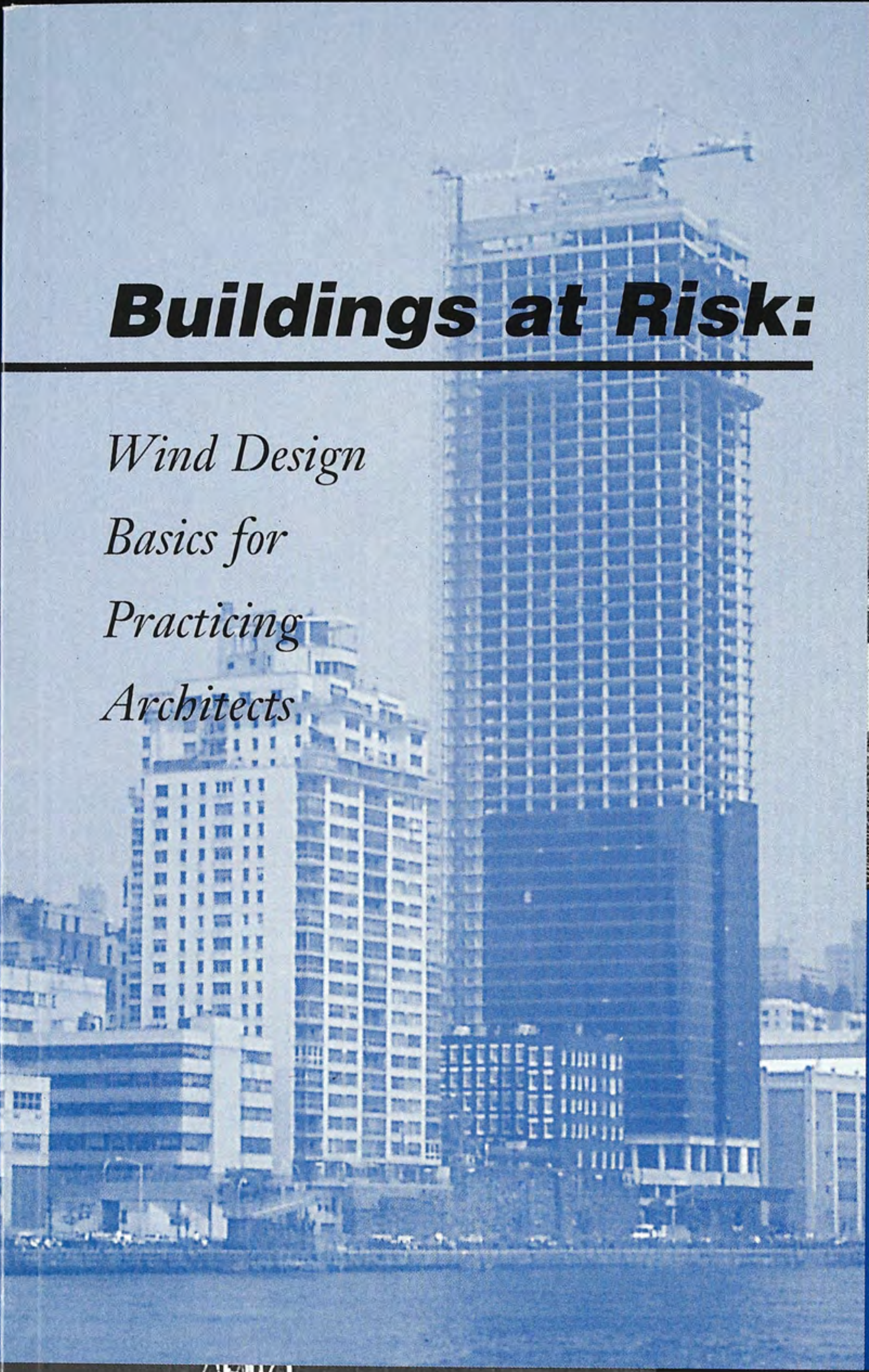
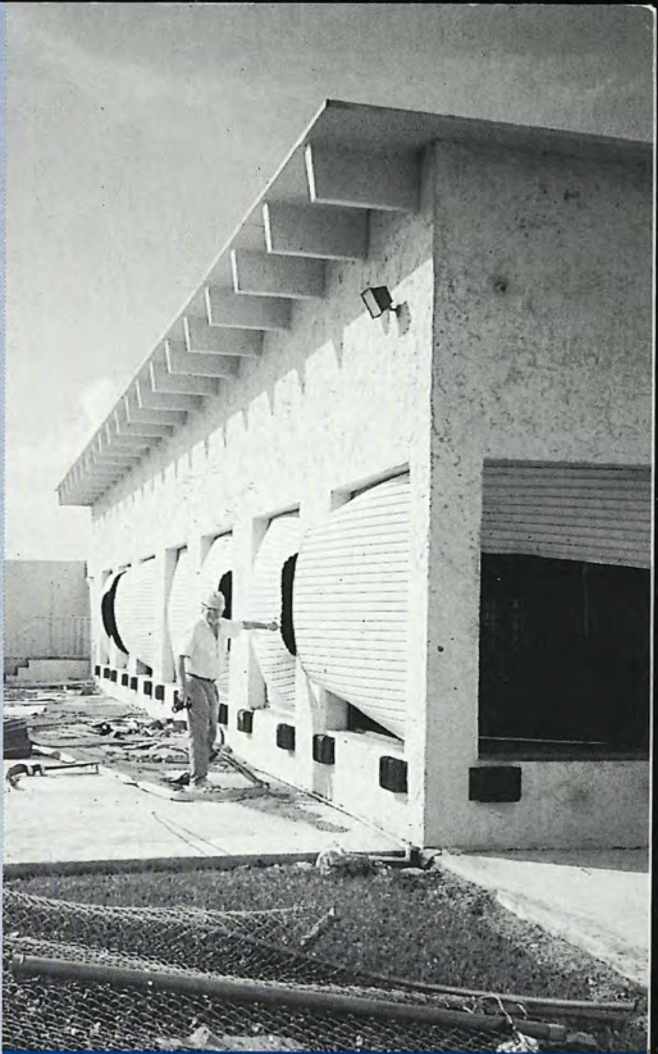
Buildings at Risk:

Wind Design Basics for Practicing Architects





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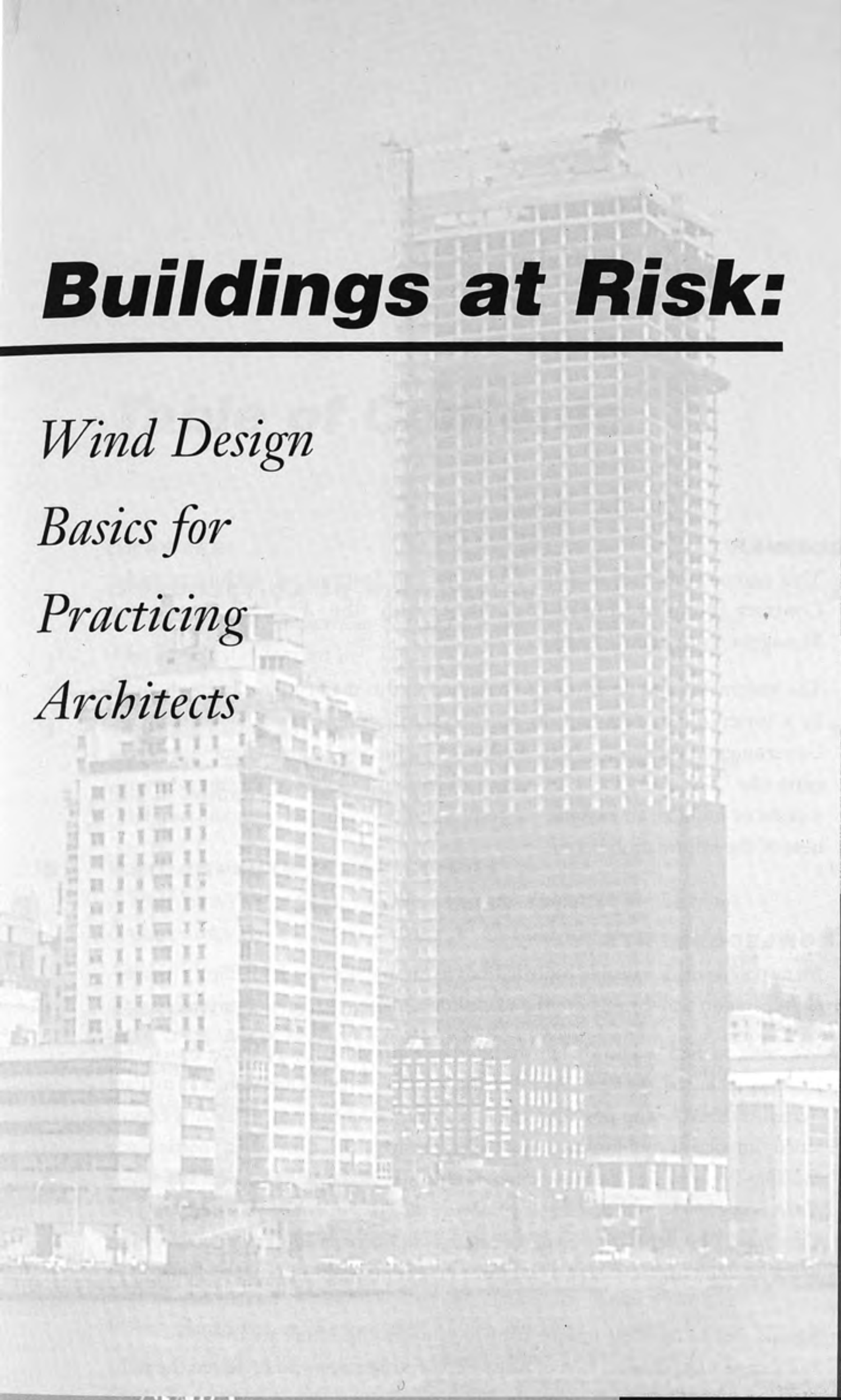

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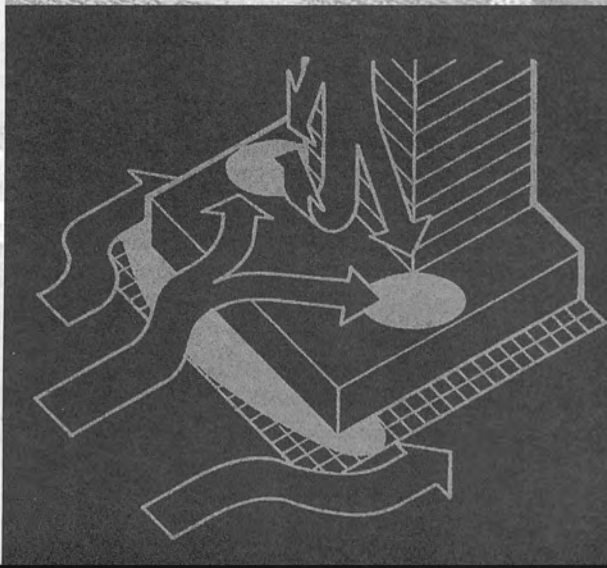

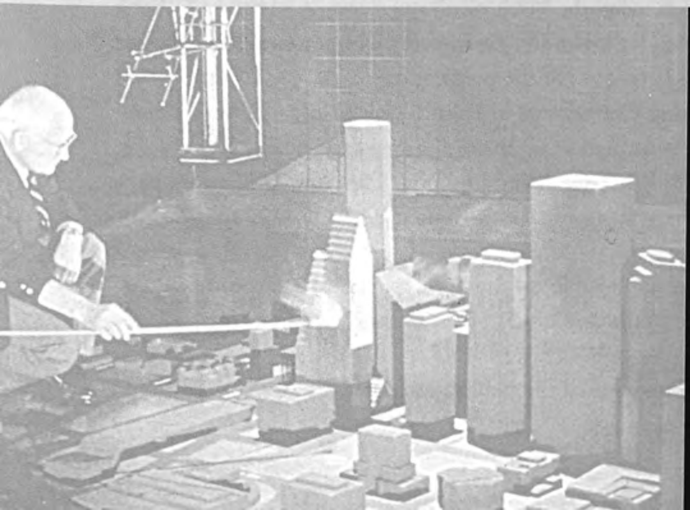

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DISCLAIMER

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Introduction to Wind Design

1.1 PURPOSE OF THIS PUBLICATION

The purpose of this publication is to inform architects about wind hazards, the effect of wind on buildings, the building components most susceptible to high winds, building damage patterns, and suggested techniques for making buildings more resistant to wind damage. The information in this publication was gathered from experts in the field of wind engineering and design.

1.2 NEED FOR DESIGN GUIDANCE

In the wake of wind disasters such as recent hurricanes, and the multitude of tornadoes and wind storms experienced throughout the United States, it has become obvious that the design and construction of many buildings contributed to their poor performance. Inherent in the information presented in this book are the assumptions that architects can play a greater role in improving the quality of design and construction, and that disaster losses can be mitigated. This book was written to help architects perform this role.

Part of the architect's role is to ensure that the project's needs are met in the design for a functional and safe new or renovated building. In areas subject to high winds, a building owner may not have considered the damaging effects of wind—to either the building proper, its contents, or (by extension) the life of a business. This level of due diligence may require more attention particularly to the design of roofing, cladding, and openings. It also increases the value of site observation as a way to ensure that the design intent is achieved.

Figure 1.1

A.G. Davenport

Figure 1.2: Aerial view of damage due to Edmonton Tornado. Note that hipped-roof structures survived better than those with flat and gable roofs.

Vulnerability to wind hazard is increasing in the United States due to changing demographics, increasing capital outlays for buildings, and deteriorating infrastructure systems. Population density is increasing rapidly in hurricane-prone areas of the country—the East Coast, the Gulf of Mexico, and the Hawaiian Islands.

Changing climate also has an impact. According to a report released by the International Conference on Wind Engineering, "A 1 degree increase in Atlantic sea surface temperature will increase the loss potential from hurricanes by 60 percent."[1]

Data suggest that the period of drought in the African Sahel is ending, portending increased hurricane activity in the United States over the next several decades.

1.3 HOW THIS BOOK IS ORGANIZED

Chapter 2 of this book presents information on the nature of wind: how it is generated, the types of winds, parts of the United States that are most susceptible to risk, how wind is measured, and the relation of wind speed to building damage. Chapter 3 examines the impact of wind on buildings, specifically on configuration, structure, and cladding. Different types of wind affect buildings in a variety of ways. Siting and the effects of wind are discussed, along with the effects of wind on roofing, openings (glazing and doors), and other building envelope components.

Chapters 4 and 5 consider the impact, respectively, of wind on single-family and multifamily residential buildings, low-rise commercial buildings (including essential facilities), pre-engineered metal buildings, and high-rise buildings. Each of these building types is examined in terms of the effects of wind on structure, openings, and the building envelope. Detailed recommendations are presented on how to mitigate wind damage.

Chapter 6 considers the changing nature of codes and insurance and their impact on wind design and construction. The limitations of prescriptive codes, and the impacts of business interruption and property damage are discussed.

A glossary of terminology is found at the end of this primer.

Dale Perry

Figure 1.3: Damage on Dauphin Island, Alabama (south of Mobile) due to Hurricane Elena, 1985.

Dale Perry

Figure 1.4: Extensive damage due to Hurricane Elena, 1985.

Figure 1.5: Aerial view of damage at Country Walk, South Miami, FL, due to Hurricane Andrew. Note dominoing of roof trusses after sheathing is lost.

CHAPTER 1 REFERENCE

1. *Proceedings of the International Conference on Wind Engineering.* London, Ontario, Canada, 1991.

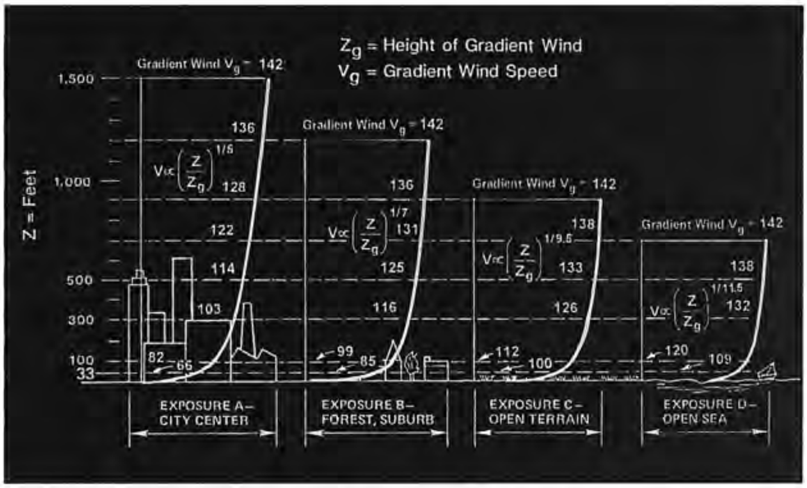
2

The Nature of Wind

2.1 HOW WIND IS GENERATED

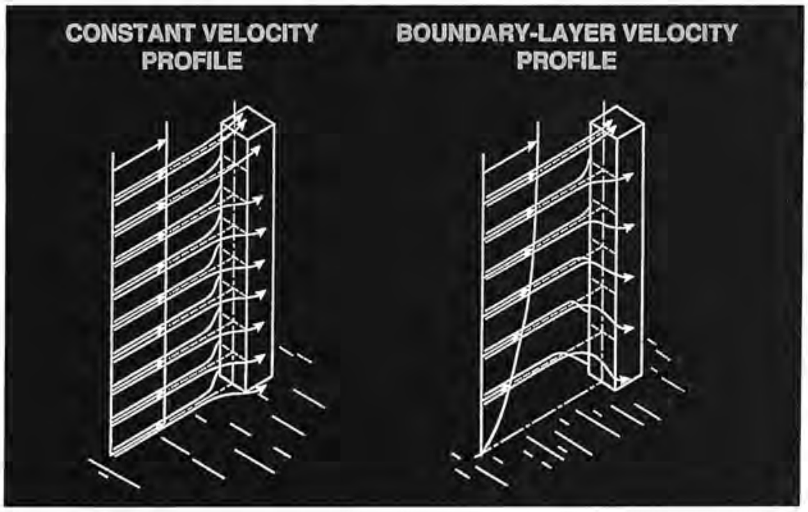
The most elemental definition of wind is "air in motion relative to the earth." It is three-dimensional and multi-directional, with combinations of horizontal and vertical components, although the vertical component normally is small (except wind flowing over large topographic features or in the case of localized downbursts). The term "wind" usually refers only to the movement of air horizontally. Winds near the earth's surface—as opposed to upper-air flows—impinge most directly on buildings. The prevailing wind direction at a site may suggest how best to configure and orient a building to enhance natural ventilation and prevent the development of undesirable winds at street level. Strong wind gusts buffeting buildings can lead to occupant discomfort and eventual fatigue of the structure and envelope. A knowledge of probable, extreme wind speeds is required so that buildings may be designed to resist these wind effects.[1]

Near-surface wind is the most variable of all meteorological elements. The portion of the air in which speed is affected by the earth's surface is called the "boundary layer," (which extends several hundred feet above the Earth's surface.) Wind speed increases with height above the Earth's surface (Figure 2.1).[2] Due to friction, wind speed nearly disappears at ground level.



Dale Perry

Figure 2.1: Profiles of gust (3 sec) wind velocity over level terrains of differing roughness.



Dr. R.D. Marshall

Figure 2.2

Under most conditions, wind speed varies continuously in the lower portion of the boundary layer. As wind speeds increase, some of the variations can become more abrupt and of greater amplitude—these are called "wind gusts." Thus, high winds are a dynamic force on buildings, highly fluid and quickly changing, and must always be considered as multi-directional.

2.2 TYPES OF WIND

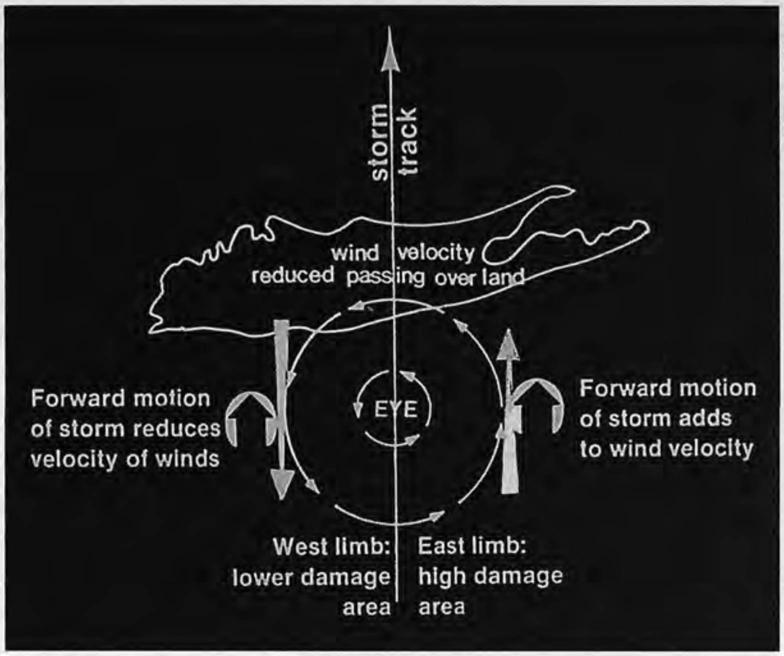
There are several terms that describe winds that pose a danger to life and property and are of concern to the architect in designing for high wind loads. While only a few of the terms are discussed here, a more extensive list of wind design terminology is found in the glossary at the end of this book.

Cyclones: These storms can be described as any atmospheric system in which atmospheric pressure diminishes progressively to a minimum value at the center, and toward which the winds blow spirally inward from all sides, resulting in a lifting of air and eventually in clouds and precipitation. Cyclones are the lows on weather maps. Circulation in a cyclone is counterclockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere. The name does not suggest any degree of intensity and is applied to moderate as well as intense storms. Cyclones are divided into tropical and extratropical groups, depending upon characteristics of the surrounding air masses. Hurricanes in India and Australia are referred to as cyclones.

Tropical Cyclones: This is the general term for cyclones that originate over the tropical oceans, from tropical disturbances to hurricanes or typhoons.

Extratropical Cyclones: During the later stages of their life cycle, tropical cyclones may move into nontropical environments, which modifies their circulation pattern and causes them to be classified as extratropical. In these situations, the size of the circulation usually expands, the speed of the maximum wind decreases, and the distribution of winds, rainfall, and temperatures around the center of the cyclone becomes increasingly asymmetric. While these characteristic features develop, some tropical features may be retained for a considerable time—such as a small area of strong (often hurricane-force) winds near the center, the remnants of an eye, and extremely heavy rainfall. The devastating 1938 New England Hurricane is a good example of an extratropical cyclone that still maintained hurricane-like characteristics. There are no wind speed criteria associated with the term extratropical.

Anticyclones (or highs): An anticyclone is an area of high pressure with a center from which air spirals out in all directions. These systems are associated with sinking air and good weather. Cold anticyclones move rapidly south or southeastward out of the polar regions and are comparatively shallow or short-lived. Warm anticyclones like the Azores-Bermuda High are deep systems extending high into the upper atmosphere and often are stationary or quasi-stationary over the oceans. Their influence on atmospheric processes is profound; the Azores-Bermuda anticyclone's oscillations produce changes in weather in the continental United States and affect the tracks of hurricanes.



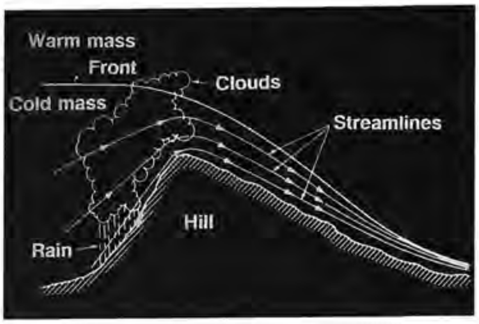
Dr. Orrin H. Pilkey, Jr.

Figure 2.3: The geometry and high translational speed of this 1938 hurricane caused the east limb of the storm to have a significantly higher velocity than the west limb.

Hurricanes: These cyclonic storms are of primary concern to architects in the United States, as large portions of populated areas are subject to hurricanes. The distinguishing features of hurricanes are that they are generated in equatorial areas and migrate toward higher (north or south) latitudes. Hurricanes are spawned by low pressure areas over the ocean and receive energy from latent heat due to condensation of moisture. They travel 0-60 mph laterally, with an average speed of 24 mph, and have a funnel shape with a diameter of 180 to 300 miles at bottom, and up to a 600-mile diameter at top. They have sustained wind speeds near the ground of 75 to 165 mph, with a wall at the "eye" where speeds are greatest. Hurricanes can create tidal surges or wind-driven waves that also cause much damage. Hurricanes are known as typhoons in the Far East and South Seas and cyclones in India and Australia. Hurricanes in northeastern United States regions often have fast translational velocity but are less intense and less frequent than in the southeastern United States. The 1938 New England Hurricane, for example, had a translational speed in excess of 60 mph. As a consequence, the wind velocities in the east limb of the storm passing over eastern Long Island were substantially greater than the west limb velocities. (Figure 2.3)

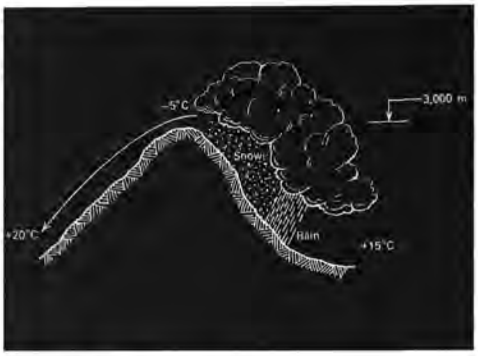
Tornadoes: These cyclonic storms generally are small. The vast majority are less than one mile in diameter; many are less than 100 yards. They have been recorded in every month of the year; the peak season is April through July. Tornadoes usually are spawned by severe thunderstorms and occur almost exclusively in areas east of the Rocky Mountains. Tornadoes may also be spawned by landfalling hurricanes (Hurricane Gilbert, 1989, produced 49 tornadoes which struck Texas although the eye of the storm passed over Mexico). They have maximum wind speeds in the range of 250 to 300 mph; the vast majority are of much lower intensity. Their translational speeds are in the range of 5 to 70 mph; the average is 45 mph.

