3 Characteristics of Tornadoes and Hurricanes

This chapter provides basic information about tornadoes and hurricanes and how they affect the built environment. This information will help the reader better understand how extreme winds damage buildings and the specific guidance provided in Chapters 5, 6, and 7.

3.1 General Wind Effects on Buildings

Building failures occur when winds produce forces on buildings that the buildings were not designed or constructed to withstand. Failures also occur when the breaching of a window or door creates a large opening in the building envelope. These openings allow wind to enter buildings, where it again produces forces that the buildings were not designed to withstand. Other failures may be attributed to poor construction, improper construction techniques, and poor selection of building materials.

Past history and post-disaster investigations have shown that, to a large extent, wind damage to both residential and non-residential buildings is preventable. Mitigation opportunities for property protection have been identified along the periphery of strong and violent tornadoes, in the path of the vortex of weak tornadoes, and within the windfields of most hurricanes. In these areas, damage to property was investigated to determine whether losses could have been minimized through compliance with up-to-date model building codes and engineering standards, and whether construction techniques proven to minimize damage in other wind-prone areas were used. It has been determined that property protection can be improved to resist the effects of smaller tornadoes. This is an important consideration when building owners are considering mitigation because, on average since 1995, F1 and F2 tornadoes account for approximately 80–95 percent of reported tornadoes in any given year (based on NOAA tornado data from 1995 to 1998).

However, for tornadoes classified F3 and larger (see Table 3.1), large areas of buildings cannot be economically strengthened to resist the wind loads. If the building cannot resist the wind loads acting on it, it will fail. However, if the occupants of the building have retreated to a safe, specially designed and constructed shelter area, deaths and injuries will be avoided. Shelters designed and constructed according to the principles in this manual provide a near-absolute level of protection for their occupants.

3.2 Wind-Induced Forces – Tornadoes and Hurricanes

Tornadoes and hurricanes are extremely complex wind events that cause damage ranging from minimal or minor to extensive devastation. It is not the intent of this section to provide a complete and thorough explanation or definition of tornadoes, hurricanes, and the damage associated with each event. However, this section does define basic concepts concerning tornadoes, hurricanes, and their associated damage.

3.2.1 Tornadoes

In a simplified tornado model, there are three regions of tornadic winds:

- Near the surface, close to the core or vortex of the tornado. In this region, the winds are complicated and include the peak at-ground wind speeds, but are dominated by the tornado’s strong rotation. It is in this region that strong upward motions occur that carry debris upward, as well as around the tornado.
- Near the surface, away from the tornado’s vortex. In this region, the flow is a combination of the tornado’s rotation, inflow into the tornado, and the background wind. The importance of the rotational winds as compared to the inflow winds decreases with distance from the tornado’s vortex. The flow in this region is extremely complicated. The strongest winds are typically concentrated into relatively narrow swaths of strong spiraling inflow rather than a uniform flow into the tornado’s vortex circulation.
- Above the surface, typically above the tops of most buildings. In this region, the flow tends to become nearly circular.

In a tornado, the diameter of the core or vortex circulation can change with time, so it is impossible to say precisely where one region of the tornado’s flow ends and another begins. Also, the visible funnel cloud associated with and typically labeled the vortex of a tornado is not always the edge of the strong extreme winds. Rather, the visible funnel cloud boundary is determined by the temperature and moisture content of the tornado’s inflowing air. The highest wind speeds in a tornado occur at a radius measured from the tornado vortex center that can be larger than the edge of the visible funnel cloud’s radius. It is important to remember that a tornado’s wind speeds cannot be determined solely from its appearance.

Tornadoes are commonly categorized according to the Fujita Scale, which was created by the late Dr. Tetsuya Theodore Fujita, University of Chicago. The Fujita Scale (see Table 3.1) categorizes tornado severity by damage observed, not by recorded wind speeds. Ranges of wind speeds have been associated with the damage descriptions of the Fujita Scale, but their accuracy has been called into question by both the wind engineering and meteorological communities, especially the ranges for the higher end (F4 and F5) of the scale. The wind speeds are estimates that are intended to represent the observed

Table 3.1
The Fujita Scale

Category / Typical Damage

F0 Light: Chimneys are damaged, tree branches are broken, shallow-rooted trees are toppled.

