4 Characteristics of Tornadoes and Hurricanes

This chapter provides basic information about tornadoes and hurricanes and their effects on the built environment. This information will help the reader better understand both how extreme winds damage buildings and the specific guidance provided in Chapter 3.

4.1 General Wind Effects on Buildings

Building failures occur when winds produce forces on buildings that they were not designed or constructed to withstand. Failures also occur when the breaching of a window or door creates a relatively 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, inadequate structural systems, older building codes that provided little to no hazard-resistance provisions, and poor selection of building materials.

Past history and post-disaster investigations have shown that, to a large extent, (1) wind-induced structural damage to both residential and non-residential buildings can be minimized and (2) wind- and debris-induced damage to the building exterior (envelope) can be reduced. Experience shows that mitigation opportunities for building protection exist for properties that may be exposed to wind hazards along the periphery of strong and violent tornadoes, in the path of the vortex of weak tornadoes, and within the wind fields 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. Buildings designed and constructed above basic code requirements (i.e., “hardened” buildings), and newer structures designed and constructed to modern, hazard-resistant codes have been found to be able to resist the wind load forces from weak tornadoes

NOTE

If a standard-size window is broken by windborne debris on the wall of a typical single-story home, an opening in the building envelope can be formed that is large enough (4 to 5 percent of the wall area) that the building may experience internal pressurization. In addition to exposing the interior of the building to wind-driven rain, an increase in wind loads may result in a partial or complete structural failure.

(EF1 or weaker). Furthermore, during stronger tornado strikes, not all damage is from the rotating vortex of the tornado. Much of the damage is from straight-line winds rushing toward and being pulled into the tornado itself. Many newer homes designed and constructed to modern codes, such as the *International Residential Codes* (IRC 2000 Edition and newer), with a continuous load path to resist extreme-wind forces may survive without structural failure. The primary damage to these newer homes is to the building envelope (i.e., cladding and other exterior systems: roof covering, roof deck, exterior walls, and windows). Even this type of damage may be reduced on buildings that are designed and constructed according to the IRC 2000 (or newer) when the building experiences weaker tornadoes and the outermost winds from stronger tornadoes. This is an important consideration for building owners who are contemplating mitigation because these are the most frequent wind hazards. Based on NOAA tornado data from 1997 to 2006, EF0, EF1, and EF2 tornadoes account for approximately 80 to 95 percent of reported tornadoes in any given year.

However, for tornadoes classified EF3 and larger (see Table 4-1), larger buildings and large areas of buildings cannot be economically strengthened to resist the wind loads and debris impacts. 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 safe room area, injuries and deaths will be avoided. Safe rooms designed and constructed according to the principles in this publication provide a near-absolute level of protection for their occupants.

4.2 Wind-Induced Forces – Tornadoes and Hurricanes

Tornadoes and hurricanes are 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. Rather, this section defines basic concepts concerning tornadoes, hurricanes, and their associated damages.

4.2.1 Tornadoes

Tornadoes are one of nature's most violent storms. According to the *Glossary of Meteorology* (AMS 2000), a tornado is "a violently rotating column of air, pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud." From 1997 to 2006, in an average year, approximately 1,300 tornadoes have been reported across the United States, resulting in 67 deaths and over 1,100 injuries annually. The most violent tornadoes, with wind speeds of 250 mph or more, are capable of tremendous destruction. Damage paths can be more than 1 mile wide and up to 50 miles long. Tornadoes can occur anywhere in the United States. The states along the Atlantic and Gulf coasts have some of the highest occurrence rates of smaller tornadoes (EF0-EF2), while the Great Plains region of the country (which includes parts of Texas, Oklahoma, Kansas, and Nebraska) consistently has the highest occurrence rates of larger tornadoes (EF3-EF5). Tornadoes are responsible for the greatest number of wind-related deaths each year in the United States.