Nor'easters: Nor'easters are low-pressure cyclonic storms, similar to extratropical cyclones in that they have cold centers, and occur in the northeastern United States. Their winds come from northeast,



Henry Liu

Figure 2.4: Mountain downslope wind.



Michele Melaragno

Figure 2.5: Foehn wind.

from the sea, and may extend over a large geographical area. Nor'easters typically have speeds less than hurricane-strength, are not necessarily wet, and may last for several days.

Down-slope winds: Mountain down-slope winds occurring in different geographical regions have different names. In the Rocky Mountain region of the United States they are called chinooks, in southern California they are called the Santa Ana winds, in the Alps of Europe they are called foehns, and in Yugoslavia they are called boras (Figures 2.4 and 2.5). Foehn and bora are now being used as generic terms for warm and cold mountain down-slope winds, respectively. Many communities on the eastern slope of the Rocky Mountains are plagued by mountain down-slope winds. For example, Boulder, Colorado each year experiences more than one down-slope wind with velocities of 100-130 mph.

Thunderstorms: These storms occur with the formation of tall convective clouds generated by the upward motion of warm, moist air. At several thousand feet above terrain the decrease in temperature causes the air to condense. This condensation may produce heavy precipitation; the viscous drag forces exerted by the rain on the air through which it falls may create a strong, cold downdraft in the mature stage spreading over the ground similar to a jet impinging on a wall.

Severe, localized thunderstorms are some of the most difficult phenomena to forecast. A thunderstorm is categorized by the National Weather Service as severe when it has either or both of the following characteristics:

- winds with speeds greater than 58 mph, or
- large hail with a diameter greater than 3/4 in.

Such storms also have the potential of producing destructive tornadoes, flash flooding, and lightening strikes. Normally they develop during the spring and summer months and are primarily concentrated in the southeastern coastal states and the Central Plains. Approximately 10,000 severe thunderstorms are reported in the U.S. each year resulting in property losses exceeding $1 billion annually.

2.3 LOCATIONS OF WIND RISK

The mean annual sustained wind speed for the contiguous 48 states is 8 to 12 mph. In sheltered areas, mean speeds tend to be lower; on mountain ridges, in passes, and along coasts they are considerably higher. At most locations throughout the United States, peak gust wind speeds of 50 mph occur frequently. Nearly every area of the country will occasionally experience peak gust wind speeds over 90 mph. Many coastal regions can expect speeds of more than 100 mph. In the Central region, most of these high wind speeds are associated with frontal passages, or thunderstorms that are isolated or in a grouping such as a squall line. In the Western Mountain region, down-slope winds account for many extreme reports. Along the Eastern and Gulf Coasts, thunderstorms and hurricanes are the main sources of strong, near-surface winds.[3]

Although the highest likely near-surface wind speeds occur beneath thunderstorms and in hurricanes, very high wind speeds also can be associated with deep extratropical cyclones developed from winter low-pressure systems (Nor'easters). In these weather systems, strong winds may be found swirling around the center of lowest pressure, and in association with the steep gradients of temperature and pressure that characterize the attendant cold frontal zones.[4]

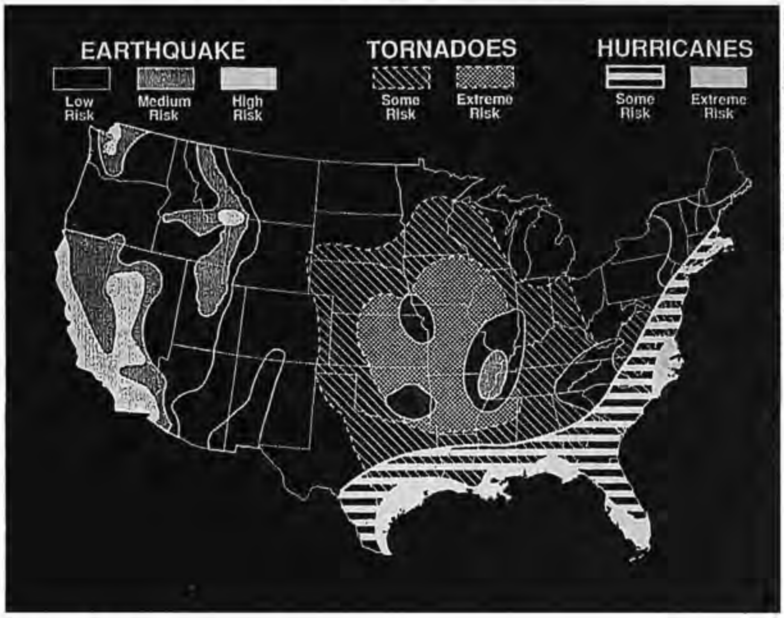


Figure 2.6: Natural hazard threat.

U.S. Geological Survey & Uniform Building Code

The West Coast and the Hawaiian islands are occasionally threatened by tropical cyclones forming off the western coast of Mexico. These seldom produce strong winds along the California coast, but can lead to very heavy rains along the coast and in the southwestern states. Hawaii receives moderate to strong winds from a tropical storm about once every four years. Hurricanes hit the islands sporadically. Several have passed directly over one of the major islands. Hurricane Dot passed over Kauai in August 1959; Hurricane Iwa passed to the west of Kauai in November 1982; and Hurricane Iniki made landfall on Kauai in September 1992.[5]

Hurricanes typically develop in the South Atlantic off the coast of Africa or in the Gulf of Mexico. They make landfall most often in Florida. However, historically these tropical systems have come ashore all along the coast, from Texas to Massachusetts. The northerly landfalls are a consequence of the Gulf Stream that transports warm water northward along the Eastern Seaboard. Over this current, cyclonic storms can maintain their tropical characteristics much farther north than they can over the central North Atlantic.[6]

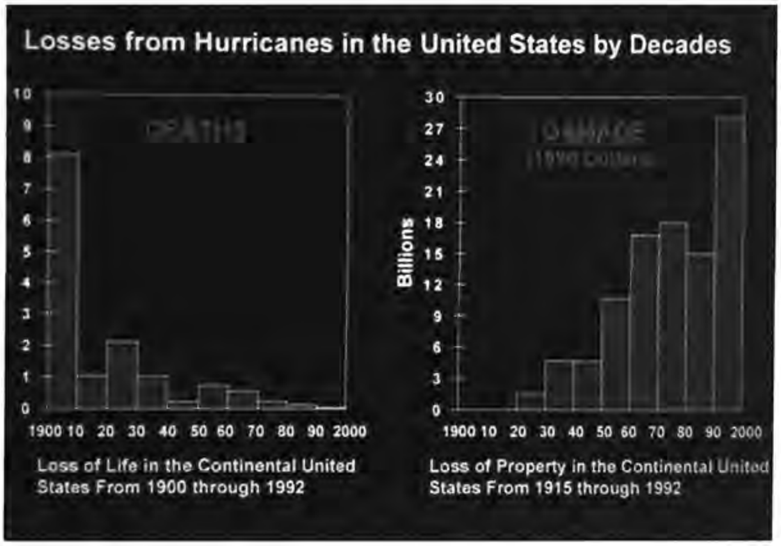


Figure 2.7

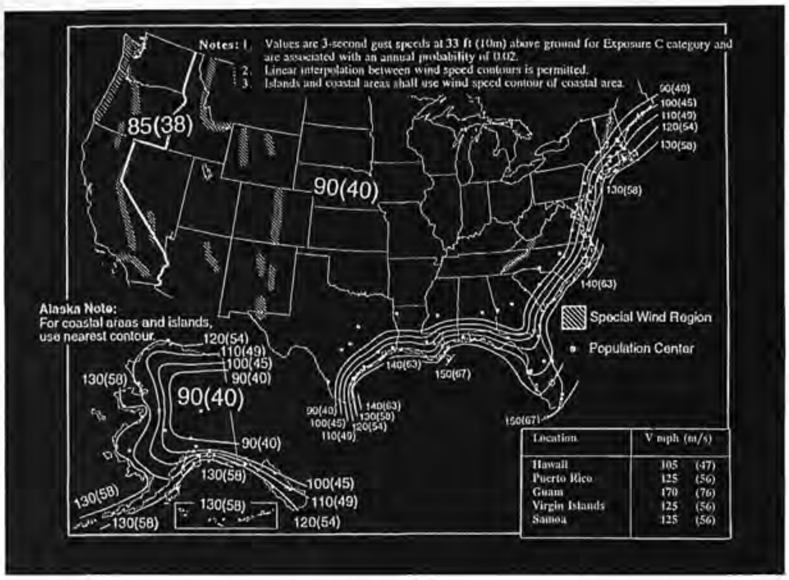
D. Perry, N. Stubbs

When a hurricane makes landfall in a populated area, there is great potential for loss of life and substantial property damage from both high winds and the storm surge (Figure 2.7). The storm surge is the rise of the sea in advance of an approaching tropical storm. The degree of rise is related to both the central low pressure and the overall wind field in the storm; it also depends on the water depths along the coastline.[7] (Figure 2.7)

2.4 MEASURING WIND AND SPEEDS THAT DAMAGE

Measured wind speed is a function of the measuring device (usually an anemometer), averaging time, and terrain upwind of the measurement site. The variations of wind with respect to height and time make it difficult to obtain values that are representative of the conditions over large regions. Near-surface winds conventionally are measured at a point some distance above the ground in flat, open terrain typical of an airport exposure. Although the recommended height is 33 ft, which also is the reference height for the "basic wind speed" designated in building codes, actual measurement heights vary widely due to the peculiarities of each observing site.[8] Anemometer heights of 17 to 21 ft are often encountered at National Weather Service stations located at airports (Figure 2.8).

ASCE 7-95


Notes: 1. Values are 3-second gust speeds at 33 ft (10m) above ground for Exposure C category and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is permitted.
3. Islands and coastal areas shall use wind speed contour of coastal area.

Alaska Note:
For coastal areas and islands, use nearest contour.

Location	V mph (m/s)
Hawaii	105 (47)
Puerto Rico	125 (56)
Guam	170 (76)
Virgin Islands	125 (56)
Samoa	125 (56)

Figure 2.8: Basic wind speed in mph (m/s).

Variations in wind speeds must be smoothed out by averaging speed and direction over time, and it is these average speeds that are incorporated into building codes and which govern building design and construction. The averaging can be done in a variety of ways, depending on the application. In the United States, the average of wind speeds measured for 1-minute durations are used to specify the sustained wind. Extreme or peak wind speeds are averaged over 2 to 5 seconds, and in the current wind load standard (ASCE 7-95) are given as 3-second peak gusts (this is the basic wind speed found on the ASCE 7-95 wind map). In Canada, wind speeds are specified in terms of hourly mean. Internationally, 10-minute averages are used to specify the sustained wind; however, adherence to this standard is not universal.[9]

To ensure comparability of readings of the mean wind from different locations, heights of measurement and averaging procedures must be standardized or the data from each station must be "adjusted" to standard conditions. If characteristics of gusts are to be compared, then the response characteristics of the measuring instruments also must be matched. In the United States, wind speeds currently are adjusted to 33 ft. high, 3-second peak gust winds.

The Saffir-Simpson Scale expresses the severity of hurricanes in terms of their maximum sustained speed (usually estimated from ship and aircraft data) and depth of the storm surge. Of the 138 hurri-

SAFFIR-SIMPSON HURRICANE SCALE

All hurricanes are dangerous, but some are more so than others. The way storm surge, wind, and other factors combine determines the hurricane's destructive power. To make comparisons easier—and to make the predicted hazards of approaching hurricanes clearer to emergency forces—National Oceanic and Atmospheric Administration's hurricane forecasters use a disaster-potential scale which assigns storms to five categories. Categories 1 is a minimum hurricane, Category 5 is the worst case. The criteria for each category are shown below.

This can be used to give an estimate of the potential property damage and flooding expected along the coast with a hurricane.

Category	Definition—Effects
ONE	*Winds 74-95 mph:* No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal road flooding and minor pier damage.
TWO	*Winds 96-110 mph:* Some roofing material, door, and window damage to buildings. Considerable damage to vegetation, mobile homes, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of center. Small craft in unprotected anchorages break moorings.
THREE	*Winds 111-130 mph:* Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris. Terrain continuously lower than 5 feet above sea level may be flooded inland 8 miles or more.
FOUR	*Winds 131-155 mph:* More extensive curtainwall failures with some complete roof structure failure on small residences. Major erosion of beach areas. Major damage to lower floors of structures near the shore. Terrain continuously lower than 10 feet above sea level may be flooded, requiring massive evacuation of residential areas inland as far as 6 miles.
FIVE	*Winds greater than 155 mph:* Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Major damage to lower floors of all structures located less than 15 feet above sea level and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5 to 10 miles of the shoreline may be required.

Figure 2.9

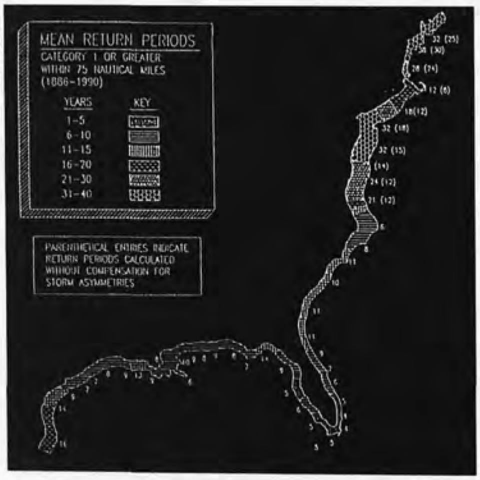
canes to reach the continental United States in the period from 1899 to 1980, 82 had maximum sustained winds from 74 to 110 mph—Categories 1 and 2 on the Saffir-Simpson Scale. Of the remainder, 54 were major hurricanes, falling into Categories 3 and 4. Only two Category 5 hurricanes have hit the mainland in the 20th century: the Labor Day hurricane at Matecumbe Key, Florida (September 2, 1935), and Hurricane Camille on the coasts of Louisiana and Mississippi (August 17, 1969).[10] It is worth noting that Hurricane Andrew—the most costly storm recorded in the United States—was only a Category 4 hurricane (Figure 2.9).

Cyclonic wind speeds are typically measured using ground-based devices such as anemometers, aircraft-based instrumentation, and Doppler radar. Tornadoes are a special case in which wind speed esti-

FUJITA TORNADO SCALE CLASSIFICATION (1976)

Scale	Fujita Classification
F	*Doubtful Tornado (winds <40 mph)* • Breaks twigs off trees • Little expected damage
F0	*Very Weak Tornado (winds 40-72 mph)* • Damage to chimneys or TV antennae • Breaks branches off trees • Pushes over shallow-rooted trees • Old trees with hollow inside break or fall • Sign boards damaged
F1	*Weak Tornado (winds 73-112 mph)* • Peels surface off roofs • Windows broken • Trailer houses pushed or overturned • Trees on soft ground uprooted • Some trees snapped • Moving autos pushed off road
F2	*Strong Tornado* (winds 113-157 mph) • Roof torn off frame houses leaving strong upright walls • Weak structure or outbuildings demolished • Trailer houses demolished • Railroad boxcars pushed over • Large trees snapped or uprooted • Light-object missiles generated • Cars blown off highway • Block structures and walls badly damaged
F3	*Severe Tornado (winds 158-206 mph)* • Roofs and some walls torn off well-constructed frame houses • Some rural buildings completely demolished • Trains overturned • Steel framed hangar-warehouse type structures torn • Cars lifted off the ground and may roll some distance • Most trees in forest uprooted, snapped or leveled • Block structures often leveled
F4	*Devastating Tornado (winds 207-260 mph)* • Well-constructed frame houses leveled • Structure with weak foundation lifted, torn and blown off some distance • Trees debarked by small flying debris • Sandy soil eroded and gravel flies in high winds • Cars thrown or rolled considerable distance, finally to disintegrate • Large missiles generated
F5	*Incredible Tornado (winds 261-318 mph)* • Strong frame houses lifted clear off foundation and carried considerable distance to disintegrate • Steel-reinforced concrete structures badly damaged • Automobile-sized missiles fly 100 yards • Trees debarked completely • Incredible phenomena can occur

Figure 2.10



Dr. Bob Sheets

Figure 2.11: Mean return periods for all hurricanes.

mates are typically derived from observation of damage. The Fujita Scale is used to rank tornadoes based on these damage observations (Figure 2.10). Doppler radar is also beginning to be used to track the speed and direction of tornadoes.

Threshold damage to single and multi-family residential buildings typically begins to occur at sustained speeds of 50 to 60 mph and usually impacts roofing materials first. Poorly designed, constructed, or maintained roofs may lose their entire structural integrity at sustained speeds as low as 70 mph.

With respect to wind speeds and damage to buildings, here are some important considerations:

1. Hurricane forecasts often refer to wind speeds measured by aircraft at heights well above the atmospheric boundary layer. Therefore, the effects of ground roughness are not accounted for and the actual near-surface winds may be significantly less (65 percent to 85 percent of measured speeds). Thus, structures that "survived" a reported 125 mph wind may have only actually been exposed to a 95 mph wind. Such variations in reported and actual wind speeds can lead to a false sense of security about the wind resistance of buildings.
2. There is a strong tendency for people experiencing hurricane winds to grossly overestimate the speeds. As an example, wind speeds based on actual measurements in Charleston, South Carolina during Hurricane Hugo were substantially less than the speeds reported by the news media and widely believed by the residents of that city. This, too, can lead to a false sense of security about a building's wind resistance. Likewise, many people on St. Croix in the Virgin Islands believe the gust speeds in Hugo were 250 mph or higher. Post-storm investigations by experts in meteorology and wind engineering indicate these speeds did not exceed 165 mph.
3. In general, wind damage in typical built-up areas will begin at gust speeds of about 50 mph. Some shingles and siding will come off, trees will begin to lose limbs or be uprooted, and overhead traffic lights and signs may come down.
4. Because of their large variation from one location to another, it is all but impossible to characterize surface wind speeds in a hurricane on the basis of a single measurement. Only from careful post-storm assessments of land-based or ocean-surface anemometer records and wind damage can the true distribution of surface wind speeds be ascertained. For this reason the Saffir-Simpson Scale, which is based on site observations and instrument readings, is the preferred preliminary measure of hurricane intensity.
5. There is a widespread misconception of the "mean recurrence interval" or "return period" for storms. A 50-year storm means that a storm of this intensity or greater would be expected to happen about once every 50 years, or that there is a 2 percent chance each year that such a storm will occur. It could happen more frequently or less frequently, and it could happen more than once in the same year. Many people mistakenly believe such a storm cannot happen again within the next 50 years (Figures 2.11 to 2.13).
6. Contrary to popular belief, storm surge is not a large wave suddenly engulfing a coastal area. The rise in water level may extend over several hours. However, wind-generated waves are superimposed on the storm surge and normal tides may increase the net water depth.

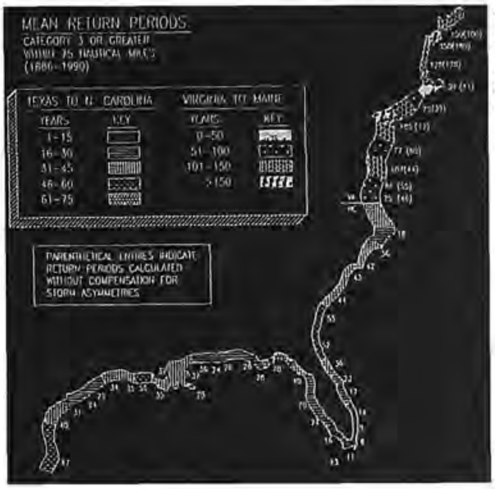


Figure 2.12: Mean return periods for all major hurricanes. (Saffir-Simpson Category 3 or greater).

Dr. Bob Sheets

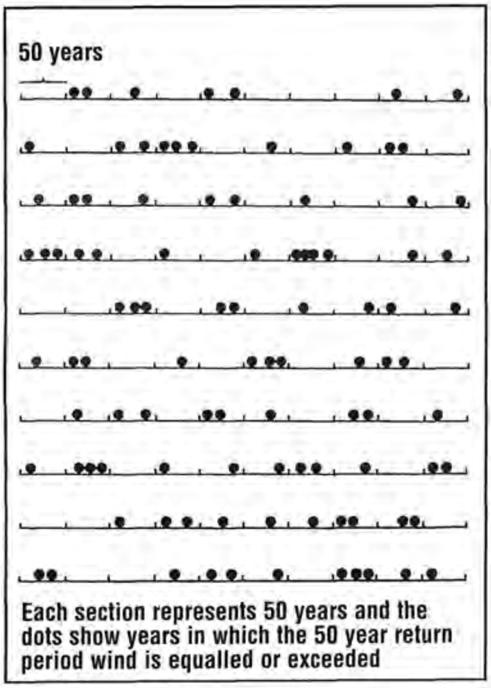


Figure 2.13: Occurrences of a 50-year return period wind over 5000 years. Note that several 50-year intervals have no occurrences while many have more than one.

Alan P. Jeary

CHAPTER 2 REFERENCES

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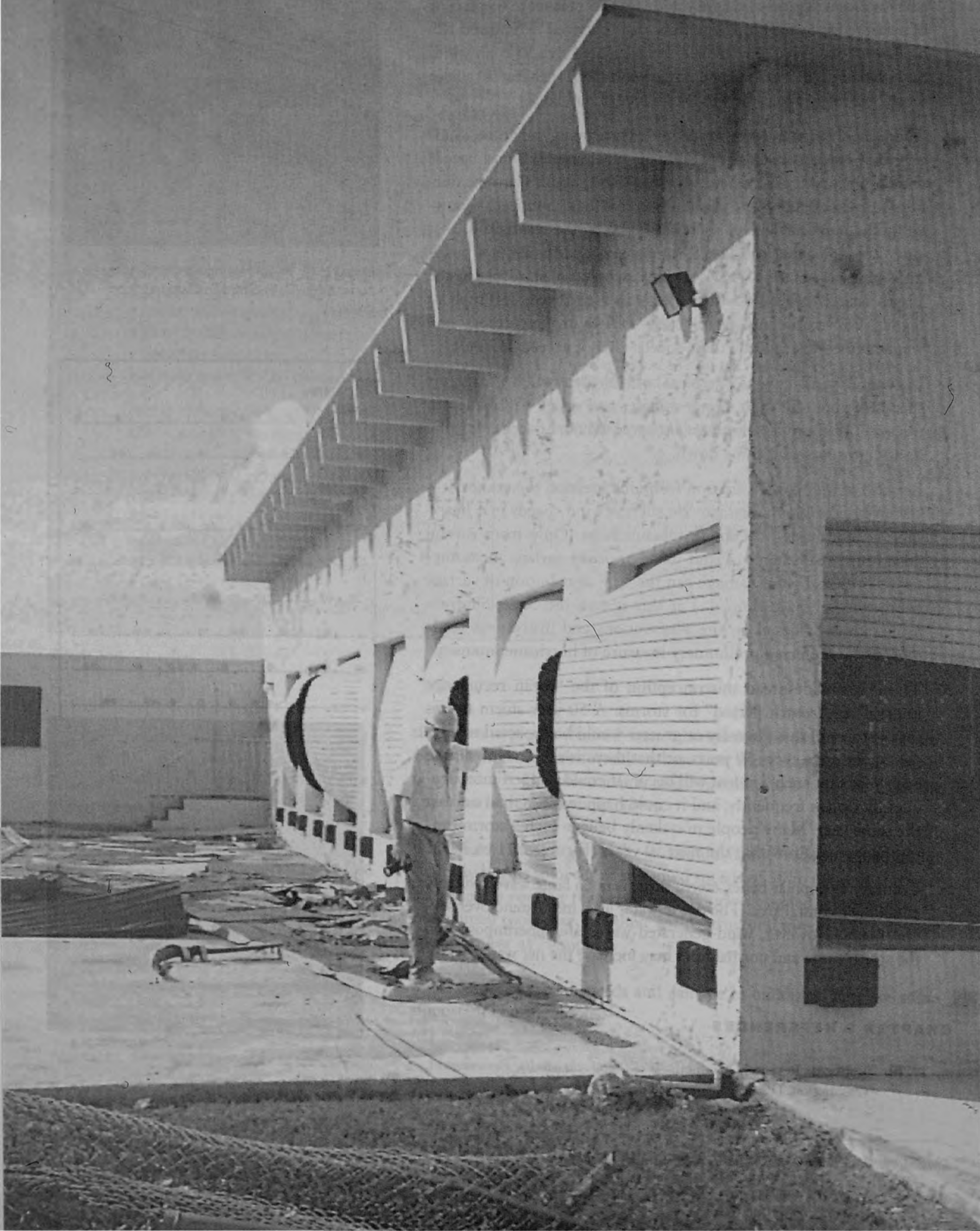
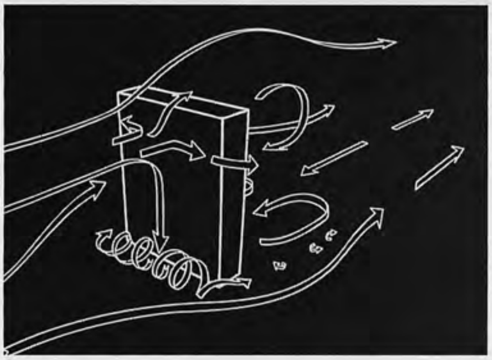


3

Wind Impacts on Buildings



R.D. Marshall

Figure 3.1: Flow of air around a high-rise building.