F1 Moderate: Roof surfaces are peeled off, windows are broken, some tree trunks are snapped, unanchored manufactured homes are overturned, attached garages may be destroyed.

F2 Considerable: Roof structures are damaged, manufactured homes are destroyed, debris becomes airborne (missiles are generated), large trees are snapped or uprooted.

F3 Severe: Roofs and some walls are torn from structures, some small buildings are destroyed, unreinforced masonry buildings are destroyed, most trees in forest are uprooted.

F4 Devastating: Well-constructed houses are destroyed, other houses are lifted from foundations and blown some distance, cars are blown some distance, large debris becomes airborne.

F5 Incredible: Strong frame houses are lifted from foundations, reinforced concrete structures are damaged, automobile-sized debris becomes airborne, trees are completely debarked.

F0, F1, F2, F3, F4, F5 IMAGES: FEMA

damage. They are not calibrated wind speeds, nor do they account for variability in the design and construction of buildings.

Tornado damage to buildings can occur as a result of three types of forces:

1. wind-induced forces
2. forces induced by changes in atmospheric pressure
3. forces induced by debris impact

Forces due to tornadic and hurricane winds are discussed in detail later in this chapter. Guidance on the calculation of these forces is provided in Chapter 5.

The atmospheric pressure in the center of the tornado vortex is lower than the ambient atmospheric pressure. When a tornado vortex passes over a building, the outside pressure is lower than the ambient pressure inside the building. This atmospheric pressure change (APC) in a tornado may cause outward-acting pressures on all surfaces of the building. If there are sufficient openings in the building, air flowing through the openings will equalize the inside and outside atmospheric pressures, and the APC-induced forces will not be a problem. However, it should be noted that openings in the building envelope also allow wind to enter the building and cause internal pressures in addition to wind-induced aerodynamic external pressures (see Section 5.3.1).

Maximum APC occurs in the center of a tornado vortex where winds are assumed to be zero. A simple tornado vortex model suggests that, at the radius of the maximum winds, APC is one-half of the maximum value. Thus, for tornado loadings, two situations of the state of the building should be considered: (1) sealed building, or (2) vented building (i.e., a building with openings). For a sealed building, the maximum design pressure occurs when wind-induced aerodynamic pressure is combined with one-half APC-induced pressure. For a vented building, the maximum design pressure occurs when wind-induced aerodynamic pressure is combined with wind-induced internal pressure. See Chapter 5 for design guidance regarding the effects of APC.

Tornadic winds tend to lift and accelerate debris (missiles) consisting of roof gravel, sheet metal, tree branches, broken building components, and other items. This debris can impact building surfaces and perforate them. Large debris, such as automobiles, tends to tumble along the ground. The impact of this debris can cause significant damage to wall and roof components. The debris impact and the high winds result from the same storm. However, each debris impact affects the structure for an extremely short duration, probably less than 1 second. For this reason, the highest wind load and the highest impact load are not considered likely to occur at precisely the same time. Design guidance for the impact of debris is presented in Chapter 6.

3.2.2 Hurricanes

Hurricanes are one of the most destructive forces of nature on earth. Views of hurricanes from satellites thousands of miles above the earth show the power of these very large, but tightly coiled weather systems. A hurricane is a type of tropical cyclone, the general term for all circulating weather systems (counterclockwise in the Northern Hemisphere) originating over tropical waters. Tropical cyclones are classified as follows:

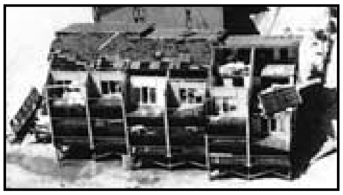
- **Tropical Depression** – An organized system of clouds and thunderstorms with a defined circulation and maximum sustained winds of 38 mph or less.
- **Tropical Storm** – An organized system of strong thunderstorms with a defined circulation and maximum sustained winds of 39 to 73 mph.
- **Hurricane** – An intense tropical weather system with a well-defined circulation and sustained winds of 74 mph or higher. In the western Pacific, hurricanes are called “typhoons,” and similar storms in the Indian Ocean are called “cyclones.”