Tornadoes come in all shapes and sizes. In the southern states, peak tornado season is March through May; peak months in the northern states are during the summer. Tornadoes can also occur in thunderstorms that develop in warm, moist air masses in advance of eastward-moving cold fronts. These thunderstorms often produce large hail and strong winds, in addition to tornadoes. During the spring in the central plains, thunderstorms frequently develop along a “dryline,” which separates warm, moist air to the east from hot, dry air to the west. Tornado-producing thunderstorms may form as the dryline moves east during the afternoon hours. Along the front range of the Rocky Mountains, in the Texas panhandle, and in the southern high plains, thunderstorms frequently form as air near the ground flows “upslope” toward higher terrain. If other favorable conditions exist, these thunderstorms can produce tornadoes. Tornadoes occasionally accompany tropical storms and hurricanes that move over land. They are most common to the right and ahead of the path (in the right front quadrant) of the storm center as it comes onshore.

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, high 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.

From 1971 until February 2007, tornadoes were typically categorized according to the Fujita Scale (F Scale), which was created by the late Dr. Tetsuya Theodore Fujita, University of Chicago. The Fujita Scale[1] categorized tornado severity by damage observed, not by recorded

[1] The text describing the Fujita Scale and the Enhanced Fujita Scale was primarily taken from the report titled: *A Recommendation for an Enhanced Fujita Scale (EF-Scale)*, October 17, 2006, by the Wind Science and Engineering Research Center, Texas Tech University.

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 were estimates intended to represent the observed damage. They were not calibrated, nor did they account for variability in the design and construction of buildings.

As a result, the Wind Science and Engineering (WISE) Research Center at TTU and other researchers from the wind engineering and meteorological communities worked together to revise and update the Fujita Scale over the past several years. The resulting tornado classification scale is called the Enhanced Fujita Scale (EF Scale). The primary limitations of the Fujita Scale were a lack of damage indicators, no account of construction quality and variability, and no definitive correlation between damage and wind speed. These limitations have led to inconsistent ratings of tornadoes.

NOTE

Dr. Fujita's group at the University of Chicago and personnel at the National Severe Storms Forecast Center (NSSFC) independently assigned Fujita Scale ratings to tornadoes in the historical records based on written descriptions of the damage. However, the primary recordkeeper of the NSSFC data became the Storm Prediction Center (SPC), which maintained the tornado track data through 1995. Tornado records since that time are kept at the National Climatic Data Center (NCDC) in Asheville, North Carolina.

Based on its vast experience in tornado damage and investigation, the TTU team assigned to the project proposed 28 damage indicators that consisted of buildings, structures, and trees. For each damage indicator (DI), several degrees of damage (DODs) are identified. The DODs are sequenced so each one requires a higher expected wind speed than the previous one. Damage ranges from the initiation of visible damage to complete destruction of the particular DI.