3.1 WIND FORCES

Buildings are continually subjected to wind forces. Generally, these wind forces are at levels that the structure is capable of resisting, whether that capability is based on an engineered design using building code-specified wind loads, or, as is the case with most residential construction, it is based on standard construction practices that have developed over time. Periodically, structures are subjected to wind forces that cause damage. In some instances, the damage is due to wind loads exceeding design criteria. In most cases, the damage results from a weakness in the building itself.[1]

Damaging Winds

Damaging wind forces usually are associated with extreme weather phenomena, such as tornadoes, hurricanes, or thunderstorms. Maps indicating wind speeds for 50-year mean return periods have been used in building codes to establish wind loads for building design. The maps and other factors in design standards take into account the varying wind loads experienced in different environments, i.e. near the coast, inland, open terrain and urban environment. Building codes and standards generally use gust and other factors that are applied to the basic wind speed to account for the dynamic effects of wind.

In practice, the actual wind loads on a building rarely exceed the design wind load. Even in cases where design-level winds are somewhat exceeded, a well-designed and constructed building should sustain relatively little damage to the structural frame.[2] The building envelope (roof, walls, and openings) is another story. Breaches to the envelope have been observed to be the major cause of damage in high wind events, and envelope systems have sustained considerable damage even at wind speeds below design levels.

Many buildings would suffer severe damage if struck directly by a moderate to strong tornado. This damage results not only from the extreme

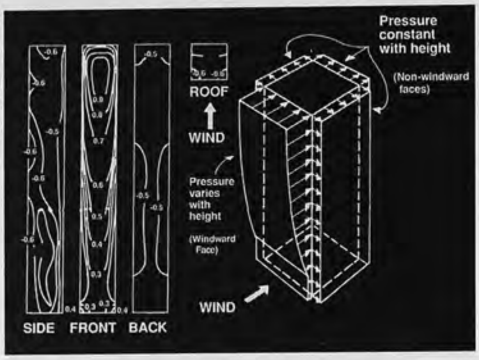


Figure 3.2: Wind tunnel analysis of the World Trade Center buildings and code approach.

Cermack, Chiu, Perry

wind speeds, but from the dynamically changing wind directions and the impact of wind-borne debris. Similarly, structures along the coast in the path of a hurricane may be simultaneously subjected to the severe forces of both wind and water, the greatest magnitude of each occurring at approximately the same time. The wind velocoties in a hurricane may exceed design levels and may subject the building to high winds first from one direction and then the other.[3]

Wind Loads

Wind loads on buildings can be calculated using the formula contained in the *American Society of Civil Engineers (ASCE 7-95) Standard for Minimum Design Loads for Buildings and Other Structures*. The wind load is an expression of the formula:

$$p = qGC$$
$$q = 0.00256K_zK_{zt}V^2I$$

where:

p = design pressure in psf
q = velocity pressure in psf
0.00256 = constant for mass density of air and appropriate conversion constants so that V may be given in mph
K_z = velocity pressure exposure coefficient
K_{zt} = topographic factor
V = basic 3-second peak gust wind speed in mph
I = importance factor, defines the level of risk depending on occupancy
G = gust effect factor, which considers spatial size of gust relative to the size of buildings, gust frequency relative to natural frequency and damping of structure, basic reference design speed, and terrain exposure
C = mean pressure coefficient (combining internal and external coefficients)

Use of this formula by an architect is relatively rare, as most wind load analysis is conducted by engineers and specialists. However, it is important for architects to be familiar with the formula so that they understand the impact of wind on the building's design and can discuss it with the engineer. Regardless of who performs the wind load calculations, it is imperative that loads be determined for the building envelope as well as the structure.

Vibration

Wind-induced structural vibration can be a concern in specialty structures such as tensile roofs, bridges, and other unusual configurations.

Buffeting vibration is produced by the unsteady loading of a building due to turbulence (velocity fluctuations in magnitude and direction) in the approaching free flow wind field. If the turbulence is generated by an upwind neighboring structure or obstacle, the unsteady loading is called wake buffeting or interference. The World Trade Center Twin Towers in New York City (Figure 3.2) and the John Hancock building in Boston are examples of buildings that experience the latter type.

Most building codes (e.g. ASCE 7) treat the along-wind vibration but do not address across-wind or torsional buffeting vibration.

The flow behind a long cylinder held perpendicular to wind is characterized by the periodic shedding of vortices (whirling air flows). Vortex shedding creates periodic lateral forces that can cause vibration of slender structures such as towers and tall buildings. Although vortex shedding is most noticeable for cylindrical buildings, it also happens to a lesser degree to tall buildings of other shapes.[4]

Vortex-shedding vibration takes place when the wind speed is such that the shedding frequency becomes approximately equal to the natural frequency of the cylinder—a condition that causes resonance. When resonance takes place, further increase in wind speed by a few percent will not alter the shedding frequency. This phenomenon is called "lock-in." Because the structure vibrates excessively only in the lock-in range, having a wind speed either below or above the lock-in range will not cause serious vibration. If the shedding frequency is the same as the natural period of the building, it can have a load impact on the structure, pulling the building back and forth in an across-wind direction.[5] (Figures 3.3 and 3.4)

Figure 3.3: Vortex shedding.

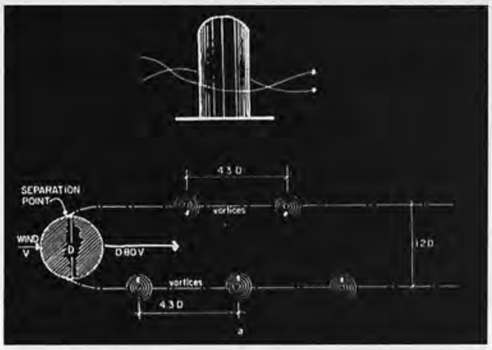


Figure 3.4: The Karman Vortex Phenomenon.

Classical flutter (or simply flutter) is a two-degrees-of-freedom vibration involving simultaneous lateral (across-wind translational) and torsional (rotational) vibrations. It occurs in structures that have approximately the same magnitude of natural frequencies for both the translational and the rotational modes. Similar to galloping and torsional divergence, flutter is produced by aerodynamic instability completely unrelated to vortex shedding.[6]

Damage Mechanisms

The four primary damage mechanisms associated with severe windstorms involve:

(1) aerodynamic pressures created by flow of air around a structure;
(2) induced internal pressure fluctuations due to a breach in the building envelope;
(3) impact forces created by wind-borne debris; and
(4) pressures created by rapid atmospheric pressure fluctuations (associated primarily with tornadoes).

Examinations of building damage caused by various types of windstorms suggest that most winds produce damage due to a combination of aerodynamic pressures and internal pressure fluctuations and, for hurricanes and tornadoes, debris impacts. Atmospheric pressure fluctuations have little or no effect on the performance of ordinary structures because most ordinary structures have sufficient building envelope permeability (or venting) to allow equalization of pressures induced by atmospheric pressure changes. In airtight structures such as nuclear containment vessels, atmospheric pressure changes can impose significant loading to the building envelope.[7]

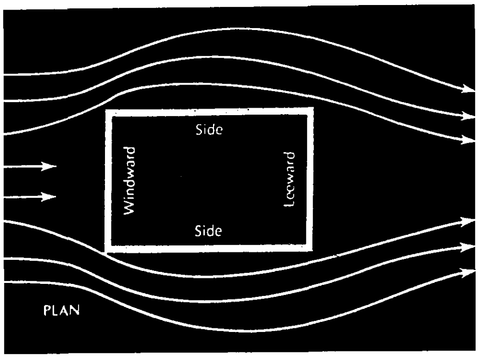


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Figure 3.5: Building in wind flow.

Wind pressures acting on buildings are distributed loads that are assumed to act normal to the building surface. Positive wind pressures act toward the surface of the building element and negative pressures (suction) act away from the building surface. The fundamental characteristics of wind pressures are described below based on the building component affected and the orientation of the building in the wind environment.[8]

As winds increase, pressure against objects is added at a non-linear rate. Pressure force against a wall mounts with the square of the wind speed so that a three-fold increase in wind speed, for example, results in a nine-fold increase in pressure. A 25 mph wind causes about 1.6 pounds of pressure per square foot. Therefore a 4x8 sheet of plywood will be pushed by a force of about 50 pounds. In 75 mph winds, that force becomes 450 pounds, and at 125 mph, it becomes 1,250 pounds.[9]

3.2 AERODYNAMIC PRESSURE IMPACTS

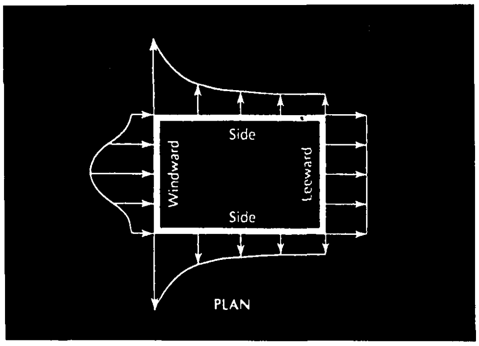

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Figure 3.6: Relative wind pressure on walls.

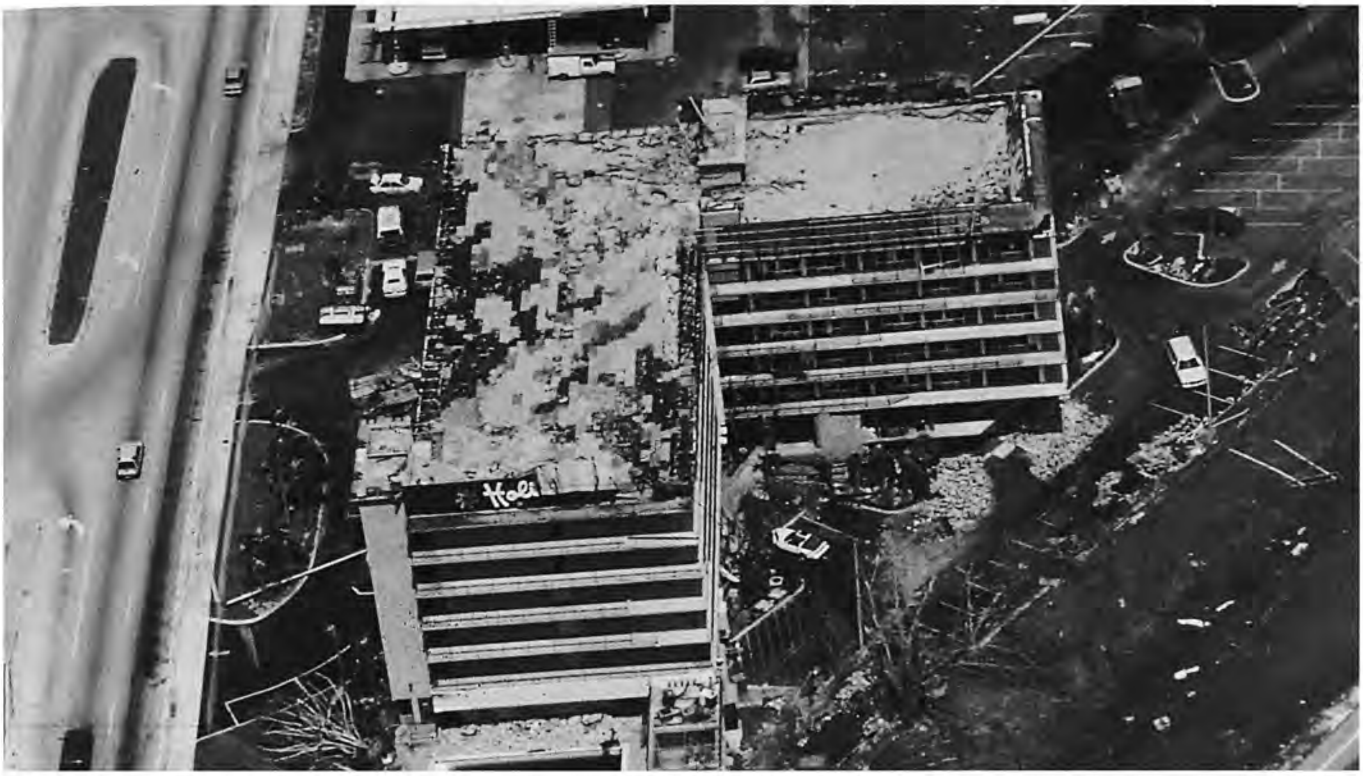
Impacts on Walls

Figure 3.5 presents a plan view of a simple rectangular building that is submerged in a wind flow as shown. Each wall of the structure is identified as a windward, side, or leeward wall depending upon its location with respect to the direction of wind flow. The windward wall is the wall facing the wind; the leeward wall is on the side opposite to the windward wall; and the side walls are parallel to the wind flow.[10]

Because the windward wall is perpendicular to the wind flow, the wind impinges directly on the windward wall producing positive pressures (Figure 3.6). As the wind flows around the windward corners, the local wind speed increases and the flow lines have a tendency to separate from the corner of the building. This causes the side walls to be subjected to negative pressures as shown. In addition, the turbulence and flow separations that occur at the windward corners of the building induce high negative pressures for short distances along the side walls. The leeward wall is also subjected to negative wind pressures that tend to be relatively uniformly distributed.[11]

Impacts on Roofs

Wind creates a greater load on the roof covering than on any other element of a building. When a FEMA team investigated wind damage to buildings in Florida in the wake of Hurricane Andrew, their field observations concluded that the loss of roof covering was the most pervasive type of damage to buildings in southern Dade County. To varying degrees, all of the different roof types observed suffered damage due to the failure of the method of attachment and/or material, inadequate design, inadequate workmanship, or debris impact. Similar damage has been observed in the aftermath of other windstorms (Figure 3.7).



Dale Perry

Figure 3.7: Extensive damage to roof; Cutler Ridge in Miami, FL in Hurricane Andrew.

According to the FEMA team, roof covering damage throughout the observed areas was pervasive. While many buildings escaped very costly structural frame damage, almost all residential buildings in the observed areas suffered some degree of roof covering and sheathing damage from wind and/or airborne debris.

Most building roofs can be classified as low-slope (flat) or steep-slope (pitched) roofs, depending on the shape of the roof. Figure 3.8 presents a side view of a building with a low-slope roof. The wind is blowing from left to right and the figure illustrates the wind pressures acting on the building. As stated previously, the windward wall is subjected to positive pressures and the leeward wall to negative pressures. As the wind flows upward and over the windward edge of the roof, the flow is accelerated and there is a tendency for the wind flow to separate from the roof. These flow characteristics result in the roof being subjected to negative pressures. In addition, locally high negative pressures can occur at both the windward eaves and roof ridge. The magnitude of the local pressure excursions depends on the slope of the roof.[12]

Figure 3.9 depicts the pressure distribution acting on a high-sloped roof with the wind blowing perpendicular to the roof ridge. The windward slope is subjected to positive pressures while the leeward slope is subjected to negative pressures. In addition, locally high pressure excursions are to be expected at the roof ridge. The magnitude of the

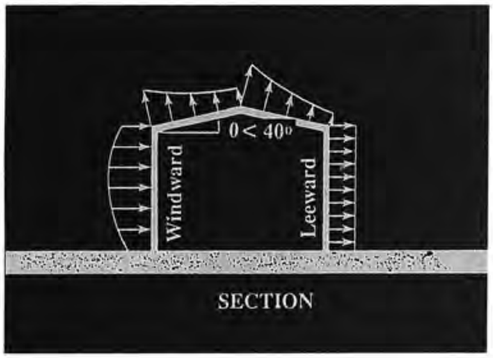


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Figure 3.8: Low-slope roof pressures.

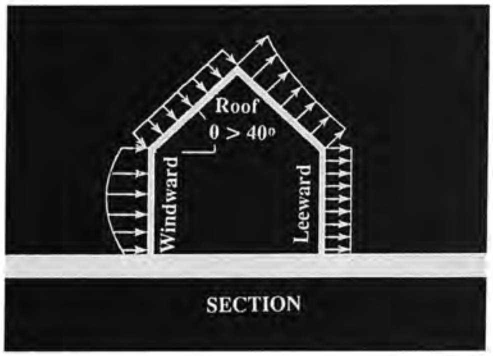

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Figure 3.9: High slope roof pressures.

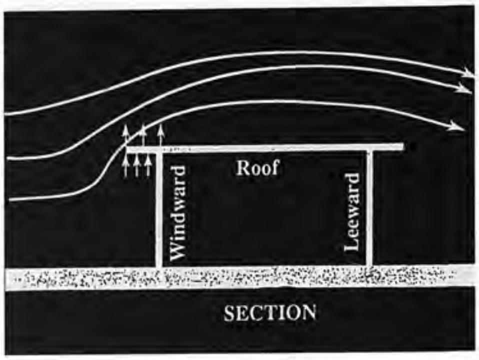

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Figure 3.10: Pressures at roof overhang.

Dale Perry

Figure 3.11: The canopy of this church in Gautier, MS suffered tremendous damage during Hurricane Elena, even though the wind speeds were only around 60 mph.

ridge pressure fluctuations will depend on the slope of the roof.[13] Shed roofs experience the highest loads (worst geometry) for wind parallel to the slope and directed toward the high wall.

If either a pitched or flat roof has an overhang, the roof will be subjected to high positive pressures on the windward overhang as depicted in Figure 3.10. If the overhang is associated with a flat roof or a low-slope roof, these forces will combine with negative pressures and add to the overall roof uplift that must be resisted. The church building shown in Figure 3.11 lost the overhangs on both sides at wind speeds approximately 60 percent of design wind during passage of Hurricane Elena. Typically, when overhangs are not properly designed to resist these forces, failures are common.[14]

3.3 INTERNAL PRESSURE IMPACTS

If breaches occur in the exterior building envelope during a windstorm, the internal building pressure is changed. The most common source of breaches in a building during windstorms is the failure of doors and windows. Debris impacts, as discussed in the following section, are a major cause of such failures. If the breaches occur primarily on the windward wall (Figures 3.13 and 3.14), the internal pressure of the building will be increased and the walls and roof of the building will be forced outward. If the breaches occur primarily on the side walls or the leeward wall (Figures 3.13 and 3.15), the internal building pressure is reduced and the walls and roof of the building are pulled inward.[15]

Dale Perry

Figure 3.12: Building subjected to internal pressure as evidenced by blown-out overhead doors.

Dale Perry

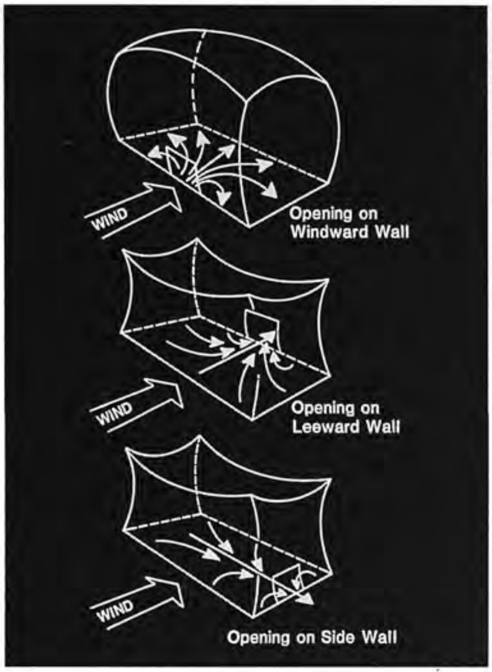

Figure 3.13: Breaches in the building envelope cause changes in internal pressure.

The internal pressures add to the external pressures to cause resultant forces on the walls, roof, and openings of the building (Figure 3.12). The circumstances affecting a particular situation must be examined closely to determine the correct combination of pressures.[16] ASCE 7-95, for example, incorporates criteria for addressing internal pressure increases.

High internal pressure can even affect building structure, as was the case with a warehouse building in Florida that suffered severe damage in Hurricane Andrew. The precast, prestressed roof girders were designed for gravity loads only and also were not connected to the plates at the top of the walls. When the gravity forces of the girders were overcome by positive internal pressures, the girders collapsed, breaking up under their own prestress forces.

A FEMA team investigating damage from Andrew concurred that "The breaching of the building envelope by failure of openings (e.g., doors, windows) due to debris impact was a significant factor in the damage to many buildings. This allowed an uncontrolled build-up of internal pressure that resulted in further deterioration of the building's integrity."[17]

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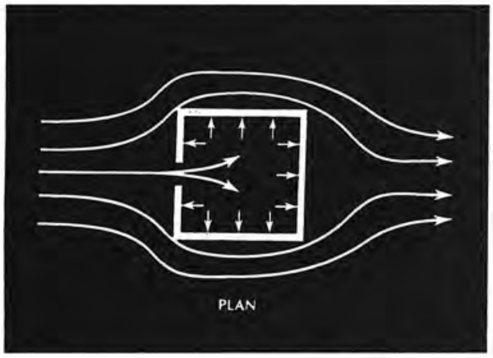

Figure 3.14: Breach in windward wall.

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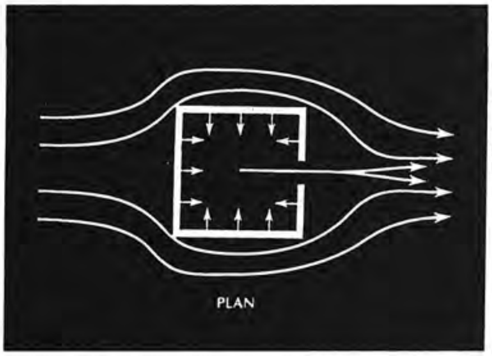

Figure 3.15: Breach in leeward wall.

3.4 DEBRIS IMPACTS


J. Minor

Figure 3.16: Curtain wall damage in downtown Houston during Hurricane Alicia due to wind-borne debris.

In addition to wind-induced pressures, structures located in the path of a severe windstorm are subject to impact forces caused by wind-borne debris. The character of the wind-borne debris depends in part on local construction practices. For current purposes, wind-borne debris can be divided into two groups: small missiles and large missiles.[18]

Small wind-borne missiles include objects such as roof ballast, small pieces of building materials, and natural materials such as pine cones and tree limbs. Small missiles are readily available and are easily propelled even in relatively moderate straight-line winds. Further, small missiles may be generated from the roofs of otherwise undamaged buildings. Once injected into the wind flow, small missiles such as roof ballast can be accelerated to velocities that approach that of the wind, and can crawl up or down the walls to hit adjacent buildings (Figures 3.16 and 3.17). Small wind-borne missiles also can be blown about in relatively moderate wind storms when measured wind speeds only marginally exceed 60 mph.[19]

The primary effect of small missiles is damage to glass. This effect is illustrated dramatically in Figure 3.16, which shows the damaged glass curtain wall of a high-rise building in Houston subjected to the effects of Hurricane Alicia.[20] While no structural damage was observed, substantial damage occurred to the contents due to water penetration.


Figure 3.17: Damage in Hurricane Alicia due to wind-borne gravel ballast from roof of adjoining parking garage.

Most types of glass, including annealed, heat-strengthened, tempered, and insulating glass can be broken by small missile impacts. When this occurs, the contents of the building may be exposed to the effects of the windstorm. In addition, the openings introduced into the building envelope by the cladding failures permit the wind to enter the building, causing internal pressure variations as discussed previously.[21] (For information on laminated glass, see Section 4.4). Finally, it is often the case that glass broken by debris impacts is not fully dislodged from the supporting frames. Broken glass that remains in the window frame presents a continued life-safety risk to building occupants and pedestrians near the building.[22]

In addition to severe damage to exterior glass, small missile impacts can inflict cosmetic damage on a variety of materials including sheet metal, wood siding, and granite panels.[23]

If the wind storm is severe enough, a wide variety of large missiles can be injected into the wind field and accelerated. These missiles include pieces of timber, sheet metal, plywood, trusses, roof-top HVAC equipment, large glass panels, and siding. Figure 3.18 illustrates a broad spectrum of missiles injected into the windstream when a building in Pascagoula, Mississippi, failed during Hurricane Elena. The photograph was taken from the leeward side of the building.[24]

Figure 3.19 shows a building that lost a major section of its roof during the passage of Elena. The roof failure was caused by inadequate anchorage between the roof and walls. Figure 3.20 shows a close-up view of a hole where a small piece of the dislodged roof hit the roof of an adjacent building located downwind from the missile source. This illustrates the destructive potential of large wind-borne missiles and is fairly typical of this type of damage.[25]

If the intensity of the windstorm event is sufficient, even larger missiles such as partially intact roof assemblies can be accelerated in the wind field. Figure 3.21 shows the collapse of a section of a building caused by impact of an intact roof section.[26]

Figure 3.18

Figure 3.19

3.5 RESISTANCE TO WIND LOADS

Continuous Load Paths

Design and construction of buildings for resistance to wind loads requires special attention to all construction and connection details. Also required is consideration that gravity loads are not the only forces acting upon the building. It is natural to assume that a building must be supported to hold it up against the forces of gravity. For many people, it is not so natural to realize that the building must also be held *down* against the uplifting forces of wind on the roof (frequently three to four times the required gravity design loads), as well as restrained against lateral movement caused by the pressures (and suction) on the walls. As the wind passes over and around the building, the change in flow direction and speed causes localized and general pressure changes that must be resisted by the structure as a whole and by the individual components of the structure—i.e., roof, walls, floors, foundations, doors, and windows—as well as by the roofing and wall cladding.[27]

Figure 3.20

Envisioning how wind forces are transferred to and through the building to the ground (the load path) will assist architects in recognizing the effect of the wind on the building. Starting with the exterior, the wind forces are received by the building envelope (roofing and wall cladding). The roof materials must transfer these forces to the supporting roof deck which must, in turn, transfer them to the roof structure (rafters, beams, and girders). The wall cladding, similarly, must transfer wind loads through the wall sheathing to the wall structure (wall studs, steel or concrete framing, or concrete or masonry walls).