Hurricanes that affect the U.S. mainland are products of the Tropical Ocean (Atlantic Ocean, Caribbean Sea, or Gulf of Mexico) and the atmosphere. Powered by heat from the sea, they are steered by the easterly trade winds and the temperate westerlies as well as by their own ferocious energy. Around their core, winds grow with great velocity, generating violent seas. Moving ashore, they sweep the ocean inward (storm surge) while spawning tornadoes, downbursts, and straight-line winds, and producing torrential rains and floods.

Hurricanes are categorized according to the Saffir-Simpson Hurricane Scale (see Table 3.2), which was designed in the early 1970s by Herbert Saffir, a consulting engineer in Coral Gables, Florida, and Robert Simpson, who was then director of the National Hurricane Center. The Saffir-Simpson Hurricane Scale is used by the National Weather Service to estimate the potential property damage and flooding expected along the coast from a hurricane landfall. The scale is a 1–5 rating based on the hurricane’s current intensity. Wind speed and barometric pressure are the determining factors in the scale. Storm surge is not a determining factor, because storm surge values are highly dependent on the slope of the continental shelf in the landfall region.

Recently, there has been increased recognition of the fact that wind speed, storm surge, and inland rainfall are not necessarily coupled. There is growing interest in classifying hurricanes by separate scales according to the risks associated with each of these threats.

Table 3.2
The Saffir-Simpson Hurricane Scale

Category / Typical Damage	
	**C1 Minimal:** Damage is done primarily to shrubbery and trees, unanchored manufactured homes are damaged, some signs are damaged, no real damage is done to structures on permanent foundations.
	**C2 Moderate:** Some trees are toppled, some roof coverings are damaged, major damage is done to manufactured homes.
	**C3 Extensive Damage:** Large trees are toppled, some structural damage is done to roofs, manufactured homes are destroyed, structural damage is done to small homes and utility buildings.
	**C4 Extreme Damage:** Extensive damage is done to roofs, windows, and doors; roof systems on small buildings completely fail; some curtain walls fail.
	**C5 Catastrophic Damage:** Roof damage is considerable and widespread, window and door damage is severe, there are extensive glass failures, some buildings fail completely.

C1, C2, C3, C4 IMAGES: FEMA
C5 IMAGE COURTESY OF NOAA, HISTORICAL DATA COLLECTION

3.2.3 Typhoons

Typhoons affect the Pacific Islands (Hawaii, Guam, and American Samoa) and, like hurricanes, can generate high winds, flooding, high-velocity flows, damaging waves, significant erosion, and heavy rainfall. Historically, typhoons have been classified according to strength as either typhoons (storms with less than 150 mph winds) or super typhoons (storms with wind speeds of 150 mph or greater) rather than by the Saffir-Simpson Hurricane Scale. For the purposes of this manual, the guidance provided for hurricanes applies to areas threatened by typhoons.

3.3 Effects of Extreme Winds and Tornado Forces

Wind-induced damage to residential and commercial buildings indicates that extreme winds moving around buildings generate loads on building surfaces that can lead to the total failure of a building. In addition, internal pressurization due to a sudden breach of the building envelope (the failure of the building exterior) is also a major contributor to poor building performance under severe wind loading conditions. If a building is constructed with a **continuous load path**, the building's ability to survive during a design event will be improved, even if a portion of the building envelope fails. This section discusses topics related to wind, wind pressures acting on buildings, and windborne debris (missiles). The importance of a continuous load path within a building or structure is discussed in Section 5.5.

CROSS-REFERENCE

Section 5.5 presents detailed information about **continuous load paths.** A continuous load path is required in a shelter in order for the shelter to resist the wind and wind pressures described in this section.