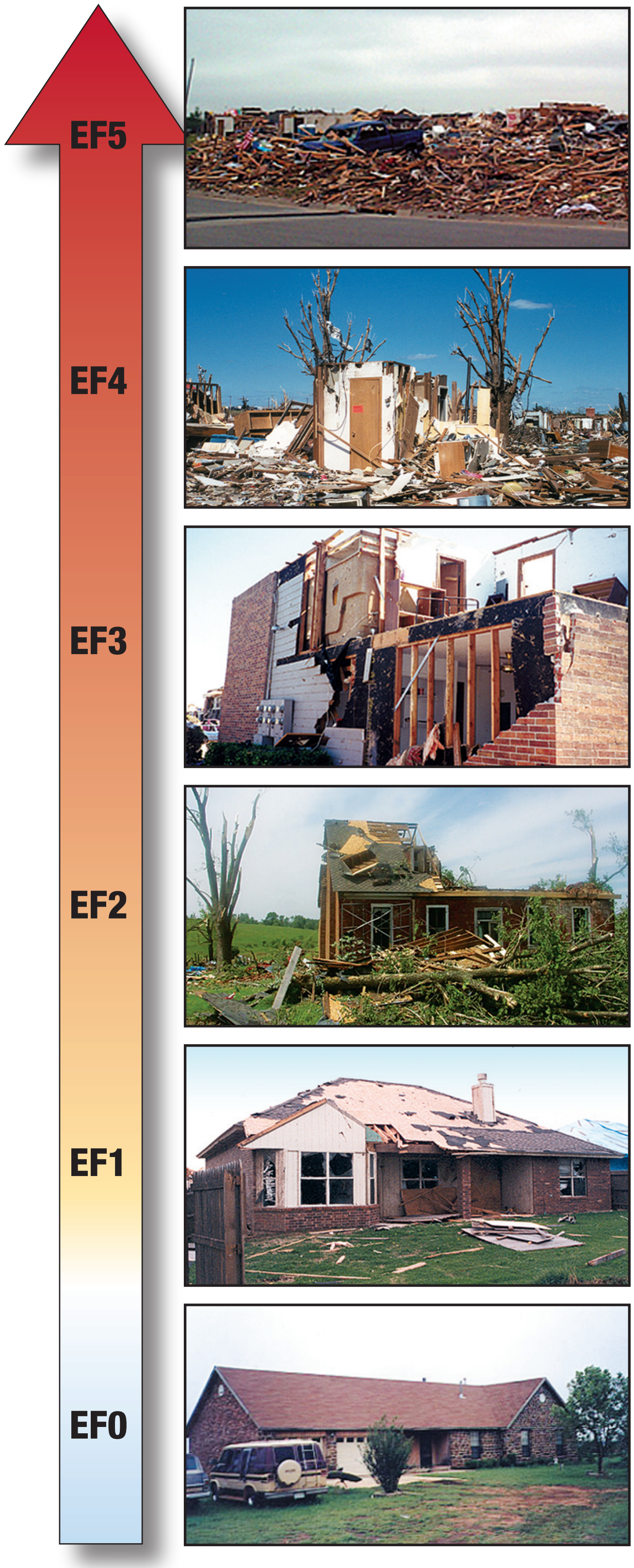
The strategy of damage indicators requires that an expected, upper and lower bound wind speed be defined for each DOD. The range of wind speed defined by the upper and lower bound wind speeds accounts for circumstances that cause the actual wind speed associated with the damage to deviate from the expected value. The expected value of wind speed to cause a given DOD is based on a set of "normal" conditions. A weak link is a discontinuity in the load path, which runs from the building surface through the structural system to the foundation.

The EF scale addresses the major limitations of the original Fujita Scale. Additional DIs are proposed along with DODs. Through an expert elicitation process, wind speeds corresponding to the described damage for each DOD are estimated. The estimated wind speed then determines the EF Scale category appropriate for the observed damage. The categories range from EF0 to EF5. The wind speed ranges in each category are related to Fujita Scale ranges by a correlation function (see the 2006 WISE paper) and are shown in Table 4-1. This correlation between Fujita Scale and EF Scale wind speeds provides a link between the two scales and thus makes it possible to express a Fujita Scale rating in terms of an EF Scale rating. The only difference is the wind speed ranges in each scale. Thus, the historical tornado database is preserved and can be easily converted to the criteria of the EF Scale. Figure 4-1 presents a description of the damage states of the EF Scale and provides photos to assist with understanding.

Table 4-1. Comparison Table for the Fujita and Enhanced Fujita Scales

Fujita Scale		EF Scale	
Fujita Scale	**3-Second Gust Speed (mph)**	**EF Scale**	**3-Second Gust Speed (mph)**
F0	45-78	EF0	65-85
F1	79-117	EF1	86-109
F2	118-161	EF2	110-137
F3	162-209	EF3	138-167
F4	210-261	EF4	168-199
F5	262-317	EF5	200-234

The Fujita Scale categorizes tornado severity based on observed damage. The six-step scale ranges from F0 (light damage) to F5 (incredible damage). Since February 2007, the National Weather Service has used the Enhanced Fujita Scale (EF Scale). This new scale ranges from EF0 to EF5. See http://www.spc.noaa.gov/efscale for further information on the EF Scale.



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

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

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

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

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

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

Figure 4-1. Typical tornado damage

4.2.2 Hurricanes and Typhoons

A hurricane, as defined by NOAA, is a tropical cyclone in which the maximum sustained surface wind (using the U.S. 1-minute average) is 74 mph or greater. The term hurricane is used for Northern Hemisphere tropical cyclones east of the International Dateline to the Greenwich Meridian. 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 westerly trade winds, as well as by their own intense 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. A comparison of the sustained wind speed measure of the Saffir-Simpson Hurricane Scale and the 3-second gust measure now used by ASCE 7-05, the ICC-500, and this publication for their respective wind speed maps is presented in Table 4-2.

