is independent of the building motion, or simply *f(t)*, the external aerodynamic load. If the structure's dynamic response is dominated by resonance, this load can be approximated by the aerodynamic moment near the base of the structure. This can be measured using a "base balance," provided that it is sufficiently stiff—and the building model sufficiently lightweight—that the model/balance system does not vibrate in the wind. The essential requirement is that the system has a natural frequency of vibration that is significantly higher than the frequency content of the aerodynamic load. This model test method is known as a high-frequency base balance (HFBB) or sometimes high-frequency force balance (HFFB), although forces themselves are often not measured in deference to moments, but they are sometimes of useful, if secondary, importance. Once the aerodynamic excitation *f(t)* is known, the equation of motion is easily solved analytically. Typically, the power spectral density of *f(t)* is determined and the theory of random vibration employed to obtain the standard deviation of the fluctuating dynamic response, *y*. This result is then interpreted the same as in an aeroelastic model test result. However, changes in the structure's dynamic characteristics can now be accommodated analytically, without the need of revising and retesting the model. This process has become so optimized that structural engineers are now routinely given static-equivalent loads for several design iterations of the mass, stiffness, natural frequency, or damping of the structure.

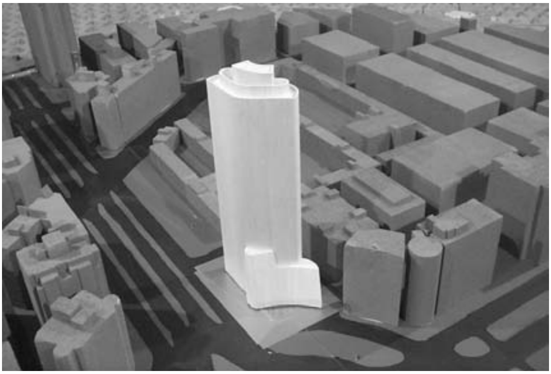


Figure 5.2: A 1:400, lightweight, balsawood, HFBB building model installed on the force balance within a city turntable.

The essential feature of ignoring motion-induced modification of the wind excitation classifies this method as an aerodynamic model as opposed to an aeroelastic model. The HFBB remains the most popular form of an aerodynamic model, but other methods have been developed. In particular, the recent availability in some laboratories to measure pressures simultaneously at a large number of tap locations (say 500 to 1000) enables the aerodynamic loading to be evaluated through the spatial integration of pressure measurements.

The advent of aerodynamic model test methods has revolutionized the application of wind tunnels to building structural frame loads. Many buildings are now tested that are medium-height (say 20 stories) or even lowrise (say 10 stories or less). However, the loads on such buildings may no longer be dominated by resonance, and the mean and background components are relatively more important than in highrise or other very flexible structures. Aerodynamic base-moment models can determine the mean, background, and resonant base forces, but distributing the corresponding forces over the height of the structure based on mass distribution and mode shape can be quite inaccurate. Other simplified methods, such as assuming a distribution shape from traditional building codes but scaling it to the known base moment, are often acceptable if the building does not have an unusual profile or is not located in a complex environment. Usually, a conventional pressure-tapped model of the same building is also tested—primarily for the purpose of obtaining peak local cladding pressures—and the mean values of all pressure tap locations can be spatially integrated to obtain an accurate vertical distribution of the mean structural frame loading. The integrated-pressure method is theoretically capable of evaluating the distribution of background loading as well, both vertically (among floor diaphragms) and horizontally (within each floor). However, this requires very careful and complex analysis of test data that may be warranted only in special cases.

The decision of what type of test to perform is largely that of the wind-tunnel laboratory, depending on test equipment and data processing capabilities, but must also be coordinated with the structural engineer. Decisions must be made regarding whether aeroelastic response can be neglected for highrise buildings, whether dynamic resonance can be neglected in lowrise buildings, and whether detailed vertical and horizontal distributions of load are important. Future developments are likely to merge the most favorable characteristics of all methods to provide a unitized testing and data processing methodology to address all of these considerations.

Top-Floor Accelerations

Buildings and structures respond to wind excitation in a complex way with motions occurring predominantly in a horizontal plane and are occasionally combined with torsional motions, as shown in Fig. 5.3. Flexible, tall, and/or slender buildings are more prone to wind excitation and, occasionally, the wind-induced building motion reaches a level perceptible to the occupants (Fig. 5.4).

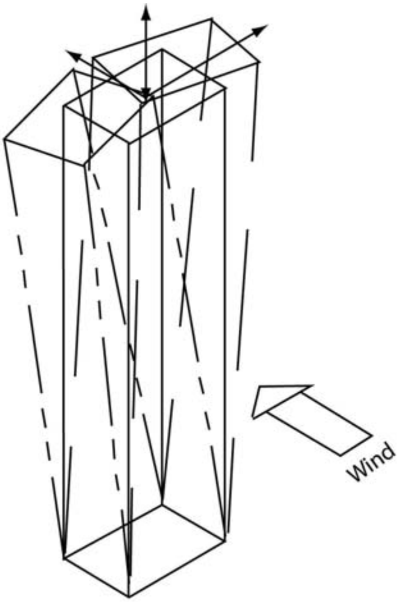


Figure 5.3: Wind-induced motions of a tall building.

Figure 5.4: Super-tall buildings need to be assessed for top-floor accelerations as part of the design process.

People perceive motion primarily through the sensory organs in the inner ear. External stimulus, such as audio cues (for example, wind noise and squeaking partitions) and visual cues (for example, swinging objects and sloshing water), enhance the perception of motion. The physical state of a person, such as posture, activity, tiredness, psychological state of mind and even expectation of motion in a tall building during high wind also accentuates the feeling of motion.

The wind-induced motions of tall buildings, as shown in Figure 5.5, are mostly cyclic oscillations at a frequency depending on the building height. The taller the building, the lower the frequency and vice versa. Evidently, occupants more readily perceive building motions at a high frequency than those at a low frequency. For tall buildings ranging from 100 m to 300 m in height and with a frequency of, typically, 0.15 to 0.5 Hz, the majority of occupants will feel building motions that correspond to a peak acceleration of around 10 milli-g (one milli-g is one thousandth of gravitational acceleration). In practice, those buildings that frequently exhibit wind-induced motions exceeding 10 milli-g are unlikely to be acceptable to most occupants. Although occupants often become acclimatized to the building motions, remedial measures, such as the installation of dampers, may be necessary to reduce the building motions to a more satisfactory level.