3.3.1 Forces Generated by the Design Wind Speed

The design wind speed for construction of a community shelter should be determined from Figure 2-2. When calculating the wind pressures from the design wind speed, the designer should not consider the effects of the other parts of the building that may normally reduce wind pressures on the shelter. The designer should also ensure either that the destruction of the non-shelter parts of the building does not put additional loads on the shelter or that the shelter is designed for these additional loads.

CROSS-REFERENCE

The **design wind speed** for the proposed shelter is selected from Figure 2-2.

The design wind speed is used to predict forces on both the main wind force resisting system (MWFRS) and on the exterior surfaces of the buildings—components and cladding (C&C). The MWFRS is the structural system of the building or shelter that works to transfer wind loads to the ground and includes structural members such as roof systems (including diaphragms), frames, cross bracing, and loadbearing walls. C&C elements include wall and roof members (e.g., joists, purlins, studs), windows, doors, fascia, fasteners, siding, soffits, parapets, chimneys, and roof overhangs. C&C elements receive wind loads directly and transfer the loads to other components or to the MWFRS.

The effects of wind on buildings can be summarized as follows:

- Inward-acting, or positive, pressures act on windward walls and windward surfaces of steep-sloped roofs.
- Outward-acting, or negative pressures act on leeward walls, side walls, leeward surfaces of steep-sloped roofs, and all roof surfaces for low-sloped roofs or steep-sloped roofs when winds are parallel to the ridge.
- Airflow separates from building surfaces at sharp edges and at points where the building geometry changes.

- Localized suction or negative pressures at eaves, ridges, edges, and the corners of roofs and walls are caused by turbulence and flow separation. These pressures affect loads on C&C.
- Windows, doors, and other openings are subjected to wind pressures and the impact of windborne debris (missiles). If these openings fail (are breached) because of either wind pressure or windborne debris, then the entire structure becomes subject to wind pressures that can be twice as great as those that would result if the building remained fully enclosed.

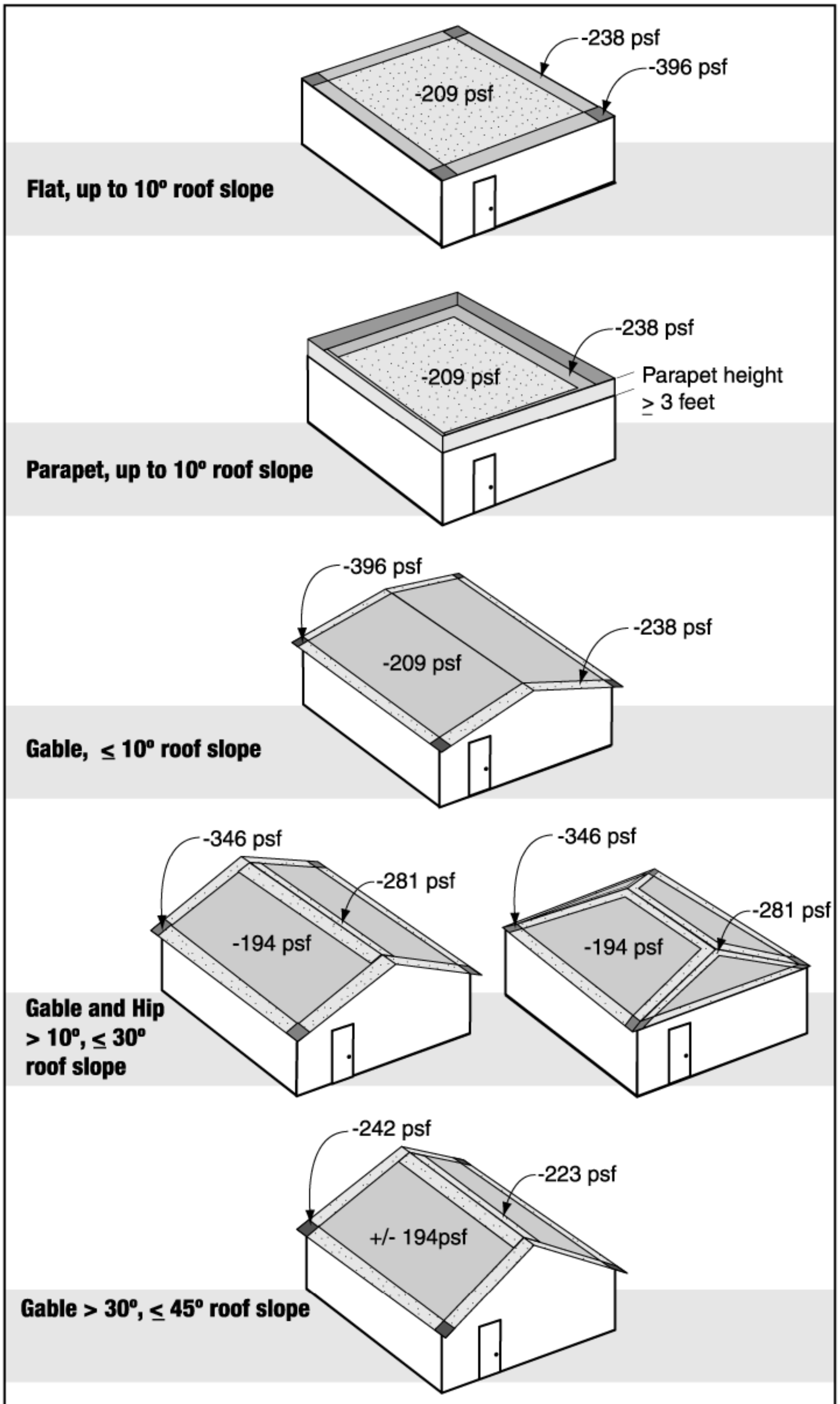
High winds are capable of imposing large lateral (horizontal) and uplift (vertical) forces on buildings. The strength of the building's structural frame, connections, and envelope determine the ability of the building to withstand the effects of these forces.