Table 4-2. The Saffir-Simpson Hurricane Scale Wind Speeds and Pressures

Strength	Sustained Wind Speed (mph)*	Gust Wind Speed (mph)**	Pressure (millibars)
Category 1	74-95	89-116	>980
Category 2	96-110	117-134	965-979
Category 3	111-130	135-159	945-964
Category 4	131-155	160-189	920-944
Category 5	>155	>189	<920

* 1-minute sustained over open water

** 3-second gust over open water

Hurricanes are categorized according to the Saffir-Simpson Hurricane Scale (see Table 4-2 and Figure 4-2), which is used by the National Weather Service (NWS) to estimate the potential property damage and flooding expected along the coast from a hurricane landfall. The scale is a 1 to 5 rating based on the hurricane’s 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 an increased recognition of the fact that wind speed, storm surge, and inland rainfall are not necessarily related. There is growing interest in classifying hurricanes by separate scales according to the risks associated with each of these threats.

In terms of wind interaction with buildings, hurricanes create both positive and negative (i.e., suction) pressures. A particular building should have sufficient strength to resist both the applied wind loads and windborne missile impact loads in order to prevent wind-induced building failure or damage. The magnitude of the pressure is a function of many factors, such as the wind speed, exposure, topography, and building height and shape.

Typhoons affect the Pacific Islands (e.g., 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 publication, the guidance provided for hurricanes applies to areas threatened by typhoons.

CROSS-REFERENCE

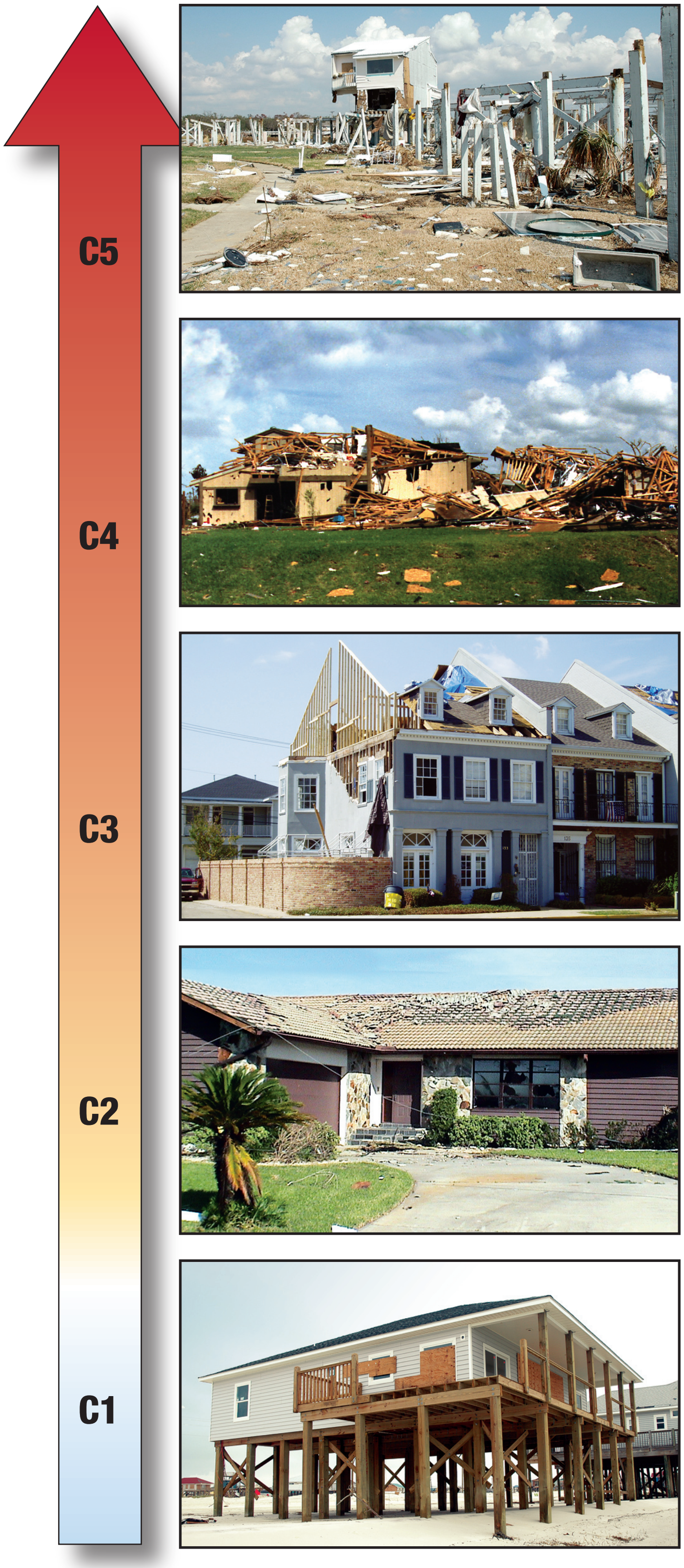
Section 6.6 presents detailed information about continuous load paths. A continuous load path is required in a safe room in order for it to resist the wind and wind pressures described in this section.