Figure 3.21

The architect should consider the difference between cladding and structural walls. Brick veneer, for example, is cladding normally attached to wood frame structural walls with corrugated metal straps. However, a single wythe of brick can also serve as the facing on a concrete block wall so that the brick and concrete block form an integrated structural bearing wall.[28] Veneers are consistent problems in high-wind environments. Integrated structural walls are less so.

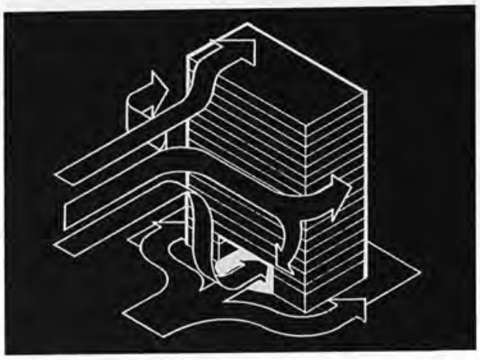

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Figure 3.22: Openings through a building at the base may induce high velocities in the opening.

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Figure 3.23: Comfort of pedestrians at the base of a building should be considered.

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Figure 3.24: A low-pedestal building concentrates wind on the roof, not at the base.

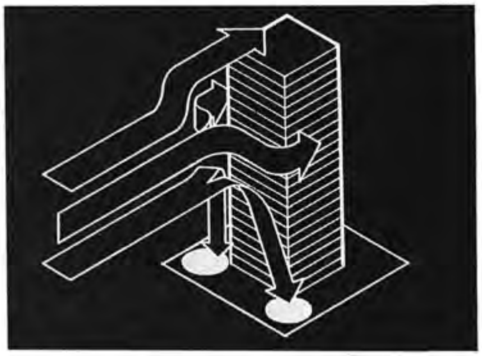

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Figure 3.25: A tall building concentrates wind at its base.

The primary building structure (the main wind force resisting system) must be designed to resist the forces transferred to it. Most importantly, the members must be connected so that the entire building is stable and acts as a system. The roof rafters, beams, and girders must be adequately connected to each other and to the walls or columns that support them; the walls or columns must be continuously connected until they reach the foundation to which they are connected; and the foundation must be capable of resisting the forces and transferring them to the ground. Similarly, the structure for each floor must be connected to the walls and columns. It must be remembered that floors and roofs frequently provide lateral support to bearing and nonbearing walls throughout the building. Thus, the connections between the various structural and nonstructural components of the building are critical.[29]

Building Configuration

Building configuration can aggravate detrimental wind effects. For example, a tall building that sits on a low-pedestal building of two to four stories can create problems on the roof surface of the pedestal building. Such forces can be as high as the negative pressures at the top of the building, or higher. Wind breaking up over the roof of the pedestal building is magnified and combined with high winds coming down from the top of the tower. These combined wind forces can tear up the roof at the corners of the pedestal building where it meets the tower (Figure 3.24). If pedestrian access is permitted on the roof of the pedestal building, high wind loads can make that space difficult to use.

For high rises, wind forces can create havoc at the base. The wind blows against the tall building and moves to either side around it, creating high pressures at the corners. Part of the wind will go up and over the top, and part of it will come straight down to ground level (Figure 3.25). On the leeward side of the building, a wake occurs with suction forces on the tower. While wind speeds on tall buildings are magnified at the base, they increase in strength at the building corners. Architects should keep these wind dynamics in mind in terms of pedestrian comfort when locating entrances in tall buildings (Figures 3.22 and 3.23). Corner entrances at the base of a high rise will be subject to the highest wind loads (Figure 3.26).

When wind blows from a diagonal across a corner, it creates conical vortices, which can be seen in wind tunnel testing (Figure 3.27). By placing a vertical element at the corners of the form, the diagonal wind is split and the conical vortices broken up and dissipated. There are still high localized loads going over the top of the configuration, but they don't compound at the corner, and a relatively small element at the corner will interrupt it.

Based on wind damage investigations after Hurricane Andrew, FEMA is encouraging the design of more aerodynamic building shapes such as hip roofs. More aerodynamic building shapes reduce direct wind forces experienced perpendicular to windward planes of buildings and also the consequent effect of whirling air flows (vortices) that accumulate at the corners and edges of the planes. The accumulation of both the direct and negative pressures resulting from these wind flows is particularly prevalent in configurations with abrupt changes in plane (wall to roof). This is one of the reasons that hip roofs perform better than gable roofs in high winds.

Siting

Siting a building on a bluff dramatically increases the loads on the building at the point closest to the bluff and to the change in topography. If the building is sited further down the slope on the windward side, or back from the bluff, the wind loads drop off significantly. Wind forces on bluffs illustrates in Figure 3.29, the critical locales on the site that architects should keep in mind when locating a building in such terrain. Photos of damage in several Hawaiian hurricanes dramatically illustrate this effect (Figures 3.30, 3.31, 3.34 and 3.35). The increased loads on the building may be as much as doubled.

Architects should be aware that it is very difficult to determine the direction from which wind will affect a building, because wind direction may change dramatically during the course of a storm. The les-

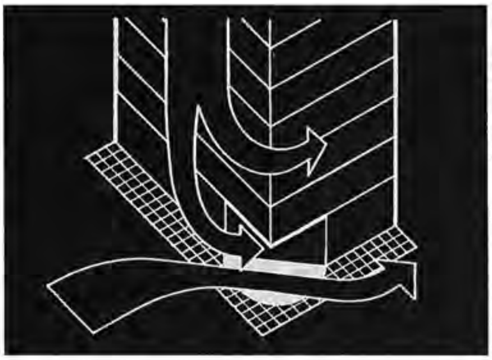

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Figure 3.26: Corner entry may accentuate wind concentration at building corner.

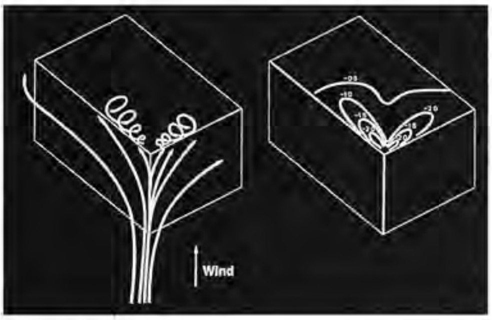

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Figure 3.27: Conical vortices occur when wind strikes a building diagonally at a corner.

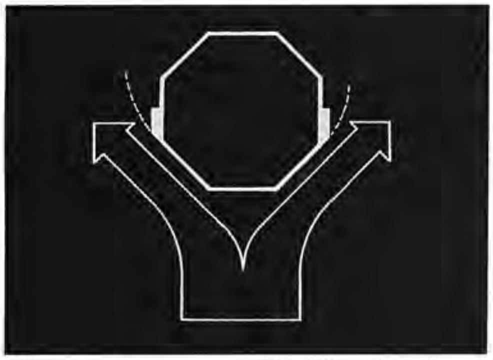

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Figure 3.28: Multi-sided buildings may not permit full development of local pressures, from loads or pedestrian level winds.

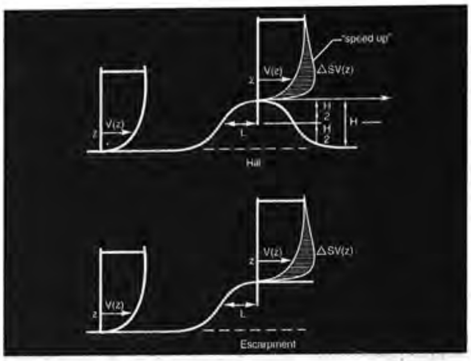

Figure 3.29: Increased wind loads as a factor of building placement on a bluff.

Cermack, Chiu, Perry

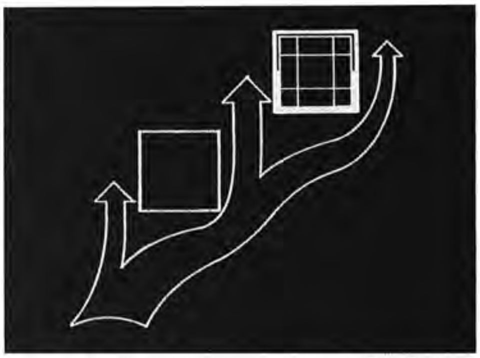

Figure 3.32: Adjacent building placement may deflect wind resulting in higher wind loads and pedestrian level winds.

Cermack, Chiu, Perry

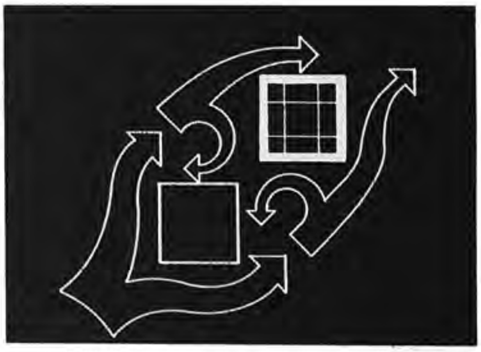

Figure 3.33: Adjacent building placement may protect from high winds reducing wind loads and pedestrian level winds.

Cermack, Chiu, Perry

Figure 3.30: Wind speed-up in St. Thomas during Hurricane Marilyn produced extensive damage to residential and commercial structures.

Dale Perry, R.D. Marshall

son for architects here is that, on sites exposed to high winds, one cannot assume that the wind loads will come only from one direction, even in locales with "prevailing breezes."

In urban areas, wind loads are magnified when wind is funneled between tall buildings. Buildings located in dense urban settings, surrounded by other buildings on all sides, will be protected somewhat from wind, as will low-rise buildings and housing sited with other structures around them in close proximity (Figures 3.32 and 3.33). Post-hurricane analysis has shown that buildings located on the outside or "leading edge" of enclaves of structures usually receive the most damage.

Figure 3.31: Localized damage due to wind speed-up Poipu Beach, Kauai due to Hurricane Iwa (1982).

Dale Perry

Dale Perry

Figure 3.34: Poipu Beach, Kauai, Hurricane Iwa, 1982

CHAPTER 3 REFERENCES

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17. *Building Performance: Hurricane Andrew in Florida*, FEMA, December 21, 1992.

Dale Perry

Figure 3.35: Localized damage due to wind speed-up; Princeville, Kauai, Hurricane Iniki, 1992.

Dale Perry

Figure 3.36: Seawall on New Jersey coastline will produce wind speed-up for wind normal to wall.

4

Residential Buildings

(Single and Multifamily)

Dale Perry

Figure 4.1: Loss of vinyl siding in wind speeds less than 70 mph, Hurricane Erin, 1995.

Single and multifamily residential buildings consistently suffer the heaviest damage from high winds and in the aggregate account for the majority of insured damage. A major reason is that these buildings typically receive little attention to wind loading/resistance, and limited field observation/inspection during construction. The critical areas of good design and construction for wind resistance are the walls and roofs and the connections between them, and the building openings. Each is discussed below. The chapter concludes with a discussion of load-path connections, which are one of the most important aspects in design and construction of wind-resistant buildings.

4.1 WOOD WALLS

Structural Considerations

The structural connections are by far the biggest problem in the performance of wood walls in high winds. Wind experts note that the primary improvement needed in this case is using better connectors for roofs and walls, one of the weakest links in most homes. Improving roof and wall connections greatly increases the ability of buildings to withstand high winds and adds only marginally to the construction cost of an average new home.[1]

According to the FEMA team that investigated damage from Hurricane Andrew, another area of concern for wood-frame walls is the transfer of loads from the walls to the concrete slabs and masonry foundation walls. For example, the use of cut nails in lieu of bolted masonry-to-wood connections was observed. Also, masonry-to-wood frame straps should be properly located.

A less commonly observed form of wind damage is the lifting of an entire house from its foundation. This type of damage is rare because the uplift force on the roof-ceiling combination must be greater than the weight of the entire house. Such large uplift forces are generated only by very strong winds. Also, it happens only when the roof is well secured to the walls, but the walls are not properly secured to the

Dale Perry

Figure 4.2: EIFS damaged in Hurricane Erin.

foundation. The problem can be corrected by proper anchorage of the walls to the foundation. Power nailing of the sole plate to the foundation should not be permitted in high wind areas or where buildings are subject to tidal surges. Mechanical fasteners (e.g. bolts) should be used in these situations. This problem also is observed in coastal areas where buildings may be subjected to tidal surges.[2]

Sheathing and Cladding Considerations

When a building is subjected to high winds, the wall sheathing and cladding should work together as a single system to provide racking resistance, and to prevent breaching of the building envelope. Sheathing materials will act as a diaphragm and provide appropriate racking resistance.

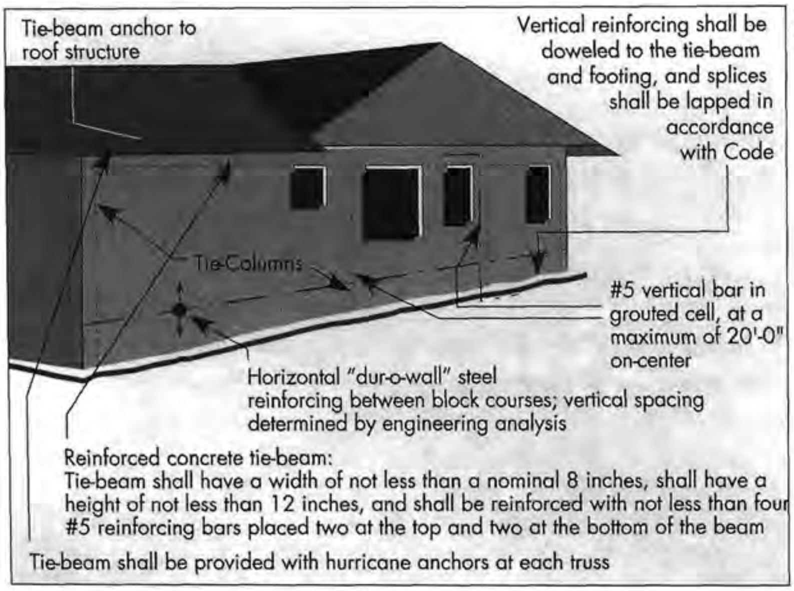
Whatever the cladding, proper attachment to the sheathing is critical. Post-hurricane survey teams report that the most prevalent cladding failures involved vinyl siding that was simply stapled onto the sheathing (Figure 4.1); exterior insulating finishing systems (EIFS) (Figure 4.2); and brick veneer walls that were not properly tied back into the structure (Figure 4.3). Architects should be aware of these observed failure patterns when using these systems.

4.2 MASONRY WALLS

Masonry bearing walls are often vulnerable to wind damage if not properly reinforced. Damage investigations show that unreinforced masonry walls are a common structural failure point even when they are subjected to winds well below the design level.

Dale Perry

Figure 4.3: Loss of brick veneer in a tornado spawned by Hurricane Gilbert.



FEMA

Figure 4.4: FEMA recommendations for masonry wall reinforcement.

Structural Considerations

According to the FEMA team that investigated damage from Hurricane Andrew, the main cause of failure in masonry buildings was a lack of vertical wall reinforcing. FEMA suggests that a tie beam of reinforced concrete should be placed in all walls of unit masonry, at each floor or roof level, and at such intermediate levels as may be required to limit the vertical heights of the masonry units to 16 ft. The use of concrete tie-columns at all corners, and at intervals not to exceed 20 ft on center of columns, is also suggested. The maximum area of wall panels of 8-in-thick unit masonry as measured between concrete members that frame the panel, such as the tie-beams and tie columns, should not exceed 256 sq ft (Figure 4.4).

Cladding Considerations

The points made above concerning masonry veneer on wood-frame walls are applicable to masonry walls as well. The critical points are connection of the cladding materials back into the building's masonry structure.

4.3 ROOFS

In Hurricane Iniki, one- and two-story wood-frame buildings sustained more severe damage than other types of construction. The primary cause was failure of the roof structural system due to uplift forces, combined with wall failure from direct wind pressure on interior and exterior walls, which lost top support once all or part of the roof structure was lost. Simply stated: the roof structure provides critical lateral support to load-bearing and non-load-bearing walls. Once the roof structure is partially or fully lost, the necessary roof


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Figure 4.5: Omaha tornado, roof assemblage damage due to lack of connections between walls and roofs.


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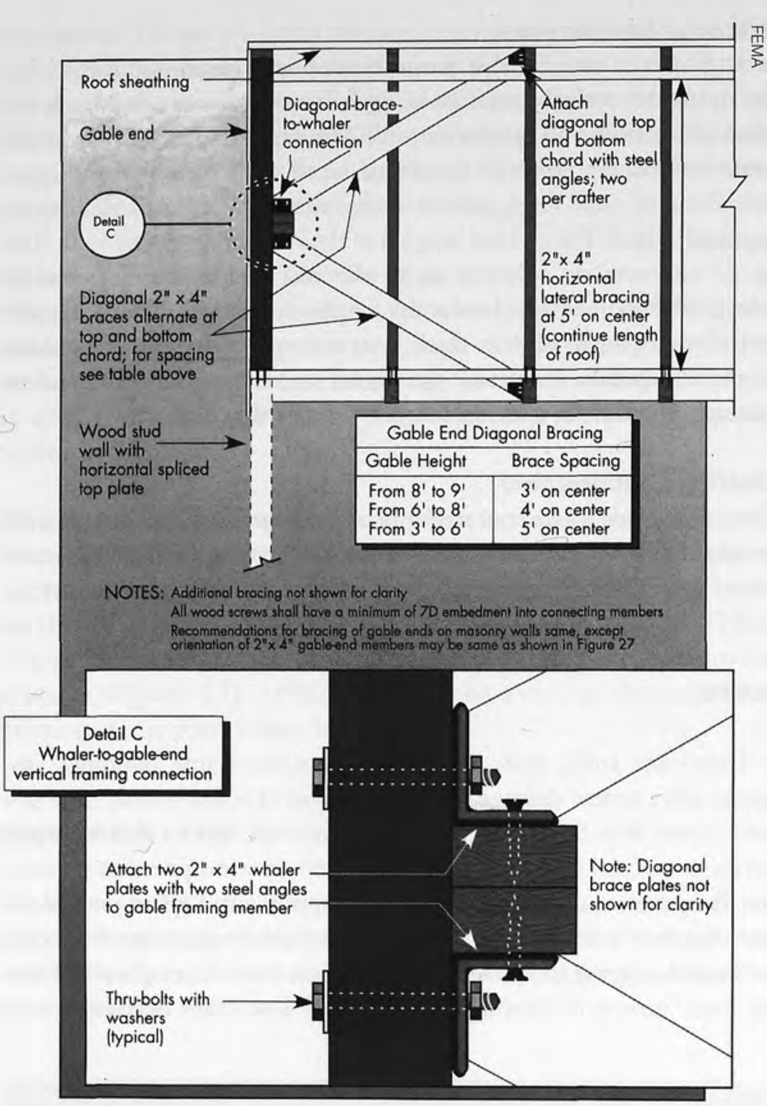
Figure 4.6: Metal roof damage in St. Croix during Hurricane Marilyn.



Gable End Diagonal Bracing

Gable Height	Brace Spacing
From 8' to 9'	3' on center
From 6' to 8'	4' on center
From 3' to 6'	5' on center

NOTES: Additional bracing not shown for clarity
All wood screws shall have a minimum of 7D embedment into connecting members
Recommendations for bracing of gable ends on masonry walls same, except orientation of 2"x 4" gable-end members may be same as shown in Figure 27

Figure 4.7: Roof bracing techniques suggested by FEMA.

diaphragm may be compromised, and the ability of the walls to withstand wind pressure is greatly diminished.

Failed roofs make up the major components of wind-borne debris. In Hurricane Iniki, the components of such debris (in decreasing order of prevalence) were roof cladding (shingles, tiles, and shakes), failed roof and wall structural components, and roof sheathing.

In hurricanes, the modes of building failure are interconnected. Loss of roofing contributes to the number of wind-borne projectiles; this in turn significantly increases the potential for breaching windows and doors (and the subsequent failure) of neighboring buildings, further adding to the debris stream.

Structural Considerations

The most pervasive type of failure in primary structural systems in houses results from uplift forces on roofs that are incompletely or inadequately connected to walls. FEMA's Iniki investigating team noted that roof trusses generally performed well under wind loads. However, because connected trusses and sheathing formed the horizontal diaphragm of the building system, truss systems tended to become unstable and failed to varying degrees when the sheathing was lost. FEMA recommends using braced truss roof systems sufficient to resist lateral forces independent of the roof sheathing. Roof structural systems can also be considerably improved with simple secondary bracing or blocking applied within the truss network, thus relieving the roof's reliance on diaphragm sheathing action alone (Figure 4.7, 4.10-4.13).

The shape of the roof also has an effect on the loads that it is subjected to, as discussed above. FEMA suggests substituting hip roofs for gabled ends as a particularly advantageous solution. The construction of a hip roof results in an inherently braced roof system. In its post-disaster investigations, FEMA has found that gabled roof structures are invariably more failure-prone. Hip roofs generally perform better than gable-end roofs, clerestory roofs (offset roof peak), and other steeply pitched roof systems. However, because gable roofs continue to represent the most economical form of construction, they will continue to be built. To ensure adequate performance special attention must be paid to framing (including proper bracing) and detailing this very common roof type.

Nailing procedures, such as toe-nailing at rafter to ridge or rafter to wall connections, are typically not adequate to withstand significant loading. Such toe-nailing does not provide an effective load path for distribution of wind uplift and lateral loads from the roof to the walls, and therefore should be avoided.

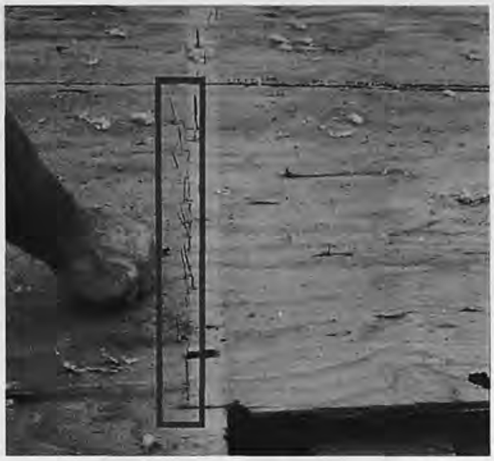
The most effective solutions to wind loads on a roof structure include:

- using special connectors (clips, plates, straps, etc.) instead of toenails at every rafter-to-top-plate joint and every joist-to-plate joint;
- using stronger-than-normal, special connectors near the corners of roofs;
- placing all rafters next to ceiling joists so that the two can be tied together.

The cost of implementing these effective measures is typically minor and can significantly increase the performance of houses in windstorms.[3]

Sheathing Considerations

FEMA's Iniki investigating team noted that loss of roof sheathing (e.g. plywood) was a consistently observed failure mode. The primary cause of sheathing loss was the lack of adequate nailing of the sheathing to the structural supports (rafters, trusses, purlins).



FEMA

Figure 4.8: Stapling of roof sheathing was off line and did not penetrate roof structure.

FEMA

Figure 4.9: Sheathing on this roof destroyed by Hurricane Andrew was only tack nailed.