Wind loads are influenced by the location of the building site (the general roughness of the surrounding terrain, including open, built-up, and forested areas, can affect wind speed), height of the building (wind pressures increase with height above ground, or the building may be higher than surrounding vegetation and structures and therefore more exposed), surrounding topography (land surface elevations can create a speedup effect), and the configuration of the building.

Roof shape plays a significant role in roof performance, both structurally and with respect to the magnitude of the wind loads. Compared to other types of roofs, hip roofs generally perform better in high winds because they have fewer sharp corners and because their construction makes them inherently more structurally stable. Gable-end roofs require extensive detailing to properly transfer lateral loads acting against the gable-end wall into the structure. Steeply pitched roofs usually perform better than flat roofs because uplift on the windward roof slopes is either reduced or eliminated.

Figure 3-1 illustrates the effects of roof geometry on wind loads. Notice that a 3-foot parapet around a roof does not have elevated roof pressures at the corners and that a gable roof with a roof pitch of greater than 30 degrees produces the lowest leeward and corner pressures. The highest roof pitches tested are 45 degrees (12 on 12 pitch) because few roofs have steeper pitches than 45 degrees and few data are available for higher slopes.

Wind loads and the impact of windborne debris are both capable of damaging a building envelope. Post-disaster investigations of wind-damaged buildings have shown that many building failures begin because a component or a segment of cladding is blown off the building, allowing wind and rain to rapidly enter the building. An opening on the windward face of the building can also lead to a failure by allowing positive pressures to occur that, in