4.3 Effects of Extreme-Wind 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, especially if that building was not designed to modern, hazard-resistant building codes. 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 ultimate-wind loading conditions. These loads should be transferred in an identifiable path from the building exterior or, in case of envelope breach, interior surfaces to the structural system and through the foundations into the ground. If a building is constructed with such a path (called 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 and wind pressures acting on buildings. The importance of a continuous load path within a building or structure is discussed in Chapter 6.

CROSS-REFERENCE

The design wind speed for a safe room designed to the criteria set forth in this publication is selected from either Figure 3-1 or Figure 3-2, depending upon the hazard or combined hazards. If the safe room is being designed as a combined hazard safe room, the highest wind speed should be selected for the proposed location on each map.



Catastrophic: Roof damage is considerable and widespread, window and door damage is severe, there are extensive glass failures, some complete buildings fail.

Extreme: Extensive damage is done to roofs, windows, and doors; roof systems on small buildings completely fail; some curtain walls fail.

Extensive: Large trees are toppled, some structural damage is done to roofs, mobile homes are destroyed, structural damage is done to small homes and utility buildings.

Moderate: Some trees are toppled, some roof coverings are damaged, major damage is done to mobile homes.

Minimal: Damage is done primarily to shrubbery and trees, unanchored mobile homes are damaged, some signs are damaged, no real damage is done to structures.

Figure 4-2. Typical hurricane damage

4.3.1 Effects of Tornado and Hurricane Wind Forces

Damage to buildings from tornadoes and hurricanes can occur as a result of three types of forces:

- Forces induced by changes in atmospheric pressure (for tornadoes only)
- Wind-induced forces
- Forces induced by debris impact

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 6.3.1).

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 6 for design guidance regarding the effects of APC.

Forces from tornadic and hurricane winds are discussed in the next few sections and guidance on the calculation of these forces is provided in Chapter 6. Forces due to debris impact are discussed later in this chapter and guidance on the evaluation of how to address these forces is provided in Chapter 7.

4.3.2 Forces Generated by the Safe Room Design Wind Speed

The design wind speed for construction of a community safe room should be determined from Figures 3-1 or 3-2 for tornado and hurricane hazards, respectively. When calculating the wind pressures based on the safe room 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 safe room. The designer should also consider that the collapse of the non-safe room parts of the building may or may not impart additional loads on the safe room and verify that the safe room is designed for these additional loads.

The design wind speed is used to predict forces on both the main wind force resisting system and on the exterior surfaces of the buildings – components and cladding. The MWFRS is the structural system of the building or safe room that works to transfer wind loads to the ground and includes structural members such as roof systems (including diaphragms), frames, cross bracing, and load-bearing 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 building 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) either because of wind pressure or windborne debris impact, 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. Further, some or all of the occupants within the safe room would become exposed to wind and windborne debris impact hazards.

Extreme winds associated with tornadoes and hurricanes are capable of imposing large lateral (horizontal) and uplift (vertical) forces on buildings. The strength of the building's structural frame, connections, and envelope determines 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 (abrupt changes in land surface elevations can create a wind speedup effect), and the configuration of the building (roof geometry and building shape).