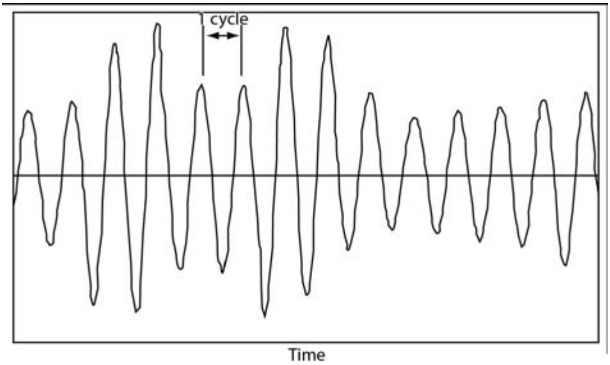


Figure 5.5: Cyclic oscillations of a wind-excited building.

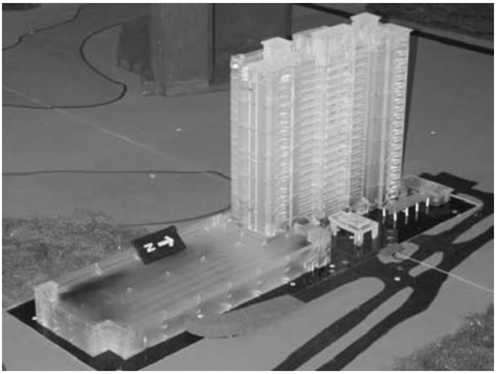


Figure 5.6: A 1:300 pressure model, with over 700 taps installed on the surface of the tower and adjacent garage structure, used to generate design cladding pressures.

Cladding Studies

The design pressures on the external skin of a building are best determined via a site-specific, building-specific study in a boundary-layer wind tunnel. The pressure model is perforated by hundreds of small holes (called pressure taps) that transmit the surface pressure collected in the wind tunnel to an equivalent number of electronic transducers. These electrical signals can then be stored and interpreted by a computer. When these pressure data are combined with the extreme wind statistics (e.g. 100-year wind speed for each direction around the compass rose) for a given location then contour plots of the largest peak design pressures may be plotted on elevations of the building being tested. The net peak design pressures are then presented in a "cladding zone" drawing, once the modest internal pressure (caused by façade leakage and, perhaps, an HVAC system) is added to the measured peak external pressures. The resulting design pressures contain the influence of building geometry, upwind approach conditions, nearby buildings and directional wind statistics. The façade consultant can then design the external cladding to have strength where it is needed, rather than waste capacity where it is not needed to the same degree. The generic nature of code guidance to cladding pressures does not allow these judgments to be made, but a site-specific, building-specific wind-tunnel study does. It is the performance of a properly conducted wind-tunnel study, for cladding pressures on the façade that frequently produces substantial financial savings for the owner.

Pedestrian Wind Studies

The architect and building owner frequently want to know if the design of their building will aggravate the ambient wind conditions around, and on, their new site. Some cities (e.g. Boston and San Francisco) have specific wind speed requirements on the streets around sites in their urban centers. Certain absolute wind velocities during a statistical time period (e.g. once per year) must not be exceeded when a new building is proposed. However, in many circumstances it is simply the desire of the owner/developer to create a quality project with good, useable, outdoor tenant space or an inviting main entrance (Fig. 5.7) that drives the need for a pedestrian wind study, rather than any local government mandate. Thus, areas within a residential development (such as the pool deck or entrance porte cochere) may also need to be calmer than elsewhere around the building for successful long-term use by the tenants.

In a public space development, such as the museum entrance in Figure 5.8, the aim is to create a pleasant and useful outdoor location for cultural gatherings. In such cases a variety of landscaping geometries may be explored in the wind tunnel, at modest expense, prior to any construction commencing. The ground-level wind speeds are typically measured by a hot-film anemometer (Fig. 1.17), or similar device that can record mean and peak wind speeds. These data are then compared to guidelines from the peer-reviewed literature to assess the acceptability of a location on or near the subject building. Sometimes comparative locations are measured, well away from the project, to see how other known conditions compare to the new ones when the building is built. Data collected with and without the new building in place is sometimes used to assess the influence of the new development on the existing conditions. All these investigations are far cheaper to explore and fine tune on a 1:300 model long before the project is built, than on the final development when there is a concern voiced by the tenants or local community.

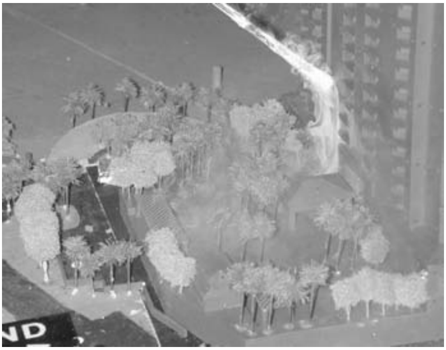


Figure 5.7: Downwash off the tower is deflected by the porte cochere and tree canopies to produce a calm inviting entrance.

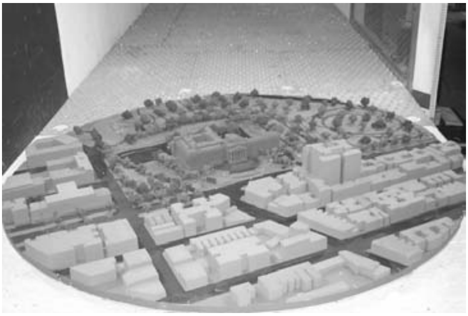


Figure 5.8: Pedestrian-wind study of a new museum entrance and public space area.

Further information on the assessment of human comfort in outdoor areas, including the combined effects of wind and thermal factors, can be found in the American Society of Civil Engineers publication "Outdoor Human Comfort and Its Assessment" (2004).