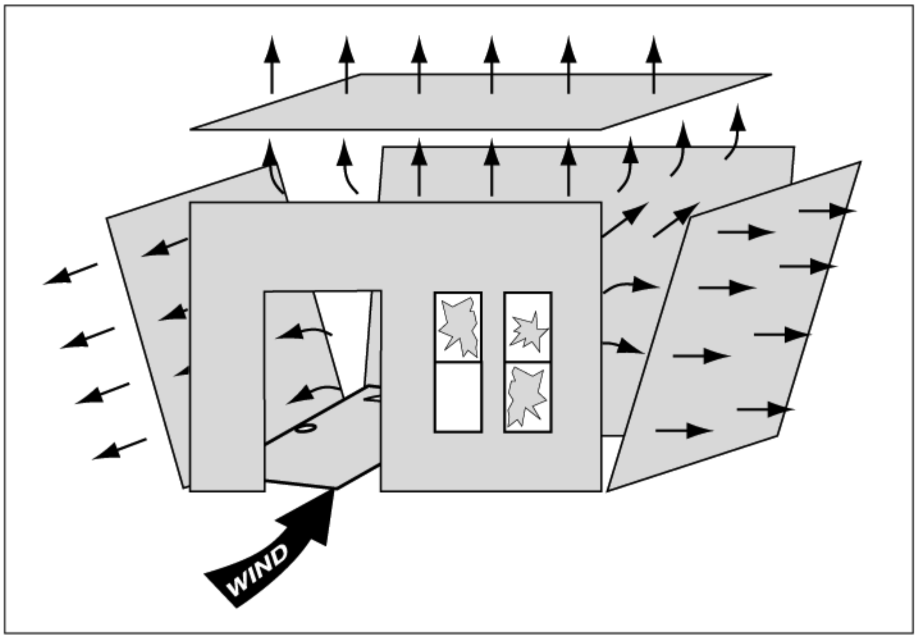


NOTE: Design pressures all assume the same basic wind speed (250 mph 3-second peak gust), Exposure C, and mean roof height.

Figure 3-1
Calculated pressures (based on ASCE 7-98 C&C equations) acting on a typical shelter. This figure illustrates the different roof pressures that result for the same building and wind speed as the roof shape is varied. For the calculation of the loads from these pressures, the shelter was assumed to be a 50-foot x 75-foot rectangular building with a constant mean roof height of 12 feet. Note: These loads do not include any additional loads from internal pressurization resulting from either a vented or breached building envelope.

conjunction with negative external pressures, can “blow the building apart.” Figure 3-2 depicts the forces that act on a structure when an opening exists in the windward wall.

Figure 3-2
Internal pressurization and resulting building failure due to design winds entering an opening in the windward wall.



The magnitude of internal pressures depends on whether the building is “enclosed,” “partially enclosed,” or “open” as defined by ASCE 7-98. The internal pressures in a building are increased as a building is changed from an “enclosed” to a “partially enclosed” building. The design criteria presented in Chapter 5 recommend that shelter design be based on the partially enclosed internal pressures. The walls and the roof of the shelter and connections between the components should be designed for the largest possible combination of internal and external pressures. This design concept is in keeping with using a conservative approach because of the life safety issues involved in shelter design.

3.3.2 Building Failure Modes – Elements, Connections, and Materials

The wind forces described in the previous section will act on a building as both inward-acting and outward-acting forces. The direction and magnitude of the forces are governed by the direction of the wind, location of the building, height and shape of the building, and other conditions that are based on the terrain surrounding the building. Chapter 5 of this manual and Section 6 of ASCE 7-98 provide information on calculating the direction and magnitude of the wind forces acting on a building once the design wind speed and openings in the building envelope have been established. Winds moving around a building or structure may cause sliding, overturning, racking, and component failures.

Building failures can be independently categorized by one or a combination of the four failure modes illustrated in Figure 3-3. A sliding failure occurs when wind forces move a building laterally off its foundation. An overturning failure occurs when a combination of the lateral and vertical wind forces cause the entire building to rotate about one of its sides. A racking failure occurs when the building's structural system fails laterally, but the building typically remains connected to the foundation system. A component failure, the most common failure seen during high-wind events (and typically a contributing failure to the first three failure modes listed), may be caused by wind pressures or windborne debris (missile) impacts. Component failures may be either full-system failures or individual element failures.