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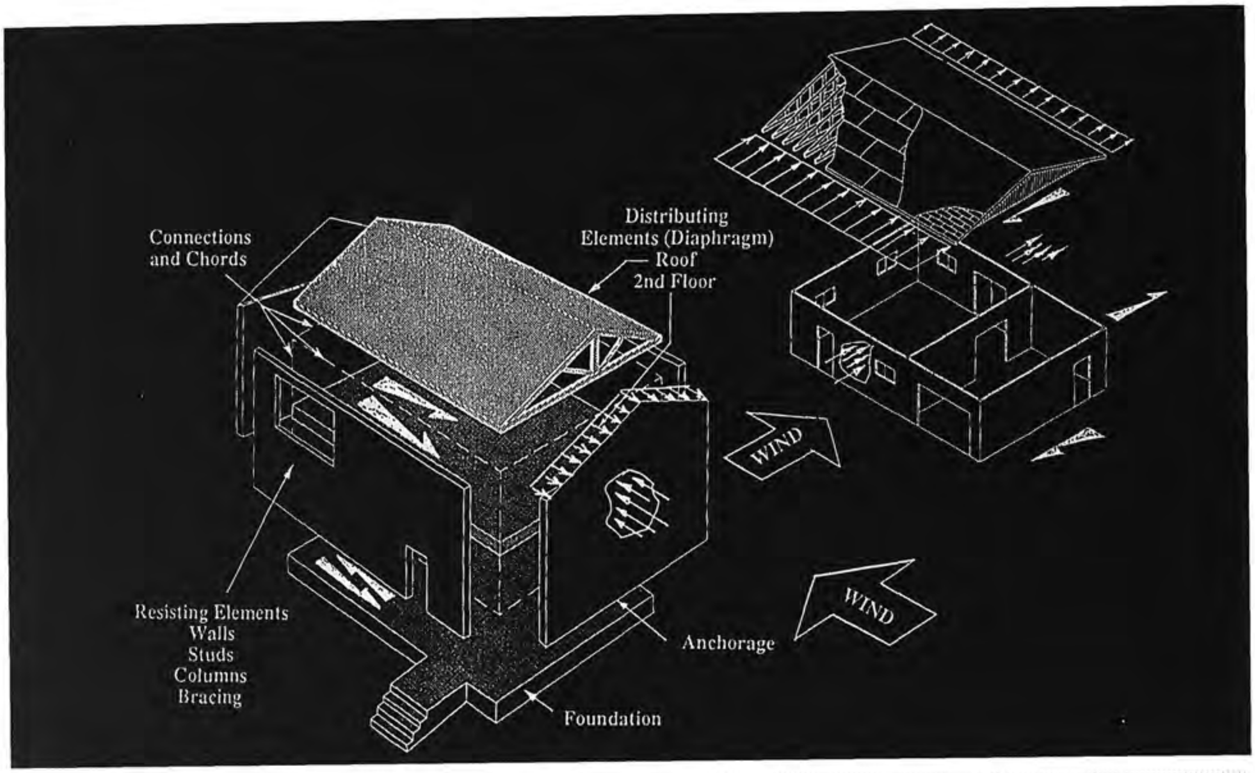


Figure 4.10: Lateral-resisting components.

FEMA

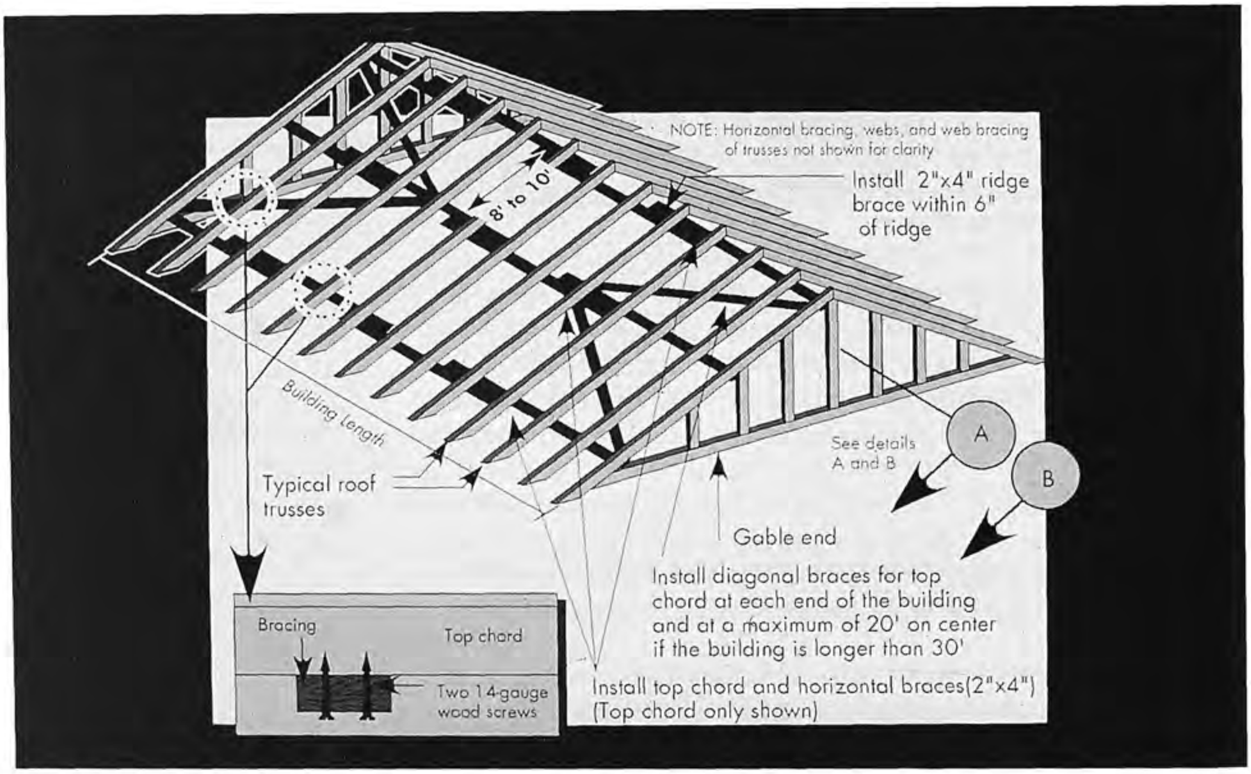
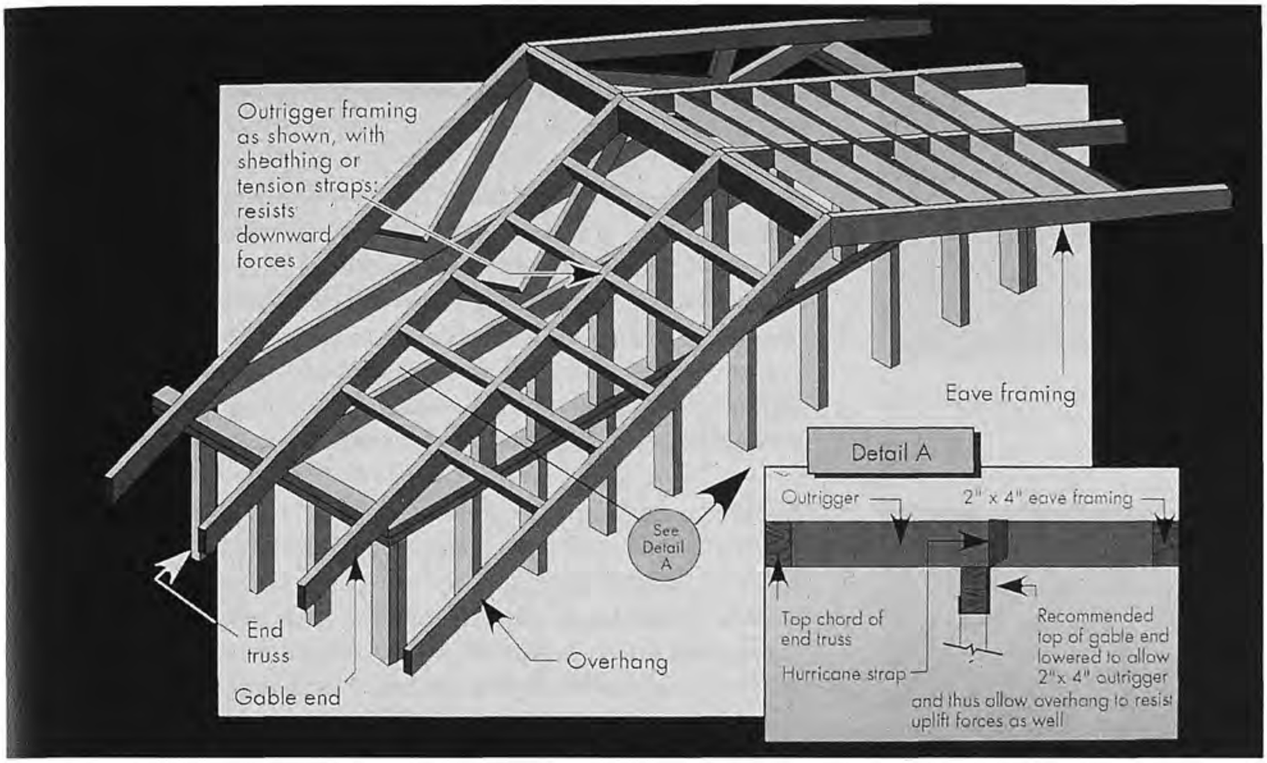


Figure 4.11: Typical roof truss top chord bracing, suggested by FEMA.



FEMA

Figure 4.12: Observed roof bracing for gable roof overhang and recommended modification, suggested by FEMA.

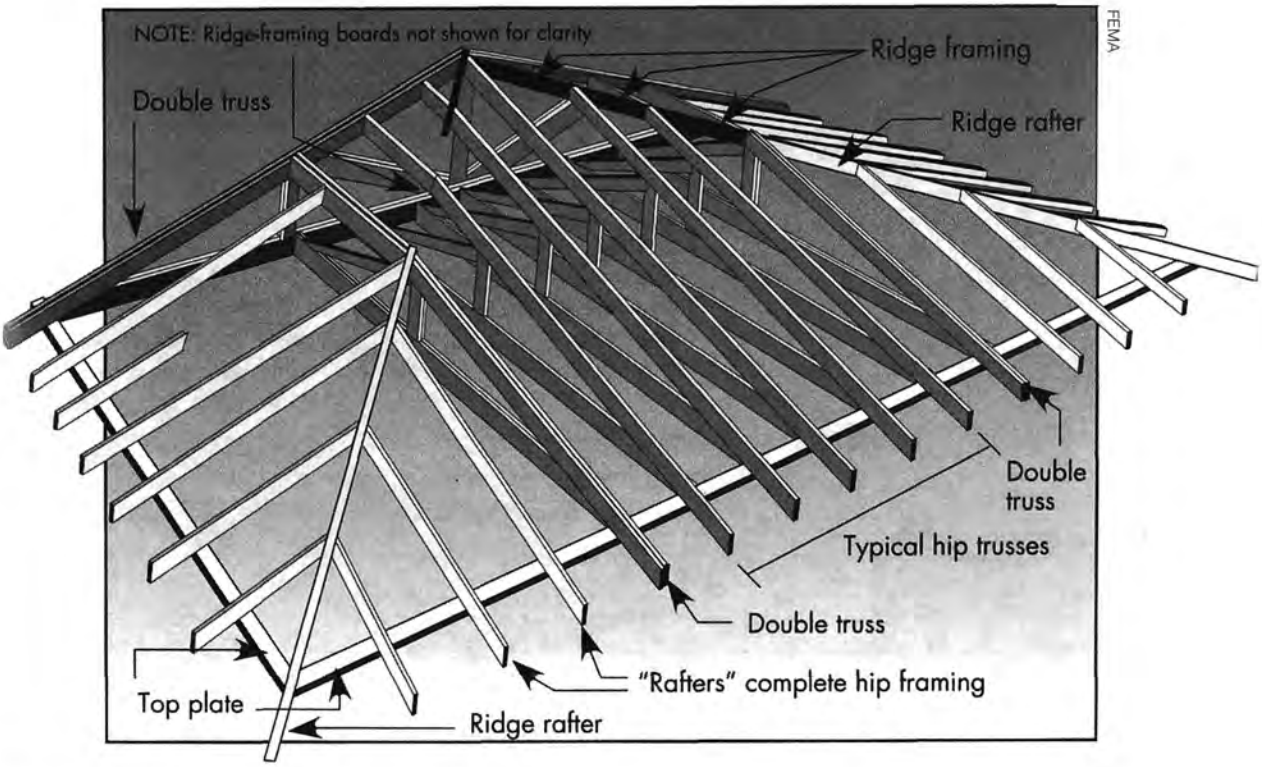


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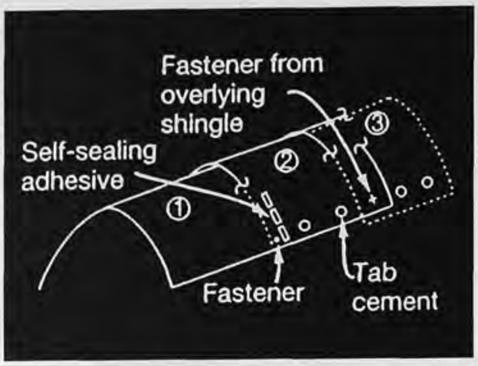
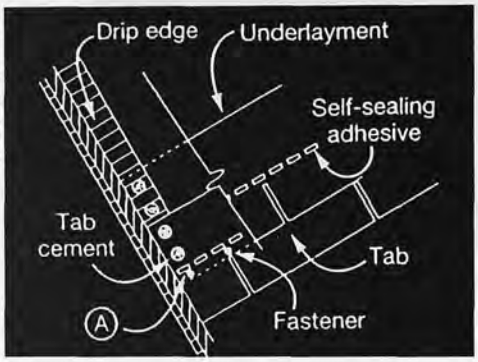
Figure 4.13: Hip roof framing suggested by FEMA.



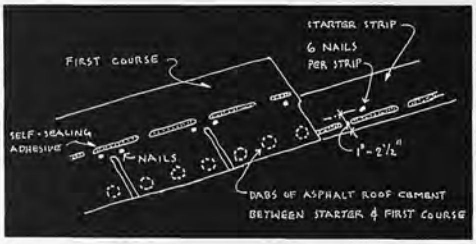
Thomas Smith, NRCA

Figure 4.14: Enhanced hip and ridge detail.



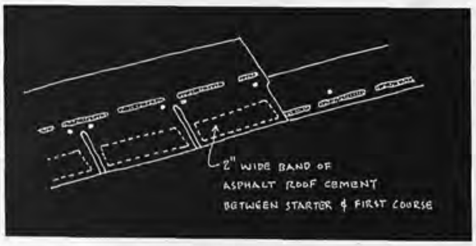
Thomas Smith, NRCA

Figure 4.15: Enhanced rake detail. Without the tab cement, the self-sealing adhesive at position "A" can become overstressed. As a result, the corner of the tab may lift up and peel.



Thomas Smith, NRCA

Figure 4.16: Sealing first course of shingles with three dabs of asphalt roof cement.



Thomas Smith, NRCA

Figure 4.17: Sealing first course of shingles with band of asphalt roof cement.

Loss of sheathing is especially critical in roof systems that rely heavily on it to provide diaphragm action. In such systems, if the sheathing fails (usually from inadequate connections) the entire roof structural system can fail as well.

Roof Covering Considerations

Damage to roof coverings is the most common and costly problem in high winds, exposing building contents to damage and contributing to loss of building use. Investigations of recent hurricanes revealed that damage to roof covering (such as concrete and clay tiles, wood shingles and shakes, asphalt shingles, and underlayment material) can be extreme. Deficient design attention and application, and inadequate or non-existent testing procedures are prime causes of covering failure.

Roofing researcher Thomas Smith of the National Roofing Contractors Association* developed the following recommendations, based on his investigations of roof performance from Hurricanes Andrew, Fran, Hugo, and Bertha. The primary observed problems on damaged asphalt shingle roofs were: shingle fastening; poor attachment at eaves; and incorrect fastener placement. Typically fasteners were above the self-seal strip, and on some roofs, they were located several inches from the rake. Although six fasteners per shingle are normally recommended for high-wind regions, on the problem jobs investigated typically four fasteners were used. On some jobs where shingles had been installed using the racking method, only three fasteners were used to attach several of the shingles.[4]

Many of the following recommendations for asphalt shingle roofs (the most common residential roofing material) are enhancements over commonly accepted practices found in *The NRCA Roofing and Waterproofing Manual.* Many of these options can result in increased construction costs. However, Smith believes that roofs with these enhancements will be more wind-resistant.[5] In high wind areas:

1. Follow the general recommendations given in the Fourth Edition of *The NRCA Steep Roofing Manual* (1996).

2. Specify attachment with six nails (rather than staples) per shingle. Locate the nails as indicated in the Fourth Edition of *The NRCA Steep Roofing Manual.* For roofs within 3,000 ft of salt water, specify hot-dip galvanized (rather than electroplated) or stainless steel nails.

---

*Smith's recommendations related to asphalt shingle and other roof systems discussed in this and other Sections have been peer-reviewed, but they have not yet gone through a rigorous consensus process and been incorporated into mainstream documents such as the *NCRA Roofing and Waterproofing Manual.* The recommendations are offered for architects to consider.

3. In lieu of the eave detail shown in Figure 17 in *The NRCA Steep Roofing Manual* (1996) specify that the starter strip be nailed approximately 1 to 2-1/2 in from the eave edge of the starter strip. One inch is preferred, but framing conditions may require that the nails be placed farther away. Specify placing fasteners in sheathing or framing lumber, rather than in trim boards. Six nails per starter shingle are recommended.

   Specify sealing the first course of shingles using one of the following options:

   - Place three dabs of asphalt roof cement (approximately 1 inch in diameter) over the starter strip so that the overlying tab of the first course will be adhered (Figure 4.16).

   - Using a putty knife, place a band of asphalt roof cement, approximately 2 in wide, over the starter strip. Leave gaps approximately 1 in wide at about 12 in on center to allow drainage of water that reaches the starter strip (Figure 4.17).

4. Specify hand tabbing rakes, ridges, and hips (for guidance refer to the December 1994 issue of *Professional Roofing*).[6] In addition, because of the extra thickness of materials at the hips and ridges, longer nails than those used in the field of the roof may be needed. Specify that nails penetrate the underside of the sheathing, or penetrate at least 3/4 in into wood plank decks.

5. At eaves and rakes, specify that the shingles overhang about 1/4 in (This is the low end of the 1/4 to 3/4 in range recommended in *The NRCA Steep Roofing Manual.*)

6. Architects should try to obtain bond-strength data from manufacturers and specify products with a strength value that is within the upper range of available strengths.

7. Architects should try to obtain nail pull-through resistance data from manufacturers and specify products with a value that is within the upper range of available strengths. (Nail pull-through resistance data should be based on the test method prescribed in ASTM D 3462.)

8. Specify either fiberglass-reinforced asphalt shingles complying with ASTM D 3462, or organic-reinforced asphalt shingles complying with ASTM D 225.

9. To minimize water damage in the event of shingle blow-off, specify two plies of underlayment (with offset side laps) as follows: Attach the underlayment with low-profile capped-head nails or thin metal disks attached with roofing nails. Fasten at approxi-

Dale Perry

Figure 4.18: Retrofit connections for a pole-house building that performed well through Hurricane Iniki.

mately 6 in on center along the laps and at approximately 12 in on center along a row in the field of the sheet between the side laps.

10. For reroofing projects, specify tear-off, rather than re-cover. (With re-cover, there is a greater possibility of having tab bonding problems because of substrate irregularities. Also, when the roof covering is torn off, the deck can be inspected.)

11. For reroofing projects, inspect the sheathing and specify additional securement if deemed appropriate. (The purpose of this inspection is to determine if the decking is adequately attached, as buildings constructed prior to the 1990s often were designed without extra securement at the roof perimeter.)

12. Specify that the application be performed by a professional roofing contractor experienced with asphalt shingles.

Smith observes that in hurricane-prone regions, tile roofs are problematic as they are vulnerable to breakage and subsequent blow-off when hit by debris. Failure of the nailing and/or the mortar connections that are used to attach tile roof systems has also occurred, as have underlayment failure, lack of attachment of each tile, and lack of mortar pads on ridge and steep-sloped sides. Smith's recommendations[7] for architects regarding tile roof design are as follows:

1. In high-wind areas, nail-on or tie-wire attachment methods are recommended for tile securement. If slope conditions require an adhesive securement, the foam-set method is recommended, rather than the mortar-set method.

2. For nail-on, tie-wire, and loose-laid systems, determine uplift loads and tile resistance in accordance with the provisions in the Standard Building Code (SBC) using ANSI/ASCE 7 criteria (if using ASCE 7-95, the tile coefficient in the SBC needs to be adjusted).

3. Specify hurricane clips designed for screw-attachment to the deck and clips or tail hooks that are sufficiently strong to avoid deformation.

Information on Wind design is also found in *Concrete and Clay Roof Tile Installation Manual.* First Edition, FRSA and NTRMA, 1996.

Roof Venting and Overhangs

The FEMA team investigating building damage from Hurricane Andrew reported that structures with adequate roof ventilation were observed to have performed better due to the ability of the ventilation to relieve induced internal pressure.

Venting with adequate openings to relieve induced internal pressures on roof structures is recommended. However, venting must be designed so that the entry of water is not allowed, although water penetration due to venting is typically minimal. The soffit should be properly attached.

The team observed that roof overhangs or soffits 3 ft or less, with adequate venting, suffered comparatively less damage from wind forces. Overhangs exceeding 3 ft in many instances failed to resist the uplift forces and were the source of progressive roof structure failure. Large overhangs need to be properly engineered.

4.4 OPENINGS

Doors

Post-hurricane inspections reveal that various entry doors, most notably french doors, and wood and metal double doors, are prone to

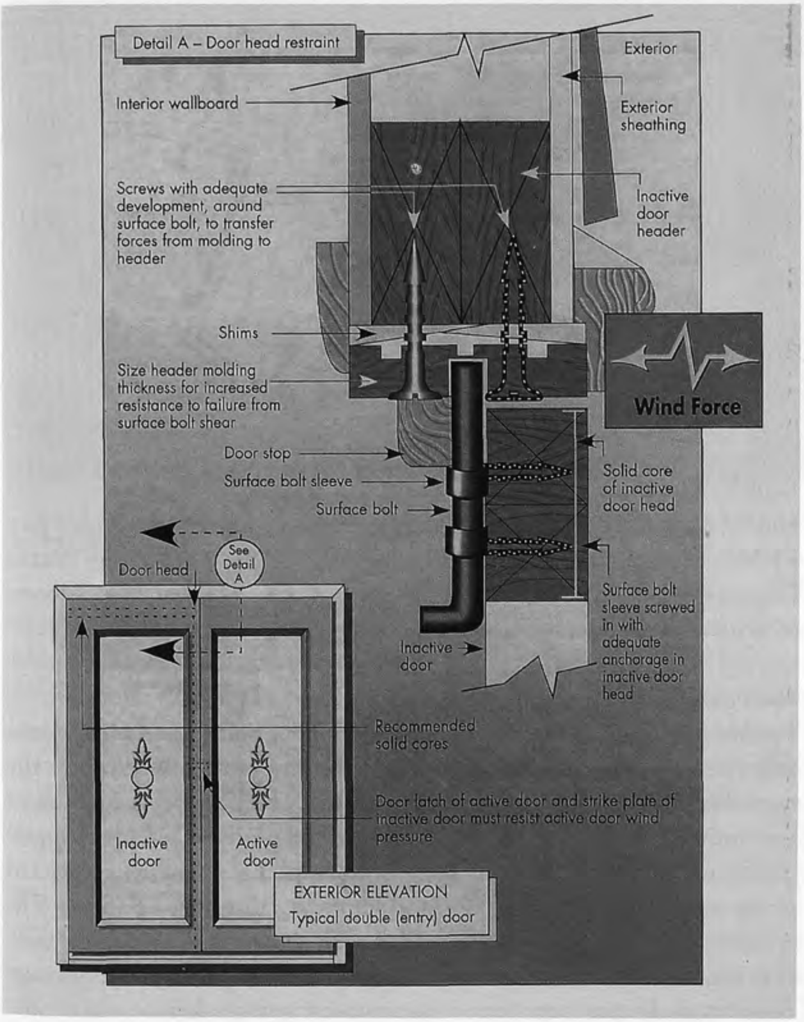


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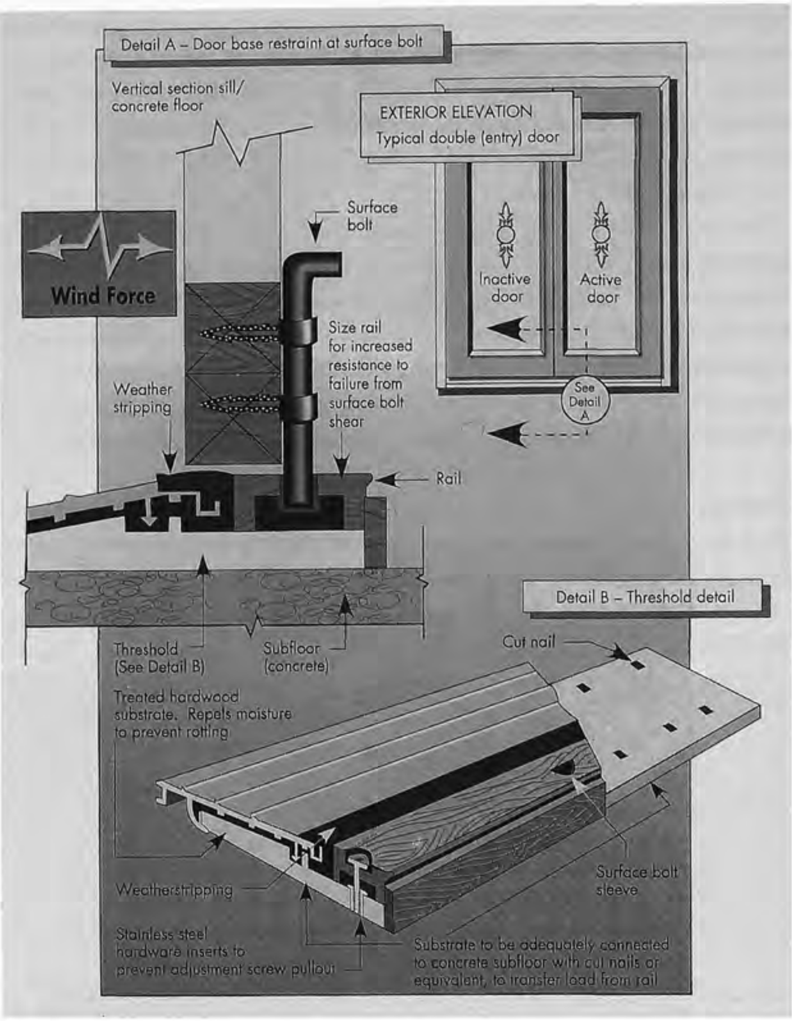
Figure 4.19: Double entry door header recommendations.