Urban Design Strategies

Important urban planning and design decisions such as street patterns are made in the very early stages of urban design. It is common for wind engineers not to be involved in urban planning or design until much later in the project, if at all. This means that decisions that could be significantly affected by wind are made without important wind considerations, such as street pattern orientation to prevailing winds and relative location of large buildings, low buildings, and open spaces. Contemporary urban planners and urban designers rarely work with wind engineers but this has not always been the case. The Ten Books on Architecture (Vitruvius 1960) describes how Roman planners of garrison towns took great care in aligning the main streets of the rectangular street grid with cooling summer breezes. In many locations this resulted in the street grid being inclined at 30 to 40 degrees to the direction of winter winds, providing some protection from wind chill. Chinese Feng Shui protocols addressed these issues for centuries in urban planning (Cotterell and Morgan 1975). Serious consideration of wind in city planning was undertaken when Portuguese colonial cities were planned for South America to accommodate trade, using the sailing ships of the time (Violich 1944). The recent urban expansion and new city development in locations such as China, South East Asia (Yeang 2000) and South America (Evans and De Schiller 1996) has revived interest in consideration of wind in urban planning. Influence of relative height of a new building on local pedestrian level winds has been studied (Isyumov and Liversey 1992). Increased mean wind speed with height above ground in urban areas has led to tall building designs such as that for the proposed new World Trade Center buildings incorporating wind turbines to supplement the energy needs of the building (ASHRAE 2004).

A report called the Wind Climate in Cities was commissioned by NATO (Cermak Davenport Plate and Viegas 1995). Summer urban heat islands develop when extensive hard paved surfaces and building facades exposed to solar radiation absorb large quantities of energy. The heated surfaces heat adjacent air by surface conductance and people in streets are subjected to heat from infrared radiation. This is the reason air temperature within urban areas is higher than air temperatures in surrounding rural areas. In summer the increase in air temperature in urban environments can impose increased difficulty in maintaining human thermal comfort in urban areas (Tso 1996). Insights into urban morphology and its relevance to urban design in various climates have illustrated the importance of airflow patterns associated with various arrangements of streets and size of buildings (Golany 1995). Straight, wide streets aligned with prevailing summer breezes are recommended for warm humid tropical climates. Urban heat island mitigation can be assisted through urban planning and design such as enhancing breeze penetration, and reduction of hard paving in favor of trees and other foliage (Aynsley and Gulson 1999). It is clear from the impact of urban heat islands that wind engineers and urban planners can contribute significantly to energy saving and thermal comfort through good urban design.

Architectural Design Strategies

The shape of a building, along with the complexity of the natural and anthropogenic surroundings, will have a substantial influence on the pedestrian conditions on and around a new development. In the case of a tall rectilinear building, fast winds at elevation are drawn down to the street level via a mechanism called “downwash.”

This vertical building flow is clearly shown by the smoke in Figure 5.7. Wind impacting the bottom two-thirds of a broad building face travels down the front of the building, while wind arriving at the top third of the building generally travels around or over the top of the structure (Fig. 5.9). This mechanism is the chief cause of strong ground-level winds and is substantial reason for the use of large entrance canopies, centrally located on the broad face of new developments, and porous trellises in pool areas. The canopy deflects the downwash from ground level and, as Figure 5.9 suggests, placing the building entrance or an outdoor restaurant at the building corner is generally inadvisable.

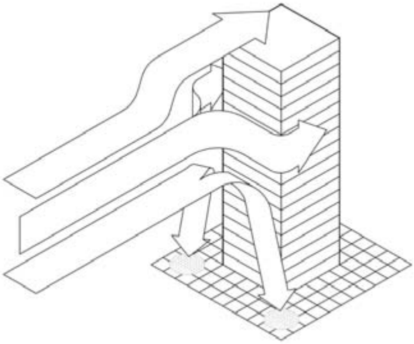


Figure 5.9: When the "downwash" flow hits street level it turns horizontally around the corners, yielding a particularly windy region at the base of the devlopment.

The second principal mechanism for creating windy conditions around the base of buildings may be generally labeled “horizontally accelerated” flows (Fig. 5.10). The most successful way to ameliorate winds effects stemming from this mechanism is a porous fence (50 to 60 percent solid) or the extensive use of bushy foliage. Both these approaches consume a lot of the kinetic energy in the flow and provide a protected wind region for six to eight barrier heights downwind.

Lastly, most penetrations across the full building depth (arcades and plazas with the building on columns above) will attract strong flows through the gap. Thus, this architectural massing should be avoided unless that development is in a definitively tropical city with low typical ambient wind speeds (for example, Singapore) and an additional breeze is desired due to the high temperature and humidity. Further discussion of these and other architectural ways to influence pedestrian-wind conditions may be found in Cochran (2004a and 2004b).

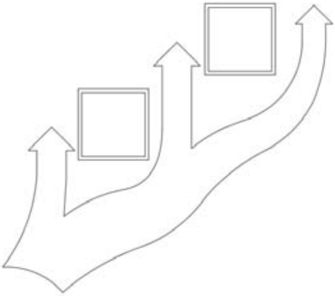


Figure 5.10: Horizontally accelerated flow between buildings, or building components, may also yield unpleasant pedestrian-wind conditions.

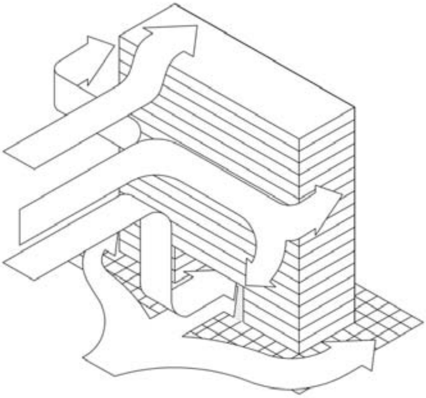


Figure 5.11: Arcades through tall buildings (or tall buildings on columns over an open plaza) are an architectural concept that should be avoided as it attracts strong winds under the development.

Topographic Effects

Wind speeds can be modified considerably by natural and man-made topography such as escarpments, embankments, ridges, cliffs, and hills.

As the wind approaches a shallow hill or escarpment, its speed first reduces slightly as it encounters the start of the slope upwards. It then gradually increases in speed as it flows up the slope towards the crest. The maximum speed-up occurs at the crest, or slightly upwind of it. A building located at or near this location will experience greatly increased wind loads compared to those on flat level ground. Beyond the crest, the flow speed gradually reduces to a value close to that well upwind of the topographic feature.