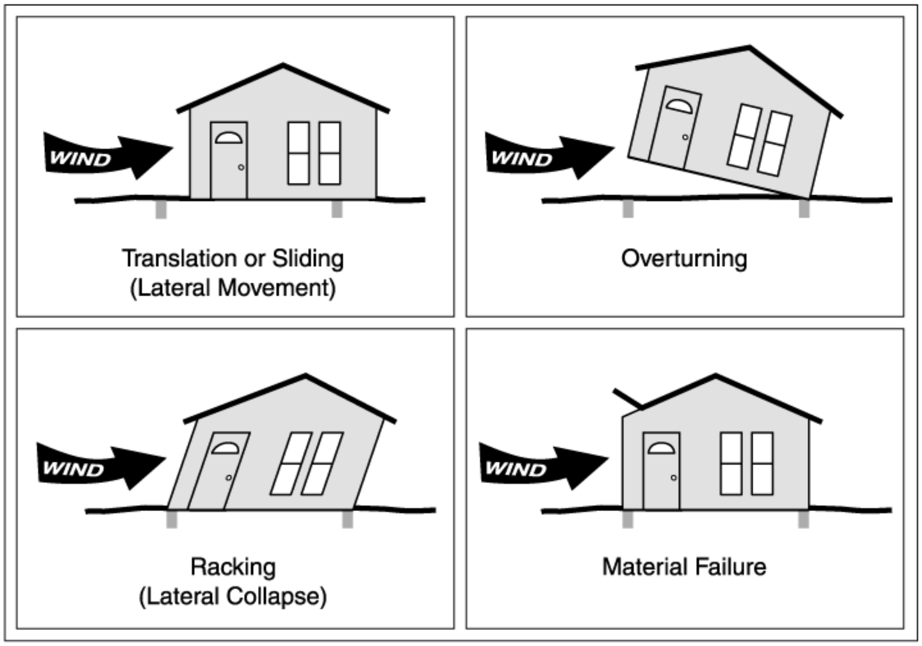


Figure 3-3
Forces on a building due to wind moving around the structure.

Most buildings are designed as enclosed structures with no large or dominant openings that allow the inside of the building to experience internal pressurization from a wind event. However, under strong wind conditions, a breach in the building envelope due to broken windows, failed entry doors, or failed large overhead doors may cause a significant increase in the net wind loads acting on building components such as walls and the roof structure . In such cases, the increase in wind load may cause a partial failure or propagate into a total failure of the primary structural system. Uplift or downward force (depending on roof pitch and wind direction) may act upon the roof of the building and cause overturning, racking, or failure of components.

3.3.3 Cyclic Loading

Both tornadoes and hurricanes have unsteady wind patterns within their circular wind fields. These effects cause cyclic loading on buildings. Tornadoes, however, generally pass over a site in a very short time. Wind experts believe that the cyclic periods of wind loads in tornadoes are short and less frequent than those in hurricanes. Thus, designing tornado shelters for cyclic loads is not recommended.

CROSS-REFERENCE

Chapter 6 presents additional information about cyclic loading for missile impact protection and for code compliance in specific regions of the country.

Hurricane winds typically impact a site for a much longer time. This can result in many repetitive cycles close to the peak loads. Failures in the roof system itself, and of roof-to-wall, wall-to-wall, wall-to-floor, and wall/floor to foundation connections, can occur under repetitive loads. Cyclic loads become particularly important when either the structure or a component is flexible or when the fastening system receives repetitive loading. When cyclic loads are to be considered, designers are advised to review loading cycles given in the ASTM Standard E 1996 or to use allowable stresses below the endurance limit of materials or connections. Structural connections of heavy steel and reinforced concrete and masonry construction, where the structural system is rigid, are likely to resist hurricane cyclic loads.