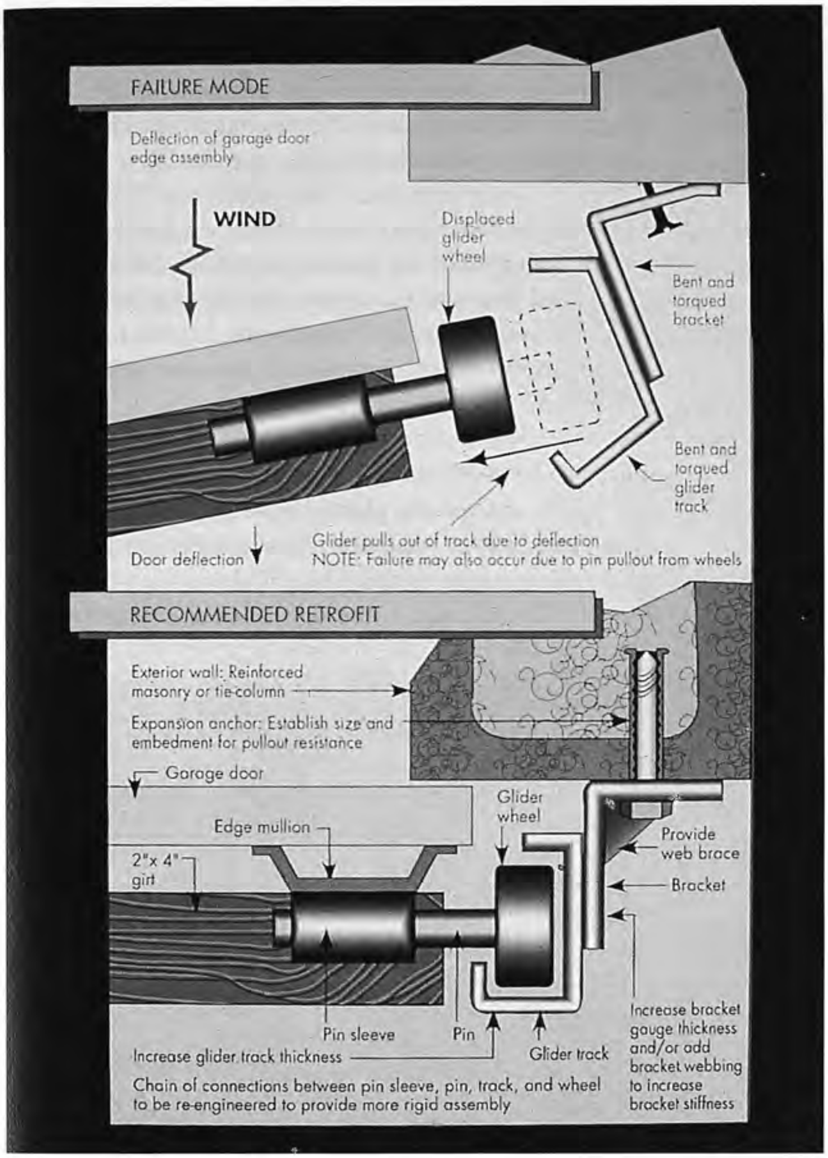
FEMA

Figure 4.20: Double entry door threshold recommendations.

failure. These doors failed as a result of pullout of their center pins and/or shattering of the door leafs at the location of the center pin. FEMA recommends that architects use the accompanying details (Figures 4.19 and 4.20) in the design of these types of entry doors, which can help maintain the integrity of the envelope.

Garage Doors

Failure of garage doors can lead to significant damage. Garage doors fail when the door deflection exceeds the amount allowed for in the manufacturer's design. This deflection causes excessive deformation of the entire assembly (panel roll-up doors and glider wheel tracks) and ultimately the separation of the door from the opening. Overhead doors with cold-formed steel track supports fail under relatively low wind speeds. Loss of the door results in an envelope breach and a sudden increase in internal pressures in the building. Single-car garage doors typically perform better than two-car garage doors.



FEMA

Figure 4.21: Plan views of suggested details for reinforcing overhead door tracks by FEMA.

Dale Perry

Figure 4.22: Dislodged overhead doors contribute to internal pressure problems.

FEMA recommends that two-car garage doors be manufactured to include mullions and girts; the security locking system should also be reinforced; and a wind-force-resistant latch should be provided. Glider tracks and track supports should be strengthened (preferably by hot-rolled sections) to prevent failure caused by guide track rotation door deflection under wind loads (Figure 4.21). FEMA also offers a number of details to improve the performance of garage doors in high-wind locations.

Windows

FEMA's Iniki investigating team noted that glazing failure occurred in two ways: shattering from projectile impact; and implosion or explosion due to the combination of wind pressure and improper installation.


Dale Perry

Figure 4.23: In St. Croix, Hurricane Marilyn did no damage to these shuttered windows.


Dale Perry

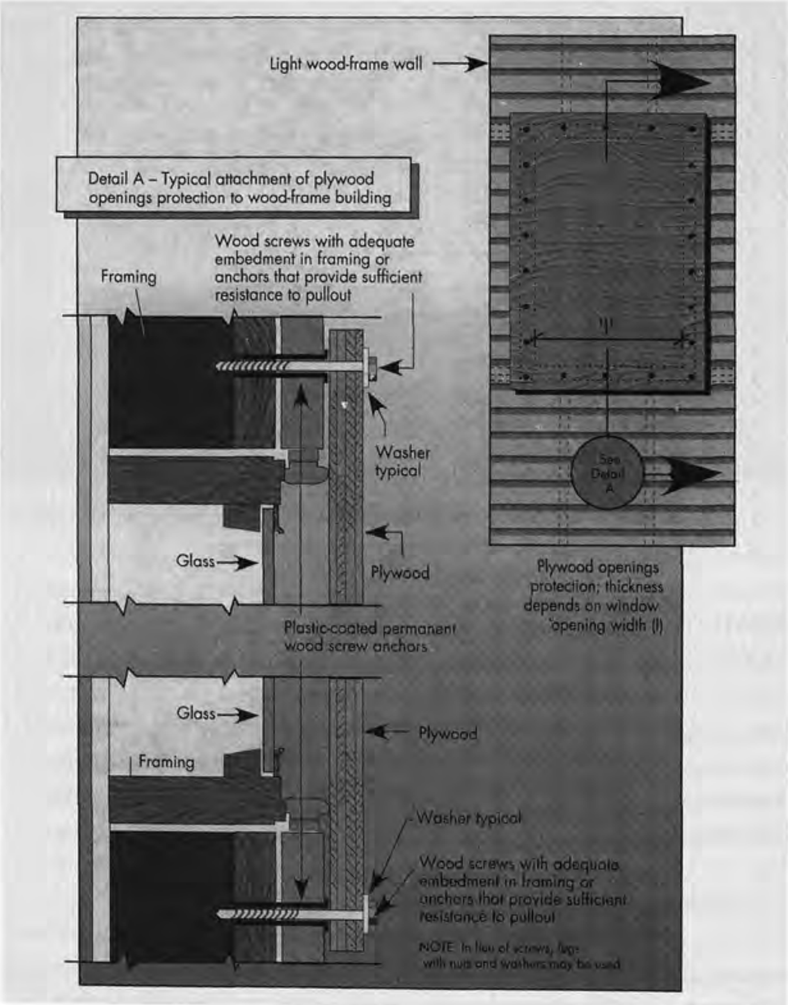
Figure 4.24: Moveable shutters are an effective means of protecting openings.

Glazing and Installation

In 1994, the South Florida Building Code was revised to require that glazing must either resist impacts from wind-borne debris according to certain performance requirements, or be protected with storm shutters that must meet similar performance requirements.[8]

Windows can be designed to resist impacts from wind-borne debris and to maintain the integrity of the building envelope. According to glazing consultant Paul Beers, this requires glazing that will remain intact, even if it is fractured by wind-borne debris. Laminated glass is one material that meets this criterion; annealed, heat-strengthened, or tempered glass will not.[9]

The glazing must also be anchored to the window frame to avoid fall-out during high winds, even if the glass cracks. According to Beers, this can be accomplished with a structural silicone anchor bead that, in effect, glues the laminated glass to the frame.[10]



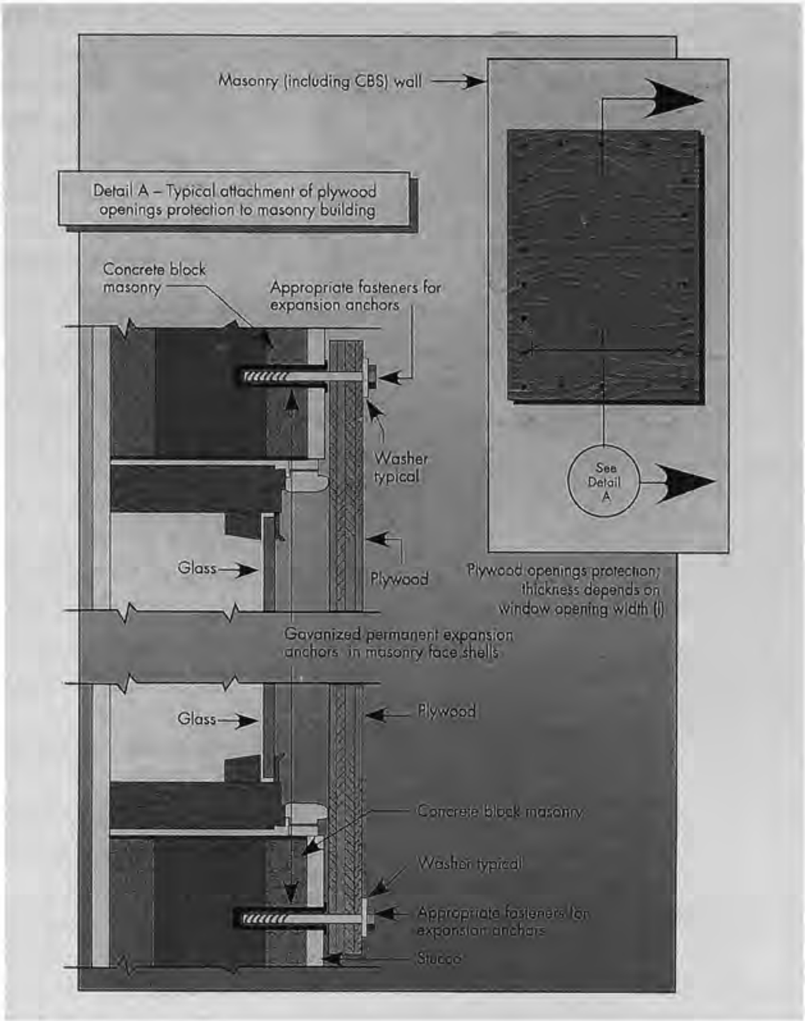
FEMA

Figure 4.25: Typical installation of plywood openings protection for wood-frame building.

Architects wishing to specify impact-resistant windows and doors should reference ASTM 1886, a missile-impact test standard for glazing, which was approved in 1997. However, it does not provide missile load criteria (ASTM is working on a separate standard for loads). Missile load and missile impact location information can be found in SCBBI SST 12-97. Also, specify the submittal of test results indicating compliance with the specified criteria.

Residential windows and doors designed and tested for wind-borne debris are available. For commercial buildings with custom glazing systems, currently available materials can be used for impact-resistant designs. All custom designs should be tested prior to approval for use.[11]

Jalousie windows continue to be widely used in the Caribbean, in both residential and industrial applications.[12] In addition to providing ventilation, they are much more resistant to wind-borne debris (one or two individual panes may be broken but the water penetration will be minimal).



FEMA

Figure 4.26: Typical installation of plywood openings protection for masonry building.

Methods of Protection

FEMA's Hurricane Andrew team noted that storm shutters and boarded windows and doors were observed to have reduced the extent of overall damage to buildings by protecting the building against wind penetration. Dale Perry and Richard D. Marshall, in conducting investigations on St. Croix in the wake of Hurricane Marilyn, found that wood shutters and protective plywood panels were most effective.

Shutters can be of the operable type of heavy wood or metal, which can swing into place and latched. Roll-down shutters, also a good choice, give the architect the option of hiding the shutter above the window.

In lieu of permanently installed shutters, FEMA and others suggest the use of plywood to cover windows in anticipation of a storm. Architects can design attachment clips for plywood, which makes the installation of the material much easier and faster. FEMA offers details for attachment clips for use in hurricane-prone regions (Figures 4.25 and 4.26). It is important to note that the attachment of plywood panels to brick veneer will not provide the needed protection.

4.5 PORCHES AND APPENDAGES


Dale Perry

Figure 4.27: All the picnic shelters along Interstate 10 near Biloxi, MS, failed during Hurricane Elena. The shelters were in a partially protected area, but due to poor design, failed in relatively low speed winds.

Accessory structures—such as light metal pool and porch enclosures, carport systems, sheds, playground equipment, and light poles—are prone to damage in high winds. The frames and attachments of screens and glazings of such systems are typically not adequately sized and fabricated for resistance to design wind speeds. They not only sustain damage themselves, but are sources of flying debris that may cause damage to buildings.

The critical point concerning porches and porticos is proper attachment to the building's structure. With porticos in particular, secure attachment to the ground to prevent wind uplift of the portico is important. Often porch and portico columns are not properly anchored, or their attachment to the ground does not consider uplift against the force of gravity. The failure of the portico on an apartment complex in Atlanta, for example, under very light winds clearly illustrates the lack of securement (Figure 4.28). Proper detailing and load-path continuity are important considerations.

4.6 LOAD PATH CONNECTIONS

Review of Importance

In a high-rise building, the wind-load-resisting system provided by moment-resisting frames, braced frames, or shear walls is clearly identifiable, and failure of part of a roof or wall will have only a marginal effect on the load-resisting system. In a low-rise building, such as a single-story house or an unreinforced masonry building, the roof and walls resist the wind loads in a complex manner. For example, a roof may resist wind forces applied directly to it, may act as a diaphragm to distribute wind forces applied to the walls, and may supply lateral support to those walls. Unfortunately, these structures are often designed as a set of isolated components without regard to their combined role in the complete system or an appreciation for the major structural consequences of an apparently minor component failure, such as window breakage or door loss.[13]

FEMA's investigations of Iniki and Andrew revealed the importance of load path connections. Noteworthy examples of properly engineered and constructed buildings were observed, and FEMA concluded that, almost without exception, successful performance resulted from adequately designed and clearly defined continuous load transfer paths. Where there was a break in the load transfer path, damage extent ranged from considerable to total, depending on the configuration, type of construction involved, and the exposure to wind loads.

Critical Load Path Points

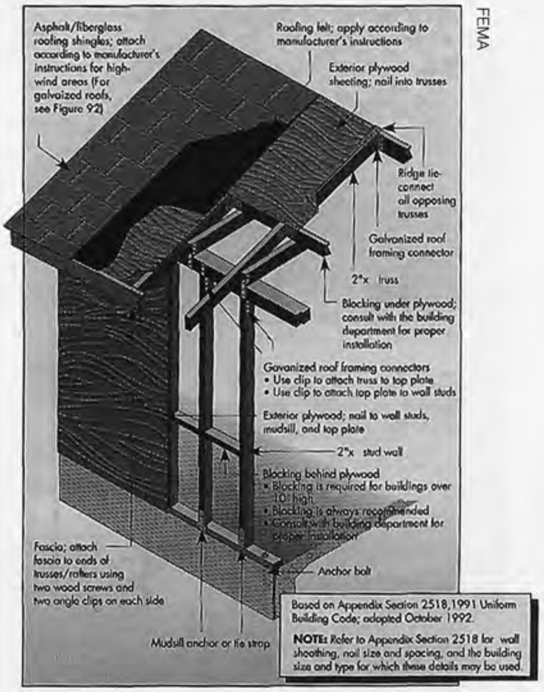
The critical load path failure points, readily observable in the wake of high-wind damage, are individual structural members connected without adequate attention to design and construction details (Figure 4.29). Deficiencies include improper sill-to-masonry and sill-to-concrete foundation connections, unbraced stud/columns, inadequate connections between exterior and interior shear walls, and faulty spliced wall top-plate systems.

It is suggested that hurricane clips and straps be used to help ensure the integrity of a structure's load path. Emphasis should be placed on the proper sizing, design, installation, and protective coating of these and other metal fasteners. However, use of hurricane clips does not, in and of itself, ensure successful building performance. Additional structural ties at the ceiling line should be provided between large exterior walls and interior walls in residential units to maintain integrity in the event of the loss of the roof.

FEMA recommends that construction documents include a narrative that explains a building system's transfer of lateral loads. An explicit depiction in the form of construction details should also be included, together with a completed load transfer path plan that is specific to the building type being designed. Such a visual and narrative delineation of the load path should be kept in mind during the design of any building.

Dale Perry

Figure 4.28: Apartment complex in Atlanta damaged by uplift forces.



Based on Appendix Section 2518,1991 Uniform Building Code; adopted October 1992.

NOTE: Refer to Appendix Section 2518 for wall sheathing, nail size and spacing, and the building size and type for which these details may be used.

FEMA

Figure 4.29: Critical load path locations for wood-frame construction.

CHAPTER 4 REFERENCES

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5

Commercial Low, Mid, and High-Rise Buildings

Many of the guidelines presented in the residential buildings chapter are applicable to structures of greater height: the critical areas of concern are roof covering, cladding, load-path connections, windows, and doors. Where recommendations are the same, they are referenced. Issues and recommendations particularly relevant to commercial buildings are discussed in detail. This chapter also includes a discussion of essential facilities (which demand special design attention), the performance of metal building systems in high winds, and wind design issues related to high-rise structures.


Dale Perry

Figure 5.1: Masonry wall failure due to roof blow off.


Dale Perry

Figure 5.2: EIFS damage on a commercial building at Cutler Ridge, South Miami, FL.

5.1 STRUCTURAL SYSTEMS

Wood Frame

The issues and recommendations regarding wood-frame construction, sheathing, and cladding discussed in the preceding chapter are applicable here.

Masonry

The issues and recommendations regarding masonry construction and cladding discussed in the preceding chapter are applicable here. However, as masonry wall construction increases in height, special consideration should be given to reinforcement and load transfer.

The height/thickness ratios specified in national standard ASCE/ACI 530 may be unconservative in high wind areas for lightweight roof systems. Investigations of hurricane and tornado damage reveal large amounts of damage to low-rise masonry buildings with light roofs. Catastrophic failure is generally restricted to buildings with metal-deck, steel-joist, or girder roof systems supported by unreinforced masonry walls and simple columns.[1]

Masonry walled commercial structures with light metal roofs are particularly vulnerable to high winds because their roof spans are usually long and the walls are high in proportion to their thickness. In many cases, such structures are more exposed because they are surrounded


Kishor Mehta

Figure 5.3: The masonry wall of this school gymnasium fell in due to positive pressure.

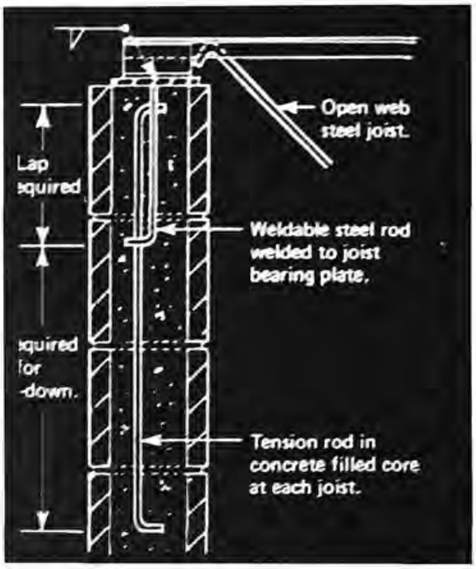


Figure 5.4: Hold down anchor for steel joists.

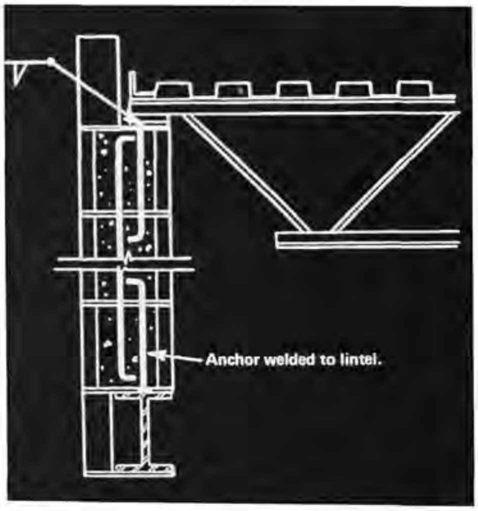


Figure 5.5: Lintel cross-section.

by extensive parking areas and are usually more vulnerable to high internal pressure because of large glazed areas subject to failure.[2]

The weight of contemporary roofs has a large impact on the stability of masonry wall construction. Although most modern roof systems do not impose a lateral thrust on the walls, some have become very light, often with a dead load of less than 10 lb/sq ft. The wind can produce uplift loads greater than this weight. Thus, far from holding the walls in compression, the modern roof may, under certain circumstances, actually induce tensile stresses in the walls. In addition, the desire for clear open spaces in buildings has reduced the number of interior walls, which in earlier buildings intersected with and provided support for the exterior walls.[3]

Masonry Wall Connections at Roofs

In connections between the roof structure and masonry walls in hurricane-prone regions, anchorage using an embedded rod in masonry without a bond beam may not be sufficient for any light roofing system since light systems rely on the weight of a few masonry units and their bond strength. A second form of anchorage that uses a bond beam would prove satisfactory only if the bond beam is properly tied to the foundation by vertical wall reinforcement.[4]

Traditional anchor rods embedded in the top of a masonry wall usually are capable of transmitting shear forces, but often lack the capacity to transmit tensile loads. Unfortunately, failure due to this weakness results in the loss of the other functions, in particular the lateral support at the top of the wall, and may impair the stability of the entire structure.[5]

Typical code-approved roof-to-wall anchors embedded in unreinforced masonry walls rely on the masonry-mortar bond strength. As such their capacities are highly variable, often well below the requirements of a building in a high-wind area. The tensile capacity of mortar is so unreliable that it probably should not be used to resist direct tensile forces. Research has shown that, even for moderate wind load requirements, it would be necessary to use anchors over 12 ft long to engage sufficient wall weight to resist the uplift forces on steel joists spaced 6.5 ft apart and spanning 39 ft. In contrast, the 1989 Standard Building Code permitted anchors embedded 15 in and spaced 6 ft apart, even on a hurricane-prone coast.[6]

The South Florida Building Code provisions overcome the greatest problem for wind resistance of masonry buildings: the very low and variable tensile strength of the material. The SFBC provisions stipulate (1) a means of anchoring the roof to properly reinforced members; (2) a continuous load path using steel bars to carry the uplift load to the ground; and (3) wall reinforcement to resist the out-of-plane wind loads.[7] Some proper roof deck to masonry wall connections are depicted in the accompanying details (Figures 5.4 to 5.7).

Figure 5.8: A masonry wall with a high height/thickness ratio failed on this church during Hurricane Andrew.

5.2 ROOF SYSTEMS

Roof Framing

As mentioned previously, the critical issue for the architect to remember in roof framing is for the structure to be adequately attached to the top of the wall to maintain the building's load path.

Roof Sheathing/Decking

Roof sheathing and decking provide critical lateral load resistance to roofs subject to high winds. Proper attachment of the sheathing to the framing is therefore a primary consideration to ensure that the decking has sufficient capacity to resist uplift loads.[8]

In new construction, architects should specify the type of deck fastener to be used and the attachment frequency, based on wind load. Thomas Smith of NRCA recommends that screw-attachment rather than welding be specified for steel decks. Deck attachment should be inspected.[9]

For reroofing, deck attachment considerations are more difficult. The architect should evaluate the existing deck's adequacy to meet current design wind loads. In high-wind areas, additional deck attachment

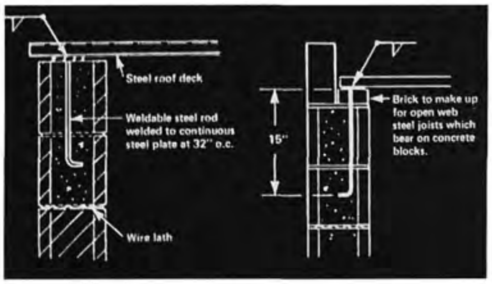


Figure 5.6: Diaphragm anchor for steel deck.

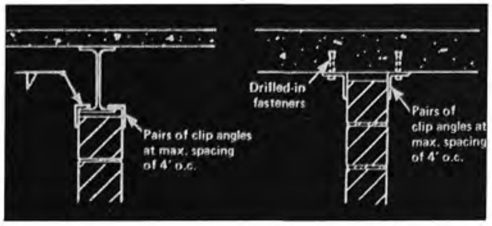


Figure 5.7: Lateral support anchors at top of partitions.


Thomas Smith, NRCA

Figure 5.9: Aggregate was blown off of this single-ply ballasted membrane during Hurricane Hugo. Some fan cowlings were also blown off.