On steeper topographic features, flow "separation" may occur, as the flow is not able to follow the rapidly changing surface slopes. Separation may occur at the start of the upwind slope, immediately downwind of the crest, and on the downwind slope for a ridge. Separations are generally associated with high turbulence or "gustiness" in the wind.

The affects of topography on winds produced by large storms, such as winter gales and hurricanes, can generally be reproduced quite well in wind tunnels that are large enough to allow sufficiently large models to be installed. Wind-tunnel models are often used to determine the affects of large-scale features. For example, Victoria Peak in Hong Kong influences the general wind environment in urban region called Central on the north shore of Hong Kong Island (Fig. 5.12), which contains many famous high-rise buildings.

Fig. 5.12: Flow over 1:4000 model of Victoria Peak in Hong Kong, China.

Snow Deposition Studies

Snow loads for design of building roofs or other structures are defined in the building codes. However, the geometries treated are limited, and provisions for many buildings are difficult or impossible to define from the code. Tests on a model in a wind tunnel or water flume can assist in defining snow loads by having a simulated snow fall on the model in the presence of wind, or by having the wind drift the simulated snow already on the roof or ground. There are recent methods available to combine the results of wind-tunnel tests of drifting, or of wind velocities over a roof, with historical meteorological data to improve the estimate of design loads. These tests can often be performed using the same model used for wind loads tests.

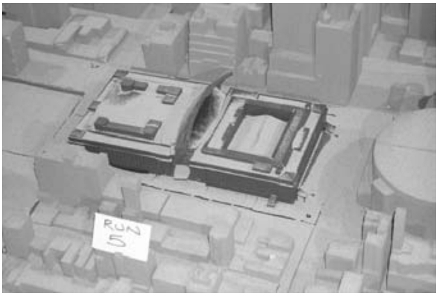


Figure 5.13: Snow deposition studies at a scale of 1:400 in the wind tunnel are helpful is assessing likely snow loads. For scaling reasons the "snow" here is made of crushed walnut shells.

Frequently Asked Questions

1. *Do I need to consider a wind-tunnel test for buildings fewer than ten storeys in height?*

Most building codes advise wind-tunnel tests for unusual buildings or where special conditions apply such as accelerated wind flow between two structures. Most tested buildings are taller than ten storeys, primarily because the budget for these projects can afford a wind-tunnel test. Since wind-tunnel tests are more accurate than building code provisions, and since wind-tunnel testing often decreases project costs, the criteria for a wind-tunnel test should probably be motivated more by project cost than project height. For example, several single-storey, multi-million-dollar homes have been investigated in the wind tunnel to assess the structural loads and ambient pedestrian-wind conditions.

2. *Can I get the same results by computer analysis?*

By computer analysis, we usually mean use of a Computational Fluid Dynamics (CFD) computer program. At this point in time, CFD analysis cannot reliably give answers equivalent to a wind-tunnel test. Because of this, CFD is not permitted as a method that satisfies building code requirements. CFD is an active research area and this answer may change sometime in the future.

3. *Do wind-tunnel data satisfy building code requirements?*

In almost all cases this is true. Most building codes today either explicitly permit wind-tunnel testing or permit use of ASCE 7, which permits it. Wind-tunnel results are permitted to replace completely the analytical provisions of the code so that the lower values often found by wind-tunnel test can be used.

4. *Can my architectural model be used for the wind-tunnel study?*

Rarely. To obtain cladding pressures, for example, the wind-tunnel model must be instrumented with hundreds of pressure taps (small holes in the model surface) and these would destroy much of the value of the architectural model. In a few cases, the architectural model might be used to obtain information on, for example, pedestrian wind acceptability in a way that does not destroy the value of the architectural model.

5. *Where are the potential savings if I do a wind-tunnel study?*

Because code loads "envelope" the loads from a number of building shapes and therefore should lie near the upper edge of the range of expected loads, the wind-tunnel test often shows smaller loads for both local cladding pressures and frame loads that can permit a more economical design. In the few cases where wind-tunnel wind loads are higher than code loads, there are potential savings from wind damage that will be avoided in the future.

6. *At what point in the design process should a wind-tunnel study be performed?*

Wind-tunnel tests are normally commissioned after the building design is substantially complete, so that wind loads for design of the frame and cladding can be obtained. There are times when earlier testing can be advantageous. For example, pedestrian wind acceptability can be examined during project massing to avoid creating windy environments in unexpected areas.

7. *Do wind-tunnel tests need to be performed at hurricane wind speeds?*

No, there are well-established methods for converting wind pressures measured at a lower wind speed to the higher speeds associated with design for hurricane winds. Testing at lower speeds is less expensive.

8. *What level of detail is needed on the wind-tunnel model?*

The level of detail required may depend on the size of the structure under study and the type of test and results needed. However, for a common example, a 91 m (300 ft) high building might have details as small as 300 to 600 mm (1 to 2 ft) reproduced. Small features such as a 76 mm (3-in.) window inset will not have any influence on a building of this size.

9. *Can a wind tunnel help with tornado design?*

In some ways, yes. While wind-tunnels do not reproduce the rotating wind of a tornado, much of the damage seen from tornadoes looks very much the same as from straight-line winds. The local tornado wind flow over many structures is approximated reasonably well by a straight-line wind, particularly for the larger diameter tornadoes. Thus, wind pressures obtained on a model at lower wind speeds in a wind tunnel can have value when translated to pressures associated with the full-scale tornado speed. However, few structures are designed to withstand the forces of a severe tornado due to the high cost of construction and low probability of occurrence. It should be pointed out that half of all tornadoes have peak speeds less than about 45 m/s (100 mph). Table 2.6 expands upon this observation. Structures designed to withstand the winds in a non-hurricane zone have a 40 m/s (90 mph) design speed and a failure speed of more than 49 m/s (110 mph). Thus, structures designed and constructed according the requirements of ASCE 7 should survive half of all tornadoes with little damage.