3.3.4 Windborne Debris – Missiles

Tornadoes and hurricanes produce large amounts of debris that become airborne. This windborne debris (missiles) may kill or injure persons unable to take refuge and may also perforate the envelope and other components of any conventional building in the path of the debris. The size, mass, and speed of missiles in tornadoes or hurricanes varies widely. Only a few direct measurements of debris velocity have been made. Such measurements require using photogrammetric techniques to analyze movies of tornadoes that contain identifiable debris. For this reason, the choice of the missiles that a shelter must withstand is somewhat subjective. From over 30 years of post-disaster investigations after tornadoes and hurricanes, the Wind Engineering Research Center at Texas Tech University (TTU) concluded that the missile most likely to perforate building components is a wood 2x4 member, weighing up to 15 lb. Other, larger airborne missiles do occur; larger objects, such as cars, can be moved across the ground or, in extreme winds, they can be tumbled, but they are less likely than smaller missiles to perforate building elements. Following the Oklahoma and Kansas tornado outbreaks of May 3, 1999, both FEMA and TTU investigated tornado damage and debris fields and concluded that the 15-lb 2x4 missile was reasonable for shelter design.

3.3.5 Resistance to Missile Impact

Relationships between wind speed and missile speed have been calculated. For a 250-mph wind speed, the highest design wind speed considered necessary for shelter design, the horizontal speed of a 15-lb missile is calculated to be 100 mph based on a simulation program developed at TTU. The vertical speed of a falling wood 2x4 is considered to be two-thirds the horizontal missile speed. Although the probability is small that the missile will travel without rotation, pitch, or yaw and that it will strike perpendicular to the surface, these worst case conditions are assumed in design and testing for missile perforation resistance. Therefore, the missile design criterion for all wind zones is a 15-lb wood 2x4 traveling without pitch or yaw at 100 mph and striking perpendicular to the surface.

After a structure is designed to meet wind load requirements, its roof, walls, doors, and windows must be checked for resistance to missile impacts. Table 3.3 summarizes missile impact speeds based on previous research for the design wind speeds presented in Figure 2-2.

Table 3.3
Summary of Previous Research on Probable Missile Speeds for a 15-lb Wood 2x4 Missile as Associated With the Design Wind Speeds From Figure 2-2

WIND ZONE	PREDOMINANT WIND TYPE	DESIGN WIND SPEED	MISSILE SPEED AND DIRECTION
I	Tornado & Hurricane	130 mph	80 mph Horizontal 53 mph Vertical
II	Tornado & Hurricane	160 mph	84 mph Horizontal 56 mph Vertical
III	Tornado	200 mph	90 mph Horizontal 60 mph Vertical
IV	Tornado	250 mph	100 mph Horizontal 67 mph Vertical

The structural integrity necessary to withstand wind forces for small residential shelters can be provided with materials common to residential construction. The major challenge in designing small shelters is, then, to protect against missile perforation. A number of designs for safe rooms capable of withstanding a 250-mph design wind are presented in FEMA 320. For larger shelters, the design challenge shifts to providing the structural integrity necessary to resist wind loads. Walls designed with reinforced concrete or reinforced masonry to carry extreme wind loads will normally prevent perforation by flying debris.

CROSS-REFERENCE

Design guidance for **missile impact** resistance of doors, windows, and other openings is provided in Chapter 6.

The roof, wall sections, and coverings that protect any openings in a shelter should be able to resist **missile impacts**. The limited testing performed at missile speeds lower than the 100-mph impact speed (90, 84, and 80 mph) does not provide enough conclusive data or result in cost savings great enough to justify varying the missile impact criterion presented in this manual. Therefore, the 100-mph missile speed is used in this manual for missile impact resistance for Wind Zones I–IV.

Doors, and sometimes windows, are required for some shelters. However, doors and other openings are vulnerable to damage and failure from missile impact. Large doors with quick-release hardware (required in public buildings) and windows present challenges to the designer. Design guidance for doors and windows is given in Chapter 6.

3.3.6 Falling Debris and Other Impacts

The location of the shelter has an influence on the type of debris that may impact or fall on the shelter. For residential structures, the largest debris generally consists of wood framing members. In larger buildings, other failed building components, such as steel joists, pre-cast concrete members, or rooftop-mounted equipment, may fall on or impact the shelter. Chapter 4 discusses how to minimize the effects of falling debris and other large object impacts by choosing the most appropriate location for a shelter at any given site. Chapter 6 presents design approaches for protecting against these other impacts through engineering design and guidance that are supported by the results of testing.