(and perhaps a framing upgrade) may be prudent, especially for essential facilities, such as schools and hospitals, built prior to 1990 (perimeter and corner wind uplift design loads increased dramatically in the three U.S. model building codes during the mid-1980s). In some limited cases, additional deck attachment can be provided by working from below the deck; if upgrading is desired, it typically will be necessary to remove the roof covering and provide additional attachment from above.[10]

During a roof evaluation, the architect should consider these common problems:

- Loose or broken welds and inadequate panel fastening are common in steel decks;
- Older cement, wood fiber, gypsum, and lightweight insulating concrete decks often have little uplift resistance because of low-strength attachments that were commonly used prior to the mid-1980s;
- Older, precast concrete decks often have little resistance to uplift loads, other than the deck's dead load. In high-wind areas, the design wind load easily can exceed the deck's weight at the roof perimeter.[11]

Roof Covering Systems

Single-ply roofing is a common roof type used in low-rise commercial structures. Roofing researcher Thomas Smith makes the following recommendations to enhance the high wind-resistance for mechanically attached single-ply systems:

- Recommended decks are a minimum of 0.7mm (22 gauge) steel, wood plank, and 19/32 in plywood. In high-wind environments thicker decks should be considered.
- Specify reinforced sheets in hurricane-prone regions. Specify attachment to the top flange of metal decks. If the membrane is placed over insulation, a suitable insulation or cover board with very high compressive strength (greater than 20 psi) is recommended.
- Specify barbed plates for membrane attachment.
- Give special consideration to fasteners in excess of 4 in long.
- In high-wind areas, "bar-over" systems should be considered.
- In high-wind areas an air retarder should be considered. If an air retarder is specified, consider also specifying air pressure equalization valves.[12]

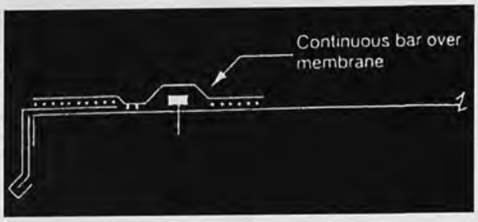
Smith makes a number of recommendations on the use of air retarders and single-ply roofing. The air retarder is the critical layer in the roof's resistance to wind loading. As wind passes over the roof, the roof system has an upward thrust from within the building, rather than a "wind grab" from above the membrane. This upward load is exerted on the first layer it meets that is impermeable to the air. If the roof system is built on an impermeable deck, such as cast-in-place concrete, both the insulation and membrane above the deck escape the uplift force. Other types of decks, such as steel, do not restrict air flow. However, with an air retarder above the deck, air pressure is stopped and the uplift load is transmitted back to the deck. This prevents the roof membrane from seeing the uplift force. With ballasted loose-laid systems that do not have an air retarder, the membrane will lift from the substrate, unless the weight of the ballast aggregate or pavers/boards is equal to or greater than the uplift load. Architects should specify an air retarder when the ballast load is less than the calculated uplift. With high wind it is impractical to apply enough ballast to resist the uplift, so an air retarder is imperative. Mechanically attached systems need air retarders to avoid flutter/fatigue loading. To avoid fatigue problems, architects should consider specifying an air retarder in areas that experience high wind loads. In areas with high winds, air retarders can also enhance a built-up roof's wind uplift resistance.[13]

Preserving the function of the air retarder around roofing penetrations is essential. Smith notes that monolithic decks such as cast-in-place concrete, gypsum, and lightweight insulating concrete are inherently good air retarders. It is necessary, though, that penetrations such as plumbing vents are sealed around the deck, and that a continuous air seal exists at the parapet or edge. Seals at penetrations can be made with sealant; butyl and polyurethane are both good. With plywood or OSB decks, specify the placement of sealant over all panel joints. Alternatively, a sheet of polyethylene can be placed over the deck and then clamped with a rigid board such as gypsum or insulation board screwed in place. Laps in the polyethylene should be sealed with sealant or poly tape. Polyethylene air retarders also can be used for steel and cement/wood fiber decks. With any air retarder, continuity at the roof edge must be maintained. Sealant between nailer faces and ends is a common approach.[14]

Various types of roof systems have unique characteristics that should be considered by the architect. This primer does not allow for detailed recommendations for each of these systems, but the references cited should be consulted for more thorough discussion. The commonly used systems and primary issues associated with them are discussed below:

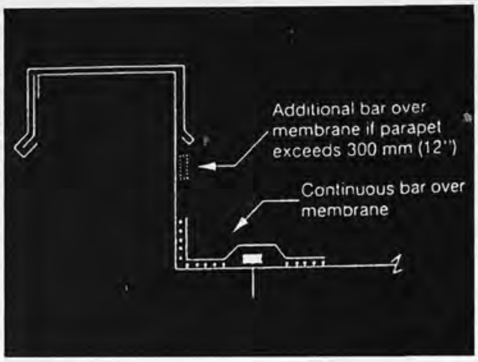
Fully adhered systems (i.e., built-up, modified bitumen, single-ply): The primary mode of failure is lifting and peeling of the membrane after displacement of the metal edge flashing or coping. For design of the metal edge flashing/coping and nailer, see *Wind Design Guide for Edge Systems Used with Low Slope Roofing Systems*, Single-Ply Roofing Institute (SPRI), April 1995.

Ballasted single-ply systems: Design in accordance with ANSI/RMA/SPRI RP-4. In addition, for aggregate ballasted systems, consider the recommendations in "Hurricane Hugo II: Testing the Performance of Aggregate Ballasted Single-Ply Systems," Thomas Smith, *Professional Roofing*, September 1992, p. 32.



Thomas Smith, NRCA

Figure 5.10: Enhanced metal edge flashing for a single-ply membrane.



Thomas Smith, NRCA

Figure 5.11: Enhanced coping for a single-ply membrane.

Aggregate surfaced BUR and SPF: In high wind environments, parapets can be effective in preventing aggregate blow-off. The more severe the environment, the taller the parapet needs to be. Alternatively, for BUR, the roof could be double-surfaced, followed by removal of loose aggregate. With double-surfacing, approximately half of the aggregate is applied in hot bitumen, followed by another application of hot bitumen and the remainder of the aggregate.

Metal panels: Consider the recommendations in "Insights on Metal Roof Performance in High-Wind Regions," Thomas Smith, *Professional Roofing*, February 1995, p. 12.

Spray-applied polyurethane foam: Consider the recommendations in "How Did PUF Roofs Perform During Hurricane Andrew?," Thomas Smith, *Professional Roofing*, Jan. 1993, p. 20.

Tiles and asphalt shingles: Recommendations are found in Section 4.3 of this book.

ASTM, FM and UL: Uplift test methods for various types of roof systems have been developed by ASTM, Factory Mutual (FM) and Underwriters Laboratory (UL). Data from these test methods may be used to determine if a proposed system has sufficient uplift resistance.

Factory Mutual also has several data sheets that provide recommendations related to wind resistance of roof systems. For FM-insured buildings, the architect should be aware of the FM requirements.

5.3 FLASHING

Thomas Smith, NRCA

Figure 5.12: This metal edge flashing unlatched from its continuous cleat during Hurricane Hugo.

Loss of the roof's metal edge flashing or coping is the primary cause of poor performance in hurricanes and other high winds for most membrane roofs, including built-up, modified bitumen, fully adhered, and mechanically attached single-plies. Because of the severe water infiltration that can occur if the metal edge flashing or coping fails and the membrane peels or tears, providing redundancy in the edge securement is desirable. For metal-edge flashings, a bar over single-ply membranes can be added. For copings on parapets less that about 12 in high, a bar can be added over the membrane near the wall/deck juncture. For parapets over 12 in, it is recommended that an additional bar be placed near the coping. Figures 5.10 and 5.11 illustrate these enhancements. To be effective the bar must be strong enough to resist bending, and it must be well attached to the deck or parapet. A maximum fastener spacing of 12 in is recommended, although in very severe windy environments, a spacing of 6 in or 4 in may be prudent.[15] Additional guidance can be gained from the Single-Ply Roofing Institute's Design Guide.

5.4 ROOFTOP EQUIPMENT

Inadequate attention to design of the attachment of rooftop HVAC equipment often results in equipment displacement (Figure 5.13). When units are blown off of their curbs, a substantial amount of water can enter through the large openings in the roof. The displaced units can also damage the roof covering, and in very high winds, the units can be blown from the roof, thereby jeopardizing life safety as well as other property. Many HVAC units also lack integrity. It is common for units to loose access doors or fan covers, which become missile threats.[16]

Architects should check to see that anchorage of HVAC equipment is properly addressed in construction documents and in the field.

Thomas Smith, NRCA

Figure 5.13: Access panels and intake hoods blew off several HVAC units during Hurricane Andrew.

5.5 ROOFTOP DRAINAGE

The trend today in low-rise commercial structures is toward a 1/4:12 roof slope (virtually flat). Clogged drains, gutters, or downspouts can lead to increased maintenance and ponding problems. This problem becomes even more of a concern when interior drainage systems are used, and on buildings with parapets (a benefit in high-wind regions), which may permit water to accumulate. Only 12 in of ponding water increases the roof load by more than 60 psf, while most roofing systems are designed for loads in the range of 12 to 30 psf. Considerable attention should be paid to the design of an adequate drainage system to keep water from ponding on the roof, and the owner should be advised to pursue a maintenance program to keep drains clear and functioning.

Dale Perry

Figure 5.14: Common roof maintenance issue on a building in Long Island, NY.

5.6 OPENINGS

Overhead Doors

Because the failure of overhead doors can compromise the building envelope, architects should follow the FEMA recommendations made in Chapter 4 regarding the design and installation of overhead doors.

Large Glass Openings

Recommendations for large glass openings are found in Chapter 4 under the discussion of "Windows," which suggests ways in which glazing can be preserved either through the use of impact-resistant glazing or storm shutters.

5.7 ESSENTIAL FACILITIES

Wind storms, or any natural disaster for that matter, often result in people being housed in temporary shelters such as schools, religious buildings, gymnasiums, armories, air hangers, etc. Other essential emergency facilities, police stations, fire stations, and hospitals must continue to function in the aftermath of hurricanes and tornadoes. For these reasons, essential facilities demand close attention to wind resistance. While the scope of this primer does not permit a detailed discussion of this building type, readers are urged to review several articles that provide design guidance, some with special emphasis on roofing.[17]

5.8 PRE-ENGINEERED METAL BUILDINGS


Dale Perry

Figure 5.15: Typical infill wall failure in a pre-engineered building damaged by Hurricane Elena.


Dale Perry

Figure 5.16 Damage to a typical pre-engineered metal roof with built-up roof.

Pre-engineered metal buildings account for a large proportion of commercial low-rise construction in the U.S. The prevalence of this building technology is obscured by the fact that they often are covered with veneer systems such as brick or stone, and do not look like pre-engineered metal buildings. The use of pre-engineered metal buildings in high-wind areas is of concern because of the way some of these buildings have performed in recent hurricanes.

The most significant factor that sets pre-engineered metal buildings apart from other forms of low-rise construction is the manner in which the product is typically engineered, marketed, sold, and erected. Buildings are sold to franchisers who then sell packages to clients, frequently acting as the general contractor. The base buildings are designed and rationalized, but the manufacturer exercises little control over the final product as it is built. Components not supplied by the manufacturer (doors, facades, glazing, foundation details) are added during an erection process that is beyond manufacturer's control. According to engineers (such as Dale Perry and Alexander Newman) who have studied the industry, loss of control over the reliability of these various, essential components of the building can be blamed for much of the damage to metal buildings in high winds.[18, 19]

Primary resistance to gravity and lateral loads in these buildings is provided by moment-resisting frames of tapered sections, which have been engineered to achieve maximum economy. Stability of the rigid frames is provided by flange bracing attached to a secondary framing system of purlins and girts. The purlins and girts are braced by the roof sheathing, which is attached to the top flange versus the bottom flange. Adequate bracing is an essential key to achieving structural integrity of the whole system. The loss of just one of the components may compromise the system and result in reduction of structural capacity. Because they are optimized in strength and construction, pre-engineered metal buildings are susceptible to "weak-link" behavior, in which the failure of any of the parts may lead to catastrophic failure of the structure as a whole. They may lack the redundancy and ductility of conventional building structures.[20, 21, 22] Discussed below are some of the major areas of concern for metal buildings in high winds that the architect should be aware of.

Dale Perry

Figure 5.17: This typical pre-engineered building's roof failed in a 40 mph wind due to high internal pressure, coupled with external pressures on roof.

Dale Perry

Figure 5.18: Complete collapse of metal building at Tomiami Airport, Miami, FL, from Hurricane Andrew.

5.9 WEAK POINTS IN METAL BUILDING WIND RESISTANCE

Standing Seam Roof Failures

The roof covering of choice for metal buildings and many other types of commercial construction has become the standing seam metal roof system (SSMRS). Roof panels are attached to internal "sliding clips" crimped in the longitudinal seam and fastened to the purlins in an attempt to permit the roof to "float" or freely expand and contract due to solar radiation and re-radiative cooling during the evening hours. Unfortunately, experience has shown that in some instances the "floating" roof may lose its ability to expand and contract in a few years as the sliding clips bind up. Bar joist roof systems, which will not permit "roll" in the direction of expansion and contraction, are particularly vulnerable. Once this occurs, the end laps experience excessive stress and the fasteners "back out" and/or hole slotting of the panels occurs. Structural degradation of the overall system may take place and the roof panels are subject to panel "blow-off." Although SSMRSs can offer exceptionally good high-wind performance, failure of these roof systems during hurricanes has become commonplace, particularly when the roof system is four to five years old. Attention to system selection, detailing, and application are keys to performance.

Overhead Door Failures

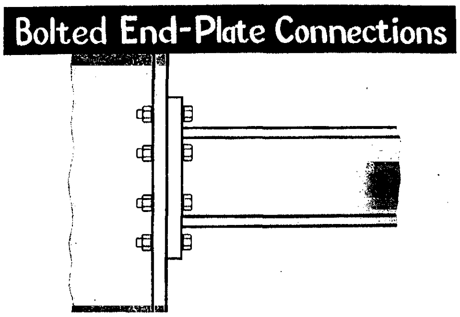
Most doors used with metal buildings are not supplied or designed by the manufacturer. It has been found that failures of doors comprising 1 percent to 5 percent of the area of the windward wall may be sufficient to produce a significant increase in internal pressure. Most overhead doors have an area of sufficient size that failure of the door can lead to

Dale Perry

Figure 5.19: The clips have disengaged along the seams of this airplane maintenance hanger in Oklahoma.

Dale Perry

Figure 5.20: Standing seam roof failure in Dutch Harbor, AK. Clips attaching roof panels are still in place.



Dale Perry

Figure 5.21: Typical beam-to-column connection used in metal buildings.

increased internal pressure and possible progressive failure of the building. The largest percentage of damage to metal building systems can be attributed to this single deficiency one that can be addressed easily with proper design of these doors (see Chapter 4).[23, 24]

Canopy Failures

Canopies are often not part of the metal building package, and replacement of them is not a significant cost. Concern here is that canopies subjected to strong uplift forces may separate from the parent structure, become airborne, and constitute a hazard to human life and other property.[25, 26]

Damage to Steel/Veneer Interface

Masonry, wood, glass, aluminum, and copper often are used to clad metal building systems. In some applications the building is first sheathed with the usual sheet metal, and the masonry veneer is then attached by metal ties. Often this veneer is stripped from the walls by the high suction pressures during severe winds. Several failures have been observed in which unreinforced concrete block walls collapsed. Some engineers suggest that the masonry must be designed to permit relative movement between the block and the rigid frames.[27, 28]

Omission of Bracing

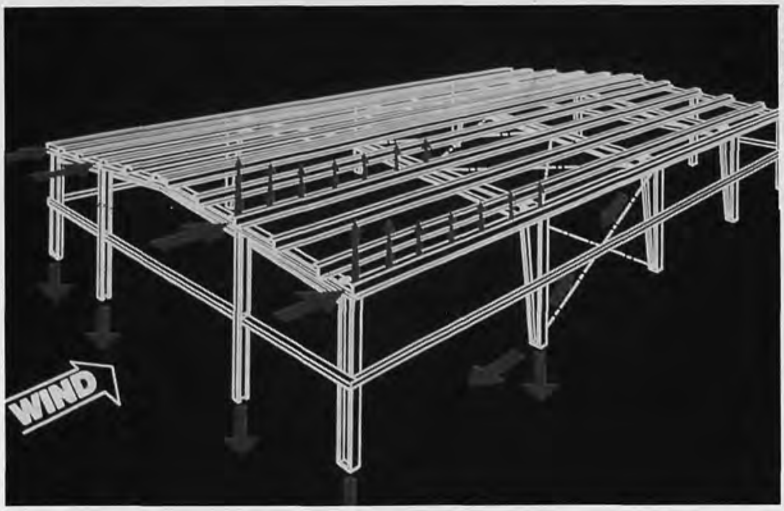
Once the building is sold, some control is lost relative to the installation of bracing called for in the plans. Of particular concern is the flange bracing at the knees of the rigid frames. Many failures in wind are reported in buildings in which the bracing had not been installed or had been removed. Thus, the rigid frame is essentially unbraced at a point of maximum bending moment.[29, 30]

Improper Foundation Details and Anchorage of Columns

Design of the column anchorage (base plate/anchor bolts, and footing details) is typically left to the franchised dealer and/or the architect/engineer of record. The need to design low buildings to withstand uplift wind forces has become apparent, and the problem has tended to disappear in new buildings, but is present in older ones. Architects involved in the renovation or rehab of older metal buildings should consider the building's anchorage to the foundation and suggest necessary retrofit reinforcement where necessary.[31, 32]

Failure of Field Connections

The most common connection of the pre-engineered metal building is the end-plate connection (Figure 5.21). Most problems with end-plate connections occur when there is a discontinuity in member depth and the stress path for the flange force is not continuous. Architects should be observant of required field connections and ensure that proper connections are made.[33, 34]



Dale Perry

Figure 5.22: Strut purlin problem. Struts must be designed for a combination of axial loads and bending.

Strut Purlin Failures

Perhaps the most common form of metal building failure is the result of strut purlins unable to resist a combination of axial loading and bending. In recognition of this type of failure, wind engineer Kishor Mehta has included in his design guide for ASCE 7-95 the proper load combinations to be used in the design of these critical elements – axial loads based on main framing considerations combined with bending loads in accordance with component and cladding provisions.[35] Some manufacturers provide additional strut members to carry the axial loads to the wind truss spanning the roof.

Shifting Interior Column Lines

To accommodate the building's use, exterior column lines are sometimes shifted a few inches from their proper location, and away from the web stiffener in the rafter, without consultation with the manufacturer's engineer. For portal frames subject to sidesway this may lead to dangerously high loads in the column, producing web crippling of the rafter web.

5.10 REMEDYING METAL BUILDING SYSTEM WEAK POINTS

According to Dale Perry, the last two decades have seen significant improvement in the performance of pre-engineered metal buildings. Two factors are primarily responsible. The ASCE-7 standard and the model building codes have undergone extensive revisions during this time. These documents more properly prescribe the high, localized loads to be resisted at the edges and corners of roofs and walls. Also, the use of UL 580 as a standard for fastener and panel resistance has improved building performance in high winds. It should be noted, however, that the UL and FM test procedures are static tests and do

Dale Perry

Figure 5.23: The columns in this building failed during an ice storm in Tennessee in 1986. Column lines were shifted from the location intended by the manufacturer.

Dale Perry

Figure 5.24: Column line moved.

Dale Perry

Figure 5.25: The U.S. Post Office in Kauai was undamaged during Hurricane Iniki. As a federal building, it was designed in accordance with ASCE-7.

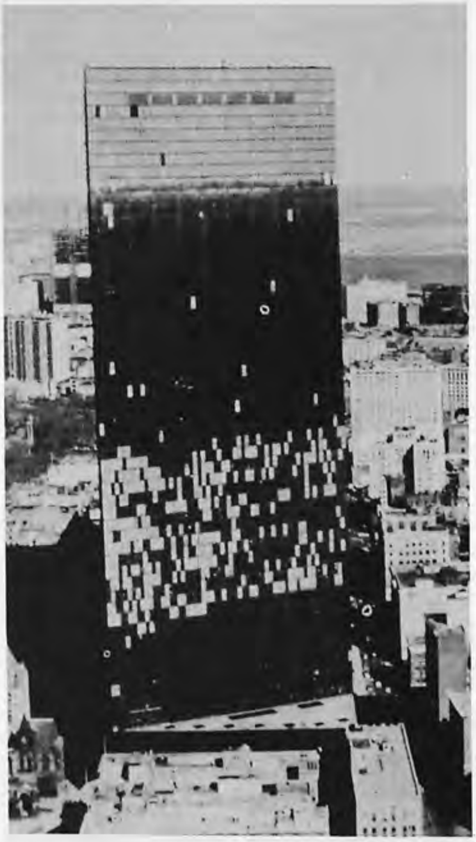
not replicate wind-induced dynamic pressures. The failure modes observed in the field do not correspond to those noted in the FM and UL tests.[36, 37]

5.11 HIGH-RISE BUILDINGS

Of all the building types that an architect is likely to be involved with, high rises are usually the most thoroughly analyzed and designed in terms of their response to high wind loads. Such structural analysis and design is the province primarily of the structural engineer, while the architect's attention is focused mainly on the building shape and the building envelope. However, the shaping of the building and the design of the envelope is an interactive process between the architect and engineer. Issues of building shape, enclosure, glazing, roofing, and openings discussed earlier are noted below as they apply to high rises.

5.12 WIND TUNNEL TESTING OF HIGH RISES

The structural design of high rises is usually subject to a rigorous analysis to determine wind loads. The architect should consult with an engineer with expertise in wind engineering to ensure that due diligence is given to the design. Working with the engineer, the architect can use analysis of the building to make informed design decisions regarding building placement on the site, building configuration, roof shape, the design of cladding and curtain wall systems, the placement of entrances, and likely impacts on surrounding structures.



R.D. Marshall

Figure 5.26: John Hancock building, Boston, MA.

Architects should be aware that the modeling of high-rise buildings in the typical codes may not be sufficient to represent the complexity of these large structures and their siting. Wind tunnel testing can provide a detailed analysis of how a high rise will behave under a variety of wind conditions, and suggest how the new building may alter the wind environment for adjacent structures and pedestrian precincts.

Wind tunnel testing is valuable in guiding the design of a high rise. It may be prudent to determine if the code values should be exceeded. Actual climate and site conditions should be used to verify the code criteria and exceed it when advisable. The architect should also discuss with the owner whether the building's use and occupancy may require exceeding the code requirements.

Wind tunnels allow the modeling of buildings within their contexts. The architect assembles information about the building site and the surroundings within a given radius, taking into consideration other buildings and their adjacency and topographical features. A model of the design and the context is placed on a turntable in a fan-generated wind stream, which can be modulated with baffles and features on the tunnel surface to model the dynamics of the wind at the specific location. Wind load measurements are taken with sensors placed on the building model. A series of readings is taken and the turntable is rotated incrementally to determine the effects of wind from a variety of directions. After the data are collected and analyzed, negative and positive wind loads on the high rise are determined for design purposes.

The taller the building, the greater the wind loads. Typically, as the building becomes taller and more slender, the more the size of its structural members will be determined by their need to resist lateral loads in addition to vertical (gravity) loads. Wind tunnel testing can reveal how the building structure will behave under these loads. It is important to understand the building's horizontal drift (how much the building deflects) in response to different wind loads and its acceleration (the rate of change in deflection). This knowledge is critical to ensure that building occupants are comfortable (sensing acceleration can be disturbing to occupants).

Wind tunnel tests are also important in studying the performance of different cladding and roofing systems. Sensors applied to the wind tunnel model can measure both negative and positive pressures on the cladding and roof surfaces, revealing where "hot spot" loads are likely to occur. The architect can then use these data to design a uniform cladding system to resist these loads, or a combination of different cladding types tailored to varying wind load conditions. Roof surface loads and uplift pressures determined by the wind tunnel are helpful in selecting the type of roof system, and the design of parapets, if any. The location of balconies and entrances can also benefit from wind load analysis. Even the selection of door hardware and elevators can be aided with wind tunnel testing information to ensure its smooth functioning under wind loads.

Cermack, Chiu, Perry

Figure 5.27: A wind tunnel experiment on a model of downtown Houston being conducted by Jack Cermack, distinguished professor at Colorado State University.

Kishor Mehta

Figure 5.28: Built-up roof aggregate damage to the Texas Oil building in Houston, TX, due to Hurricane Alicia.

R.D. Marshall

Figure 5.29: World Trade Center buildings in New York City were subject to extensive wind tunnel investigations.

5.13 DAMPING STRUCTURAL RESPONSE

A building with excessive sway and acceleration may require correction, even without the threat of structural damage. To decrease the effects of acceleration, and to provide dampening, the structure can be modified by changing the structure's stiffness. Damping is the ability of a building, through moving mass and weight (usually friction), to counter the effects of wind. Current damping practice includes the use of tuned mass dampers (massive weights near a building top that are attached to the building frame through springs); viscoelastic dampers (thousands of small devices placed throughout a building to dissipate kinetic energy in the structure); or aerodynamic farings (changes in the structure shape to reduce the wind loads causing the motion—a technique used on bridges but not practical for buildings). These approaches to limiting motion of an existing structure are relatively expensive.[38]

5.14 HIGH-RISE ENVELOPE SYSTEMS

High rises most often are clad in curtain walls of glass, metal panel, stone panel, or precast concrete panel curtain walls. Glass curtain walls are the most vulnerable to wind-borne debris. As discussed in Chapter 4, glazing systems resistant to wind-borne debris are available.

Exterior Insulation Finish Systems (EIFS) have become more commonly used as a cladding for high rises. However, according to Dale Perry, who investigated wind-related EIFS damage in Hurricane Andrew and Hurricane Opal, this material may be inadequate for high-wind regions.