10. *How can the effects of future construction or demolition of surrounding buildings be accounted for in a wind tunnel study?*

The effects of changes in surrounding buildings that are known about at the time of the tests can be examined as part of the test program. The unknown future changes in surroundings can be divided into two categories:

a) addition or demolition of buildings far upwind, having the effect of changing the general terrain roughness and thus the exposure of the site; and

b) addition or demolition of buildings close to the site which can cause changes in the local flow patterns about the study building.

Considering category (a), based on the history of most cities, development over time is far more likely to increase rather than reduce the number and height of buildings. This implies that over time the general exposure of the site is most likely to become rougher, i.e. increasingly more sheltered, making the wind tunnel results conservative. With respect to category (b), some of the local flow patterns caused by changes in nearby buildings do have the potential to increase loads. However, unless a building of unusual height is constructed nearby, the normal use of load or safety factors can be expected to cover the potential increases in structural loads. The same applies to cladding loads except in areas of the building envelope that are predicted by the wind-tunnel tests to have very low cladding loads. Such areas can be highly sensitive to changes in surroundings but potential problems can be avoided by applying a lower limit to the wind pressures actually recommended for use in the design of the cladding.

11. *What is the typical timing for a wind-tunnel study?*

When a wind-tunnel study of a new building is commissioned, and the architectural drawings are available, the common time frame for design data to be available to the client is five to six weeks. This is obviously dependent on the building complexity and how busy the wind-tunnel laboratory is, but the sequence of events is typically: design and build the scale model (2 to 3 weeks), collect data in a boundary-layer wind tunnel (1 week), data reduction (2 weeks) with the Final Report to be issued shortly thereafter.

12. *What information can I expect from a wind-tunnel study?*

There are two parts to wind-tunnel studies: a) the laboratory testing part which produces raw data, usually in the form of pressure, force and velocity coefficients; and b) the consultation part which includes setting the parameters for the tests and combining the test data with wind statistics and structural information to arrive at specific recommendations that can be readily used by the design team. Both the laboratory testing and the consulting parts of wind-tunnel studies are important and it is essential, when commissioning a wind-tunnel study, to be sure that both parts are available to the client.

The consulting part of a wind-tunnel study really begins before the test. The scope of the testing needs to be discussed to make sure a) that it is sufficient and b) that it will be cost effective. For example, on a high rise building a typical test scope would be a structural load study, a cladding study and a pedestrian-level wind study, all done using a rigid model. However, on a 20-storey concrete building in an area of high seismic activity it may not make sense to do the structural load study since seismic loads will govern the structural design rather than wind. In this case the structural study could be eliminated but the other two would still be undertaken. If the same building is located in a hurricane area with low seismicity then the complete test program would be needed. On a very tall, slender tower it may be that aeroelastic effects will be significant in which case an aeroelastic test using a flexible model may need to be added to the test program. Some of the building appurtenances such as spires or other flexible architectural features may be prone to wind-induced vibrations. In such cases special assessments or additional wind tunnel studies may be needed on these elements. The scope of pedestrian-level wind studies may need to be expanded or contracted depending on the planned usage of the outdoor areas. There may be other issues such as snow loading, dispersion of building exhausts, or wind-induced noise where the wind consultant can provide valuable services. These types of issues are best discussed with the wind consultant before finalizing the test program.

Setting the parameters for the tests and developing the test specifications are important parts of the consultation. For example, the types of boundary-layer simulation to be used in the tests for different wind directions need to be determined based on a review of the terrain surrounding the site. Where on the building will measurements be taken and what kind of measurements will be made? What kind of sample rates should be used in data acquisition? Should combinations of pressures be measured to assist in the specification of internal pressures? Should area averaged loads be measured on some parts of the structure that are particularly flexible? What surrounding structures need to be included in the proximity model and how far out should the proximity model go? Is there the potential for future buildings to be constructed nearby and how will this be accounted for in the testing? All these decisions and many others involve some engineering judgment and experience and are part of the consulting component.

The test program itself means constructing a model, setting it up in the wind tunnel and undertaking the tests according to the test specifications. It is important that the test house keep good records of the information on which the model was based and exactly what was tested. Photographs of the model in the wind tunnel can help record the test set up but the test parameters such as boundary-layer profiles used, data acquisition rates, wind speeds etc. all need to be recorded also. The laboratory should have an active quality assurance program to ensure that the models are built correctly and that the test specifications were adhered to. This typically means that someone other than the person to whom the task was assigned checks each activity. Also, laboratory procedures should be structured so as to minimize the chance of simple mistakes being made such as hooking up the wrong instrumentation channels or using the wrong calibration curves. Thus, it is reasonable for anyone commissioning a test to seek evidence that an effective quality assurance program is in place. Since a quality assurance program brings with it an added cost, this should be born in mind when comparing costs from different wind-tunnel laboratories.

To convert the wind-tunnel data into useful design information usually requires combining the wind-tunnel data with historical wind statistics. This step, which is part of the consulting component, is in most cases a critical one and is the source of most of the differences between results coming from different wind consultants. As an example, in cladding studies the wind-tunnel test will provide data on peak pressure coefficient versus wind direction. At a particular location on the building the 50-year exterior pressure could in principle be estimated by simply multiplying the highest-pressure coefficient for any wind direction by the full-scale 50-year reference pressure. However, this would represent an upper bound estimate rather than the true value. To obtain the true 50-year exterior pressure, which is often well below the upper bound value, the probability of strong winds from different directions needs to be accounted for. This is a more complex analysis, but the benefits in terms of more realistic results and cost savings in the cladding system are substantial.

Another important part of the wind consultation is the analysis of historical wind records. Just as it is important to use realistic simulations of the planetary boundary layer when undertaking the test in the wind tunnel, it is also important to use a realistic model of the planetary boundary layer when assessing the exposure of the anemometer from which the historical records were taken. This means assessing the terrain roughness upwind of the anemometer for each wind direction and making appropriate adjustments for both terrain roughness and anemometer height. It is important to use a consistent set of boundary layer assumptions in both the analysis of wind records and the wind-tunnel simulation. Mixing and matching of different boundary-layer models (e.g. a simplified code model for the analysis of wind records and then a more scientifically based model in the wind tunnel) for the two parts of the studies can lead to erroneous results. The wind consultant’s report should be clear as to what the various assumptions concerning boundary layer models were for each study.

In general the information coming from a wind consultant should be such as to be readily useable by the designer and to be in the form of engineering recommendations rather than a laboratory data report. For example, wind loads for structural design need to incorporate the effects of the dynamic properties of the structure, the effects of wind statistics and directionality, the potential effects of future buildings, and perhaps the influence of internal pressure (for roofs), and be clearly tabulated on a floor-by-floor basis or in the form of pressure diagrams. Also, the possible combinations of loads in different directions and in torsion need to be identified. As another example, recommended cladding loads need to be clearly displayed on building elevations and plans and should include the contribution of internal pressures. Also, they should again take into account in some way the uncertainties due to possible future construction (or demolition) and the possible internal pressures caused by openings in the building envelope, whether due to operable windows or the breaching of the envelope by flying debris. Curtainwall designers typically need the zones of different pressures to be unambiguously displayed using the building grid system as a reference, a form of presentation usually referred to as block diagrams. If all that is displayed are the predicted pressures at individual points then someone still has to make decisions as to how to interpolate between the points. When commissioning a test it is best to be clear as to whether the wind consultant is going to fully interpret the data and provide block diagrams or whether only point pressures will be supplied, leaving the interpolations to be done by the design team.

From the above discussion it is clear that to obtain the most from wind-tunnel studies it is important for there to be close communications between the designers and the wind consultant, particularly at the start of a project when many important decisions are made affecting the scope of the studies.

Glossary

Alongwind Force: The aerodynamic force in the direction of the mean wind velocity; sometimes referred to as drag.

Atmospheric Boundary Layer: The lower part of the atmosphere, typically 250 m to 600 m thick, in which the properties of the flow are directly influenced by the Earth's surface. There is a pronounced increase in the mean wind speed with increasing height. The flow is highly turbulent, particularly near the surface of the Earth.

Cladding: Components of the exterior skin or envelope of a building or structure which keeps out the "weather" but does not contribute to the overall resistance to wind action. The cladding resists local wind loads and transfers them to the main structural system. A specific type of cladding associated with high-rise structures is called the curtainwall.

Coriolis Force: The force applied to an object in flight (or atmospheric winds) to account for the observed curved trajectory due to our rotating frame of reference (the Earth). This results in winds moving parallel to the isobars in the atmosphere, instead of in the direction of the pressure gradient as it would be in a non-rotating reference frame.

Crosswind Force: The aerodynamic force in the direction perpendicular to that of the mean wind velocity, sometimes referred to as lift.

Cyclone: See "Hurricane."

Ergodic Process: An ergodic process is a stationary random process involving a collection of time history records where time averaged results are the same for every record. It follows that these time averaged results from any single record will then be equal to corresponding ensemble averaged results over a collection of records (Bendat and Piersol, 2000).

Extra Tropical Cyclone: A large scale, low-pressure system outside the "tropics" that rotates anti-clockwise in the northern hemisphere and is typically 800 to 1300 km in diameter. In the southern hemisphere the rotational flow is clockwise. This type of weather system is the main source of extreme winds in temperate regions.

Foehn Winds: Warm (adiabatic compression) and dry (moisture lost on the windward ascent) winds that flow down the lee side of a mountain range. In the United States one of best examples of a wind of the Foehn type is the Chinook in the lee of the Rocky Mountains that can be intense and turbulent.

Frequency Response: The range of frequencies to which an instrument can respond without significant distortion of the measured quantity.

Hot-Wire Anemometer: An instrument for measuring wind speed in the wind tunnel that is sufficiently responsive to detect velocity fluctuations due to turbulence. It consists of a small heated wire (typically at about 250° C) immersed in the airflow. The wire may have a length to diameter ratio as high as 200:1 and is often made of a Tungsten alloy. The cooling of the wire by the flow provides the measure of the wind speed. A more robust design which is now more commonly used has larger length to diameter ratio, say 20:1 to 40:1, and is referred to as a “hot-film.”

Hurricane: A tropical cyclone (referred to as “typhoons” in Asia and “cyclones” in the Indian Ocean and Southern Hemisphere) with surface wind speeds exceeding 120 km/h. Tropical cyclones are storms which generally originate in latitudes between 5 and 20 degrees north and south of the equator and derive their energy from the latent heat of water vapour when over the ocean; loosing their intensity when crossing over land. One prerequisite for the maintenance of a hurricane is that the sea surface temperature be greater than 26° C, (Pielke, 1990).

Neutral Stability: A stratification of the atmospheric boundary layer in which the vertical variation of the mean air temperature follows the adiabatic lapse rate. This is characteristic of strong winds during which buoyancy forces become negligible.

Prandtl Pitot Tube: A pair of concentric tubes—the inner one open to the oncoming flow and the outer one closed, but with peripheral openings some ten to twelve diameters downstream from the streamlined end. The inner tube is used to record the pressure of the stagnation flow while the peripheral openings in the outer tube record the ambient pressure at that location. The difference of these values is the velocity head that, with knowledge of the local fluid density, may be used to measure the flow velocity. A well-designed Prandtl Pitot tube will have a calibration coefficient of 0.99, or better, and so corrections may not be required.

Pressure Tap: An opening or hole in the surface of a model or full-scale building or a structure that allows the wind-induced pressure at that location to be communicated to a pressure transducer.

Random Phenomenon: A physical process which ... “cannot be described by an explicit mathematical relationship, because each observation of the phenomena will be unique,” (Bendat and Piersol, 2000).

Reynolds Number: The ratio of typical inertial forces to viscous forces in the flow under consideration.

Roughness Elements: A regular or random pattern of objects placed on the smooth wind-tunnel floor designed to generate the desired boundary-layer profile. In the case of city building studies this is analogous to the upstream suburbia that influences the natural wind. Typically the height of the roughness elements is approximately 30 times (Schlichting, 1978; Meroney, 1989) the local z_o.

Spectrum: A spectrum is a description of a quantity in terms of any function of frequency.

Standard Deviation: The standard deviation is the positive square root of the variance. The standard deviation is equal to the rms value if the mean is zero (Bendat and Piersol, 2000).

Stochastic: A process of a random nature, taken from the Greek word stochos (a guess). This expression was first applied to random processes by the mathematician and physicist Jakob Bernoulli, 1654 to 1705 (Sadeh and Koper, 1978).