Regardless of the cladding system, it is recommended that a full-scale mock-up of the wall be constructed and tested for its response under simulated high wind conditions or previous test information submitted. Based on analysis of the tests, modifications to the cladding system can be made.

Dale Perry

Figure 5.30: This Y-shaped hotel suffered extensive damage during Hurricane Andrew.

5.15 HIGH-RISE ROOFING

Roofs on high rises are most often membrane systems or metal panels. The suction forces on high-rise roofs are a function of the height of the building. The higher the building, the higher the load on the roof. Architects should note that parapet walls higher than 3 ft tend to reduce external uplift pressures at the roof corners of high-rise buildings. Most damage to high-rise buildings involves failure of the roof covering, which frequently results in damage to the building contents. For example, a hotel in Hawaii remained out of service for almost four years in the wake of Hurricane Iniki. Only the roof covering failed, which resulted in water damage to most of the ceiling, floor, and wall surfaces throughout the building.

Dale Perry

Figure 5.31: Damage to EIFS in Cutler Ridge during Hurricane Andrew.

Recommendations for roofing design in high-wind areas can be found in Section 5.2. Note that adequate roof drains must be provided to prevent water from ponding on roofs with parapets.

5.16 ROOFTOP EQUIPMENT AND ENCLOSURES

As is discussed above, rooftop equipment and the enclosures that surround it must be designed with attention to the impact of wind loads. Architects should give particular attention to ensuring that equipment and enclosures are properly anchored to the building.

5.17 OPENINGS

Openings in high rises, such as service and garage bay doors, need to be designed to resist high-wind loads. Failure of such doors can expose portions of the building interior and its contents to wind and water damage. Recommendations for the proper design and construction of wind-resistant doors are discussed in Chapter 4.

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6

Codes and Insurance

6.1 CODES, INSURANCE, AND THE WIND RISK

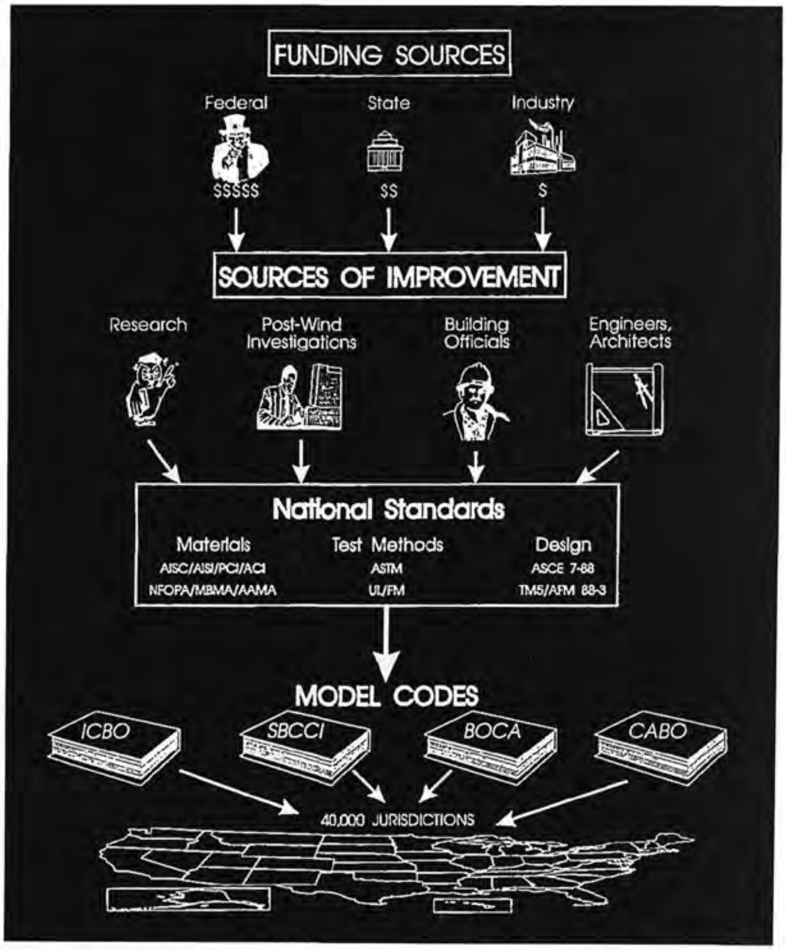
Codes and insurance are complex. The architect should be aware of the code process, how codes are modified, and how prescriptive codes differ from performance codes. The critical point here is that prescriptive (or "deemed-to-comply") codes are not always conservative when it comes to designing for wind resistance, which may require buildings to exceed code in regard to wind design.

The content of the codes regarding wind design, and the possibility of codes not being properly enforced, has brought the insurance industry into the arena to lobby for better wind-resistant design and construction. This activity will continue to have an increasing impact on the way buildings are designed and constructed, and architects should be aware of the issues involved in order to respond properly to them.

6.2 CODES AND WIND LOADS

Local building codes control design and construction of buildings and structures in that locality. Most communities in the United States adopt, in large part, one of three model building codes: the National Building Code of the Building Officials and Code Administrators International, the Standard Building Code, or the Uniform Building Code. Wind-load provisions in these model building codes are patterned to some extent after the ASCE Standard on Minimum Design loads for Buildings and Other Structures, ANSI/ASCE 7.[1]

ANSI/ASCE 7 is the only consensus wind-load standard currently available in the United



Dale Perry

Figure 6.1: The code development and adoption process.

Dale Perry

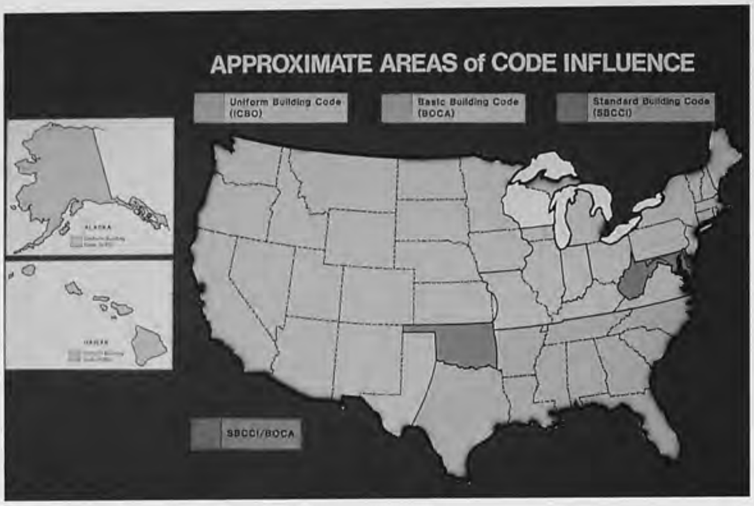


Figure 6.2

States. All three model codes use the basic wind-speed map presented in the ANSI/ASCE 7-93. However, the similarity in wind-load provisions between model building codes and the ANSI/ASCE 7 stops with the wind-speed map.[2]

The factors that influence the magnitude of wind loads on a building, in addition to wind speed, are the terrain surrounding the building, the shape of the building, and the desired level of safety of the building frame and components. The model building codes use some of these factors from the ANSI/ASCE 7, modify some factors based on experience, or traditionally ignore some of the factors.[3]

Even with these modifications, final wind loads for most buildings are fairly consistent in all model building codes, though anomalies exist. All three model building codes provide the use of ANSI/ASCE 7 as an alternative to be applied at the discretion of the designer.[4]

6.3 PRESCRIPTIVE CODE LIMITATIONS

Empirical-based provisions generally specify minimum wall thickness or minimum member sizes and spacing, along with some rudimentary bracing requirements. Generally, these requirements are not a function of the design wind pressure alone. On the other hand, engineering analysis and investigations of wind damage show that it is necessary to properly tie the various structural elements together to provide a continuous load path to the foundation if the structure is to survive the effects of high winds. Usually, these latter requirements are missing from empirical provisions.[5]

Dale Perry

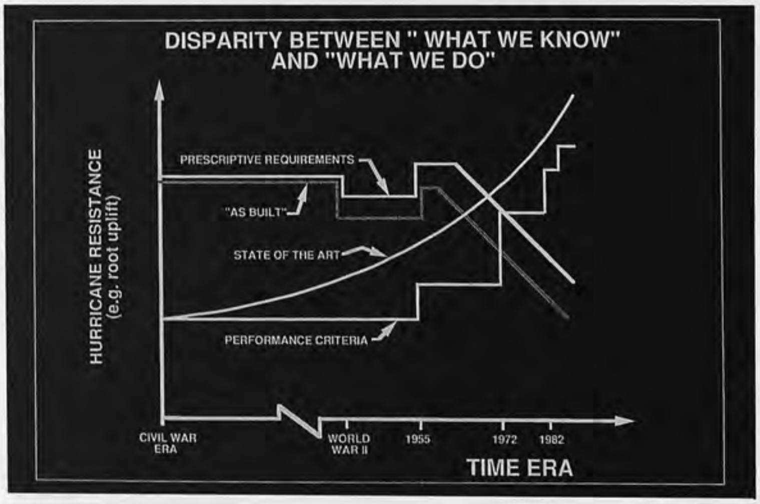


Figure 6.3

Over the last two decades, the increasing desirability of coastal sites has led to the construction of a large number of structures that are extremely vulnerable to high winds. Due to extensive hurricane damage in coastal areas during this period, and the continuing development of these vulnerable zones, code-making bodies are now focusing more attention on building code requirements for coastal areas. According to a National Research Council report, these efforts have raised many questions about the validity of some empirical provisions, because when subjected to a rigorous, rational engineering analysis, they simply do not work.[6]

Several years ago, North Carolina revised its state building code to require more stringent empirical provisions for non-engineered structures built along the Atlantic coast. Many areas of Florida, Texas, and other Gulf states subject to high winds have also enforced prescriptive requirements for small buildings that are based on engineering evaluation, but the requirements have not been applied consistently in all areas of concern.[7]

The problem rests with the adoption and implementation of these measures by the 40,000 or so jurisdictions throughout the U.S. The quality of building code enforcement in local communities could be improved. Review and revision of empirical provisions in the codes must be undertaken in order to increase the ability of small buildings to withstand high wind loads. The major impediments to mitigation appear to be embedded in social and political factors at the state and local levels.[8,9]

Even though existing building codes contain imperfections and could be improved through further research, the fact remains that much of the nation's wind damage every year could be prevented if more structures were built in compliance with existing codes. In some instances, failure to meet these standards is the result of deliberate decisions by state and local governments not to adopt them in the belief that the expected benefits of higher construction standards do not justify the increased costs.[10] Even in communities that do adopt the standards, many structures are built without conforming to the codes. In many cases, communities provide inadequate staffing or insufficient will to enforce the codes. In other instances, builders are not adequately familiar with the codes or with sound wind construction techniques.

Performance codes, which specify loads that surfaces and components must withstand, are more difficult to implement or to comply with than prescriptive codes, which specify construction techniques such as component dimensions and connection spacings.[11] Additionally, architects often select materials (roof coverings, cladding, etc.) from evaluation reports issued by each of the model codes (National Evaluation Service), based on limited test data, not necessarily replicating actual field conditions.

Over the years, local and model codes have developed empirical provisions to regulate common types of construction (such as wood-framed or masonry buildings not exceeding two or three stories in height). These empirical provisions contain minimal requirements for lateral loading, give little consideration of resistance to high winds, and are based on construction practices that have "withstood the test of time" without any type of verification. Technically, adherence to the empirical requirements does not set aside the need to verify compliance with the additional provisions for wind loads. However, it is common practice for building permits to be issued for buildings "designed" to comply with code empirical requirements that have not been subjected to an engineering analysis to determine if the structure can resist the required wind loads.[12] In other words, as building practices and the size and strength of materials have changed, there has not been a corresponding change in the prescriptive codes to reflect these changes. There is a growing gap between what we know about materials and construction, and how prescriptive codes dictate that they shall be used.

Wood-frame structures in particular do not have clearly defined paths for transfer of wind loads from point of application to the ground. This lack of clear load path results in a need for complicated engineering analysis of this type of structure. For this reason, current building codes include "deemed-to-comply" provisions that, while not strictly for that purpose, imply that a frame structure constructed according to specified rules (for example, wood studs placed 16 inches on center in walls) is presumed to satisfy the performance wind load requirements of the code (e.g., structure is capable of resisting 90 mph wind without damage). The large amount of damage to frame structures by less than design-level winds, as observed during many post-disaster studies, clearly highlights the limitations of this approach.[13]

With the awareness of these limitations in the codes, and less-than-ideal code enforcement, the architect needs to exercise a standard of care that will meet the code, and where appropriate, exceed the code provisions. The architect also must be diligent during on-site observations to ensure that buildings are constructed according to the design intent. The opportunity here is for architects to fulfill an oversight role that ensures the quality of the built environment and their clients' financial and safety interests.

6.4 CODES AND INSURANCE

Building codes traditionally have focused on the preservation of public health, safety, and welfare. Reeling from catastrophic claims in recent years, and eager to find ways to contain loss payouts, the insurance industry is now becoming more vocal about the need for buildings to be designed and constructed to mitigate property damage and loss. This view of the role of wind-resistant design may be new and unfamiliar to most architects, but the insurance industry will continue to exert its influence to modify codes in this fashion.

Dale Perry

Figure 6.4: This hotel was out of service for four years after hurricane damage to the roof.

Architects also must realize that the impact of wind damage extends beyond the building. Post-disaster visits have revealed that many commercial structures suffer little if any structural damage, but breaches in the building envelope allow extensive water damage to interiors and contents, making the buildings uninhabitable. Too often, such damage results in extended business interruptions and the insurance industry is currently re-evaluating its coverage of such down time. This exacts a financial toll on building owners and occupants (particularly businesses), creating interruptions that affect the local economy. Wind damage also strains the social fabric of communities, as families are forced to find new housing or suffer from financial and emotional burdens. Better building design and construction can ease this toll.

As insurance companies bear down on property owners and the building industry to improve building performance in high winds (and, in many cases, are rewarding better design and construction with lower premiums and/or lower deductibles), architects have an important role to play. As the participants in the building team who have traditionally served to safeguard the quality of the built environment and the interests of their clients, architects are in a powerful position to act with oversight on the part of owners and the insurance industry to ensure that buildings are designed and constructed to mitigate wind damage.

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Glossary of Terminology

A ZONE

Includes the areas of the base flood plain inland of the V Zone where the wave action is less than 3 ft in height. Although the waves pose less of a threat in this zone, it is important to realize that high-velocity water may still occur due to the momentum of breaking waves. National Flood Insurance Program regulations for new construction require the lowest floor elevation to be above the base flood elevation (BFE) such that flood waters will not inundate the structure or, for non-residential buildings, the floor levels below the BFE must be flood proofed.

ANEMOMETER

An instrument used to measure wind speed. Several types of anemometers are in use, the most common being mechanical anemometers that employ either a propeller or a set of rotating cups. Most of these devices will not survive wind speeds in excess of 150 mph. Some specifically designed mechanical anemometers are rated at wind speeds up to 200 mph.

ANTICYCLONE (OR HIGH)

An area of high pressure from the center of which air spirals out in all directions, implying sinking air and good weather. Cold anticyclones move rapidly south or southeastward out of the polar regions and are comparatively shallow or short-lived. Warm anticyclones like the Azores-Bermuda High are deep systems extending high into the upper atmosphere and are often stationary or quasi-stationary over the oceans. Their influence on atmospheric processes is profound; the Azores-Bermuda anticyclone's oscillations produce changes in continental U.S. weather and affect the tracks of hurricanes.

ATLANTIC BASIN

The area including the entire Atlantic Ocean, the Caribbean Sea and the Gulf of Mexico.

BASIC WIND SPEED (ASCE 7-93)

Fastest-mile wind speed at 10m (33 ft) above ground level in flat, open country and having an annual probability of 0.02 of being equalled or exceeded (50-year return period).

BASIC WIND SPEED (ASCE 7-95)

Peak 3-second gust wind speed at 10m (33 ft) above ground level in flat, open country and having an annual probability of 0.02 of being equalled or exceeded (50-year return period). This is currently the standard measure in the United States of wind speed.

BLIZZARD

A cold, northerly gale occurring in the northern part of the Midwestern United States, especially in North and South Dakota. Bringing rapidly falling temperatures and fine crystallized snow, this suffocating wind often kills animals that are stranded out in the open.

BOUNDARY LAYER

A region extending upward from the ground surface to a height of several hundred feet in which the wind speed is slowed by the ground roughness (buildings, trees, hills, etc.). In fact, the wind speed becomes zero right at the ground surface. Beyond the top of the boundary layer the wind speed is fairly uniform. Typically, the wind speed at a height of 30 ft is 60-85 percent of the speed near the top of the boundary layer.

BREEZE

The general name given to light winds blowing along seashores and lakes. During the daylight hours, when the land temperature is warmer than that of the water, the air over the land rises, creating a low-pressure area. Cold air from the sea or lake then blows toward the land, beginning very gradually after sunrise, increasing to a peak in the afternoon and diminishing in the evening. At night, when the land temperature drops below that of the water, the process is reversed, and there is a flow of air from the land toward the water. This seaward breeze starts gently in the evening, increases to a peak during the night, and is still by morning.

CYCLONES

Any atmospheric system in which atmospheric pressure diminishes progressively to a minimum value at the center and toward which the winds blow spirally.

EL NIÑO (EN)

A 12- to 18-month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Hurricanes thrive over warm water. Moderate or strong El Niño events occur irregularly, about once every five to six years, on average. The presence of El Niño in the Pacific tends to reduce hurricane activity in the Atlantic.

EYEWALL

Annular region of secondary circulation in a hurricane marking the transition between the calm eye and the region of strongest winds.

FASTEST-MILE SPEED

The wind speed averaged over the time required for a mile-long column of air to pass a fixed point.

FOHN (OR FOEHN)

The general name given to all winds descending from the tops of mountains and moving down along their sides. This air, usually warm and dry, is compressed, and its temperature rises. A distinction is made between north and south fohns. Typical of the northern side of the Alps, the south fohn is strong and gusty, bringing warm, dry air that melts the snow and evaporates any clouds on the mountain top. The north fohn blows over the southern side of the Alps and has the same characteristics as the south fohn, although it is not as strong or as warm. Many winds of different names throughout the world have characteristics similar to the fohn and can be included in the same category.

FUJITA SCALE
A scale from F0 to F5 specifying a range of wind speeds based on observed damage as depicted in words and a set of damage photographs. This scale is applied extensively by meteorologists and the news media in categorizing extreme wind events.

GEOSTROPHIC WIND
Wind characterized by a state of equilibrium between pressure, gravity, and the Coriolis force.

GALE
A wind measuring 32 to 63 mph.

GUST
The sudden increase in a wind's speed, lasting only a few seconds.

GUST EFFECT FACTOR
A factor that accounts for the effects of wind gusts on the response of the structure or structural component, based on 3-second gust basic design wind speed (ASCE 7-95).

GUST RESPONSE FACTOR
A factor that accounts for the effects of wind gusts on the response of the structure or structural component, based on fastest-mile basic design speed (ASCE 7-93).

GUST SPEED
The maximum speed averaged over a period of from 1 to 5 seconds. Generally, the gust speed is 20 percent to 30 percent higher than the corresponding sustained speed (1-minute average).

HURRICANE (OR TROPICAL CYCLONE)
A system of spiraling winds converging with increasing speed toward a center where they rise vertically around an area of relative calm. Spreading over an area between 50 and 600 miles in diameter, the hurricane travels over the ocean at speeds from 10 to 25 mph while tangential wind speed varies from 40 to 200 mph. A hurricane is formed over the ocean by the rising of a hot, humid column of air that rotates

in a counterclockwise direction in the Northern Hemisphere. As the warm air rises and cools, the vapor is condensed into rain, and the latent heat that is released is the energy source that feeds the hurricane system. Associated with the storm is a tide from 10 to 25 ft high that is produced by the low pressure of the air above the ocean waters. Usually lasting from 8 to 12 days, hurricanes occur in the United States predominantly from June 1 to November 30.

HURRICANE DAY

Four 6-hour periods during which a tropical cyclone is observed, or estimated to have, hurricane-intensity winds.

HURRICANE DESTRUCTION POTENTIAL (HDP)

A measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed for each 6-hour period of its existence.

INTENSE HURRICANE

A hurricane rated Category 3 or higher on the Saffir-Simpson Scale.

INTENSE HURRICANE DAY

Four 6-hour periods during which a hurricane has intensity of Saffir-Simpson Category 3 or higher.

INVERSION

In meteorology, a departure from the usual decrease or increase with altitude of the value of an atmospheric property; the layer through which this departure occurs. As used here, inversion refers to a departure from the normal cooling of air with increasing height at low and intermediate altitudes; from the base of the inversion, air grows warmer with increasing altitude until the inversion is passed, after which the air cools normally with increasing height.

IMPORTANCE FACTOR

A factor introduced in codification to account for the degree of hazard to human life and damage to property. In ASCE 7, the importance factor adjusts the mean recurrence interval of the basic wind speed.

ISOTACH

Line connecting points of equal wind speed on a map.

KOHALA

A gale in Hawaii.

KOILO

A gentle breeze in Hawaii.

KONA

A southerly wind in Hawaii.

LANDFALL
The transition of a hurricane from over-water to over-land exposure.

MEAN RECURRENCE INTERVAL
The number of years, on average, that would elapse before a wind event of approximately the same intensity or higher would revisit a given location.

MOUNTAIN WIND (also downslope winds or drainage winds)
Descending mountain winds that form the fohn family, which includes the Swiss and Austrian fohns, the chinook of the Rocky Mountains, the Santa Ana of Southern California, the zonda of Argentina, the puelche of the Andes, the Canterbury north wester of New Zealand, and others. As the wind rises over mountain slopes, it expands, cools, and loses moisture through condensation. As the wind descends the other side of the mountain, it is dry and becomes hot by compression.

NAMED STORM
A hurricane or a tropical storm.

NAMED STORM DAY
Four 6-hour periods during which a tropical storm is observed or estimated to have attained tropical storm or hurricane intensity winds.

NOR'EASTER
A cold, violent wind; of the same family as the blizzard. It is typical of New England, blowing in from the northeast.

NORTHER
A wind generated by a low pressure in Texas or in the Gulf of Mexico, pulling cold polar air from the north. The norther lasts for about one day.

PRESSURE
Air pressure in excess of or less than ambient. Negative values are less than ambient, positive values exceed ambient.

RIDGE
In meteorology, the opposite of a trough—an elongated area of relatively high atmospheric pressure, commonly used to distinguish this from the closed circulation of an anticyclone; a ridge may include a High, an upper-air ridge may be associated with a surface High, and a High may have one or more distinct ridges radiating from its center.

ROUGHNESS LENGTH
A theoretical quantification of the wind-turbulence-inducing nature of a particular type of terrain.

SAFFIR-SIMPSON HURRICANE SCALE
A numerical scale used to rate the intensity of hurricanes from 1 (least

intense) to 5 (most intense). The scale considers factors such as wind speed, type and intensity of damage, and height of storm surge.

SANTA ANA

A dry, hot, northerly or northwesterly descending wind, blowing into the Los Angeles basin from the Mojave Desert in southern California. It is the cause of the very warm winters in this area.

STANDARD EXPOSURE

The conditions under which official wind speed measurements are made. In particular, standard exposure means an anemometer height of 10 meters (33 ft) in flat, open terrain typical of airport locations.

STORM SURGE

The gradual increase in coastal water depth as a hurricane approaches land. The increase in depth depends on several factors, such as wind speed and direction, barometric pressure, coastline geometry, and normal water depth.

SUSTAINED SPEED

The wind speed averaged over a period of one minute. Unless stated otherwise, a reported wind speed is assumed to be a sustained speed. In parts of the world outside the U.S., averaging time corresponds to 10 minutes; in Canada an hourly mean is used.

TORNADO

A very intense funnel-shaped storm (vortex) with a diameter that is typically less than 1,000 ft. The tangential speeds in a tornado are the highest known wind speeds and may exceed 200 mph. Although tornadoes usually are associated with intense thunderstorms, they can be spawned by hurricanes.

TRADE WIND

A prevailing wind blowing over the ocean in a belt extending around the world from 30° south latitude. In the Northern Hemisphere, this wind blows in a northeasterly direction, while in the Southern Hemisphere, its direction is southeasterly.

TROPICAL CYCLONES

The general term for cyclones that originate over the tropical oceans, from tropical disturbance to hurricane or typhoon.

TROPICAL STORM

A tropical cyclone with maximum sustained winds between 39 and 73 mph.

TROUGH

In meteorology, an elongated area of relatively low atmospheric pressure, commonly used to distinguish this from the closed circulation of a cyclone; a large trough may include one or more Lows, an upper-air trough may be associated with a lower level Low, and a Low may have one or more distinct troughs radiating from it.

TYPHOON
A hurricane on the Pacific Ocean.

V ZONE (COASTAL HIGH HAZARD AREA)
Encompasses areas within the base flood boundary subjected to velocity wave action of three feet or more in height. The coastal V Zone presents an extreme hazard to life and structures because of the high water velocity and additional forces resulting from the wave action.

WATERSPOUT
A phenomenon similar to a tornado only less violent and destructive. Forming over water, it consists of winds spiraling around a fresh- or saltwater core due to vapor condensation that rises into the funnel-shaped mother cloud. When water spouts form over the ocean, only the first few feet of the spout contain salt water sucked from the sea's surface. Spouts can occur on lakes as well and can travel on land for short periods of time.

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