Synoptic: Large-scale atmospheric phenomena with scales of several hundred kilometers.

Tornado: A rapidly rotating column of air in contact with the ground and originating from, and may be connected to, a cumuliform cloud.

Turbulence: A collection of descriptions and/or definitions that exemplify the phenomena well are presented here:

> "Turbulence is a three-dimensional motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow. It is the usual state of fluid motion except at low Reynolds numbers." (Bradshaw, 1971).
>
> "One can succinctly state that turbulence is a continuous flow phenomenon that is random, rotational, nonlinear, time dependent and three dimensional which occurs in shear flows for real fluids at relatively large mean flow Reynolds numbers to warrant the growth of flow inborn and/or physically induced instabilities and which is further characterized by specific time and space scales determined by the viscous forces and the boundary conditions, a high degree of macroscopic diffusiveness (mixing) and a continuous transfer of energy from larger to smaller spatial scales effected through stretching and tilting of vortex tubes that results, in the end, into turbulence dissipated into heat." (Sadeh, 1988).

Typhoon: See "Hurricane"

von Kármán Vortex Street: The regular series of alternating eddies shed off a bluff body as flow passes by. The shedding frequency is a function flow velocity, sectional shape and across-flow object width.

References and Recommended Reading

Architectural Institute of Japan, “AIJ Recommendations for Loads on Buildings.” English Translation, Tokyo, Japan, 1996.

American Society of Civil Engineers (ASCE). “Wind Tunnel Model Studies of Buildings and Structures. *Manual of Practice Number 67*, 1999.

ASCE. *Minimum Design Loads for Buildings and Other Structures (ASCE 7-05,)* 2006.

ASCE. *Minimum Design Loads for Buildings and Other Structures (ASCE 7-02,)* 2003.

American Association for Wind Engineering (AAWE).“Wind Engineering: New Opportunities to Reduce Wind Hazard Losses and Improve the Quality of Life in the USA,” *American Association for Wind Engineering Report*, 1997.

ASHRAE, “Harvesting Wind at Ground Zero.” *Industry News, ASHRAE Journal* (February 2004): p. 8.

ASHRAE. ”Airflow Around Buildings.” *ASHRAE Fundamentals,* Ch. 15, 1997.

American Society for Testing and Materials International (ASTM). “Standard for Performance of Exterior Windows, Glazed Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes, ASTM E 1996-02, West Conshohocken, PA, USA: ASTM International, 1996.

Australasian Wind Engineering Society (AWES). *Quality Assurance Manual for Wind-Engineering Studies of Buildings* (AWES-QAM-1), 2001.

Aynsley, R.M. and Gulson, L. “Microclimate and Urban Planning in the Humid Tropics.” Paper presented at the proceedings of the RAPI 27th National Congress, Darwin, September, 1999.

Aynsley, R.M., Melbourne, W., and Vickery, B.J. *Architectural Aerodynamics*. London, United Kingdom: Applied Sciences Publishers Ltd., 1977.

Battan, L.J. *The Nature of Severe Storms*. Garden City, NY, USA: Anchor Books, 1961, p. 158.

Bendat, J.S. and Piersol, A.G. *Random Data Analysis and Measurement Procedures,* Third Edition: John Wiley & Sons Inc., 2000.

Bradshaw, P. *An Introduction to Turbulence and its Measurement*. The Commonwealth Library of Science Technology Engineering and Liberal Studies, First Edition: Pergamon Press, 1971.

Cermak, J. Davenport, A., Plate, E., and Viegas, D., Editors. *Wind Climate in Cities,* NATO Series E: Applied Sciences, Vol. 277. Dordrecht, Holland: Kluwer Academic Publishers, 1995.

Cochran, L.S. *Wind Engineering as Related to Tropical Cyclones.* edited by Roger Pielke Sr. and Roger Pielke Jr., Storms Book – Ch. 14: Routledge Press, London, United Kingdom, 2000: 242-258.

Cochran, L. “Causes of Unpleasant Pedestrian Wind Conditions.” Proceedings of the Eleventh Australasian Wind Engineering Society Workshop, Darwin, 2004a.

Cochran, L. “Solutions to Unpleasant Pedestrian Wind Conditions.” Proceedings of the Eleventh Australasian Wind Engineering Society Workshop, Darwin, 2004b.

Cochran, L.S., “Design Features to Change and/or Ameliorate Pedestrian Wind Conditions”, Proceedings of the ASCE Structures Congress XXII, Nashville, Tennessee, May 22-26, 2004c.

Cotterell, A. and Morgan, D. *China: An Integrated Study.* London, United Kingdom: Harrap Publishing, 1975.

Davies-Jones, R., Trapp, R.J., and Bluestein, H.B. *Tornadoes and Tornadic Storms. Severe Convective Storms.* Boston, MA, USA: American Meteorological Society, 2001.

Eurocode, prEN1991-1-4, “EUROCODE 1: Actions on Structures, General Actions, Part 1-4, Wind Actions”, CEN TC 250, 2004.

Evans, J. and De Shiller, S. “Application of Microclimate Studies in Town Planning: A New Capital City, an Existing Urban District and Riverfront Development,” *Atmospheric Environment,* Vol. 30, No. 3, , (1996): 361-364.

Fujita, T.T. *Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity.,* SMRP 91 Research Project, Department of Geophysical Sciences, University of Chicago, 1971.

Goff, R.C. “Thunderstorm-Outflow Kinematics and Dynamics.” *NOAA Technical Memorandum ERL NSSL-75.* Norman, OK: U.S.DOC, National Severe Storms Laboratory, (December 1975): p. 63.

Golany, G. *Ethics and Urban Design: Culture, Form and Environment.* New York,, NY, USA:John Wiley and Son Inc., 1995, p. 260.

Golden, J.H. “An Assessment of Windspeeds in Tornadoes.” Symposium on Tornadoes: Assessment of Knowledge and Implications for Man. Lubbock, TX, 1976.

Gray, W.M., Schaeffer, J.D., and Landsea, C.W. "Climate Trends Associated with Multi-Decadal Variability of Intense Atlantic Hurricane Activity," in *Hurricanes, Climate Change and Socioeconomic Impacts: A Current Perspective,* edited by Diaz, H.F. and Pulwarty, R.S.: Westview Press, 1996. p. 49.

Green, W.E. Private communication to Leighton Cochran. 1990.

Houghton and Carruthers. “Wind Forces of Buildings and Structures: An Introduction.” 1976.

Holmes, J.D. *Wind Loading of Structures,* Second EditionUnited Kingdom: Taylor and Francis, 2007.

“International Building Code (IBC 2000),” 2000.

Isyumov, N. and Liversey, F. “The Influence of Relative Height of a New Building on Local Wind Environment.” Paper presented at the ASCE Structures Congress, San Antonio, 1992: 360-367.

Lee, B.E., Hussain, M., and Soliman, B., “Predicting Natural Ventilation Forces Upon Low-Rise Buildings.” *ASHRAE Journal* February 1980): 25-39.

Lui, H. *Wind Engineering: A Handbook for Structural Engineers*. Prentice Hall Publishers, 1991.

Markee, E.H., Beckerley, J.G., and Saunders, K.E., “Technical Basis for Interim Regional Tornado Criteria.” *WASH-1300 (UC-11),* Washington, DC: Office of Regulation, US Atomic Energy Commission, 1974.

McDonald, J.R. and Mehta, K.C. “A Recommendation for an Enhanced Fujita Scales (E-F Scale).” Wind Science and Engineering Center, Texas Tech University, Lubbock, TX, 2004.

Meroney, R. Private communication to Leighton Cochran. 1989.

Mehta, K.C., McDonald, J.R., Minor, J.R., and Sanger, A.J. “Response of Structural Systems to the Lubbock Storm - SRR03,” Institute for Disaster Research, Texas Tech University, Lubbock, TX, 1971.

Mehta, K.C., Minor, J.R. and McDonald, J.R. “Windspeed Analysis of the April 3-4 1974 Tornadoes.” *ASCE Journal of the Structural Division,* Vol. 201, No.ST9, (1976): 1709-1724.

Minor, J.R. and Mehta, K.C. “Wind Damage Observations and Implications.” *ASCE Journal of the Structural Division,* Vol. 105, No. ST11, , (1979): 2279-2291.

Newbury, C.W. and Eaton, K.J. *Wind Loading Handbook.,* Building Research Establishment Report, US DOE, HMSO, 1974.

National Hurricane Center. “Typical Damage by Hurricane Category.” 2002.

Penwarden, A.D, “Acceptable Wind Speeds in Towns.” in *Building Science,* Vol. 8. United Kingdom: Pergamon Press, , 1973: 259-267.

Pielke, R.A. *The Hurricane.* Routledge Chapman and Hall Inc., 1990.

Sadeh, W.Z. "Trends in Turbulence Measurements." Presented at the proceedings of the Third International Symposium on Refined Flow Modelling and Turbulence Measurements, Tokyo, Japan, July 1988.

Sadeh, W. and Koper, C.A. “A Method for Determining the Weak Statistical Stationarity of a Random Process," *American Institute of Aeronautics and Astronautics Journal,* Vol. 16, No. 11, 1978: 1196-1202.

Schlichting. Boundary Layer Theory. Seventh Edition, 1978.

Simiu, E. and Scanlan, R.H. *Wind Effects on Structures: an Introduction to Wind Engineering,* Third Edition.New York, NY, USA: John Wiley & Sons, 1996.

Srivastava, R.C. “A Model of Intense Downdrafts Driven by the Melting and Evaporation of Precipitation,” *Journal of Atmospheric Science,* Vol. 44, 1987: 1752-1773.

Standards Australia, “Australian/New Zealand Standard, AS/NZS 1170.2 Structural Design Actions, Part 2: Wind Actions,” 2002.

Stathopoulos, T. “Pedestrian Level Winds and Outdoor Human Comfort,” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 94, No. 11, 2006: 769-780.

Stathopoulos, T., Saathoff, P., and Bedair, R. “Wind Pressures on Parapets of Flat Roofs,” *ASCE Journal of Architectural Engineering,* Vol. 8, No. 6, 2002: 49-54.

Stathopoulos, T., Wang, K., and Wu, H. “Wind Pressures Provisions for Gable Roofs of Intermediate Roof Slope.” *Journal of Wind and Structures,* Vol. 4, No. 2, , 2001: 119-130.

Stathopoulos, T. and Zhu, X. “Wind Pressures on Buildings with Mullions,” *ASCE Journal of Structural Engineering*, Vol. 116, No. 8, Proceedings Paper 24982, 1990: 2272-2291.

Storm Prediction Center, *Tornado Database 1950-1994.* 1994.

Tacoma Fire Department, 1940. Film of the Tacoma Narrows bridge wobbling and eventually collapsing. Prelinger Archives, Stillman Fires Collection, PA2096. http://www.archive.org/details/Pa2096Tacoma (accessed Feb. 15, 2012).

Tso, C. “A Survey of Urban Heat Island Studies in Two Tropical Cities,” *Atmospheric Environment,* Vol. 30, No. 3, 1996: 507-519.

Van der Hoven, "Power Spectrum of Horizontal Wind Speed in the Frequency Range from 0.0007 to 900 Cycles per Hour," *Journal of Meteorology,* Vol. 14, 1957: 160-164.

Vitruvius, *The Ten Books on Architecture,* translated by Morris Hickey Morgan, Dover, New York, NY, USA: 1960.

Violich, F., “Cities of Latin America; Housing and Planning to the South”, Reinhold, New York, 1944.

Wakimoto, R.M. “The Life Cycle of Thunderstorm Gust Fronts as Viewed with Doppler Radar and Rawinsonde Data,” *Monthly Weather Review,* Vol. 110, 1982: 1060-1082.

Xie, J. and Irwin, P.A. “Key Factors for Torsional Wind Response of Tall Buildings,” Presented at the proceedings of the ASCE Structures Congress, Philadelphia, PA, May 2000.

Yeang, K., *The Green Skyscraper: The Basis for Designing Sustainable Intensive Buildings.* NY, NY USA: Prestel 2000.

Zehr, R. Private communication to Leighton Cochran. 1992.

Web Sites:

American Association for Wind Engineering: **www.aawe.org**

Australasian Wind Engineering Society: **www.awes.org**

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