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 extreme winds because they have fewer sharp corners and 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

(roofs angled to the horizontal at 30 degrees or more) usually perform better than flat roofs because uplift on the windward roof slopes is either reduced or eliminated.

Figure 4-3 illustrates the effects of roof geometry on wind loads. Notice that the roof with the 3-foot parapet around the edges does not have elevated roof pressures at the corners. By comparison, the flat roof without parapet has corner roof wind loads more than 1.5 times the edge pressures of the roof with parapet. Also, the gable-end and hip roofs 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, 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 build up inside, which, in conjunction with negative external pressures, can "blow the building apart." Figure 4-4 depicts the forces that act on a structure when an opening exists in the windward wall.

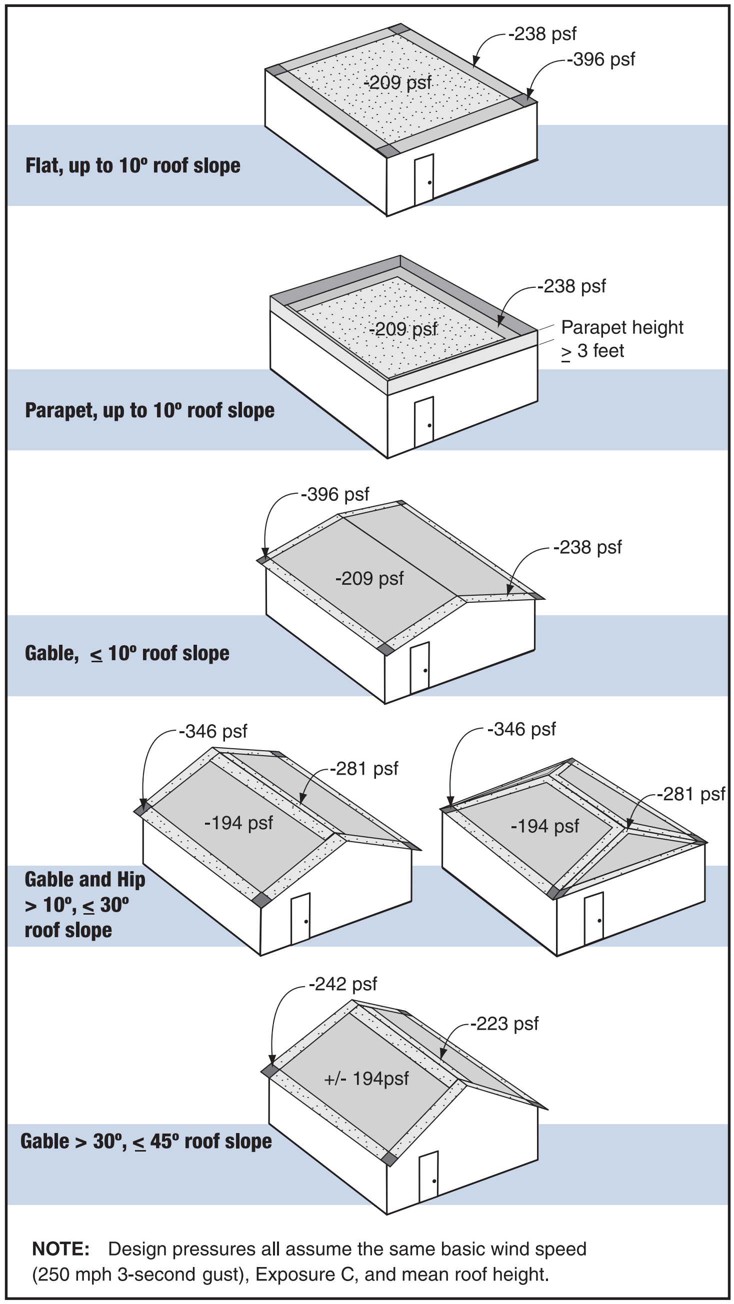


Figure 4-3. Calculated pressures (based on ASCE 7-05 C&C equations) acting on a typical safe room. This figure illustrates the different roof pressures that result for the same building and wind speed as the roof shape is varied. For the calculation of the loads from these pressures, the safe room was 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.

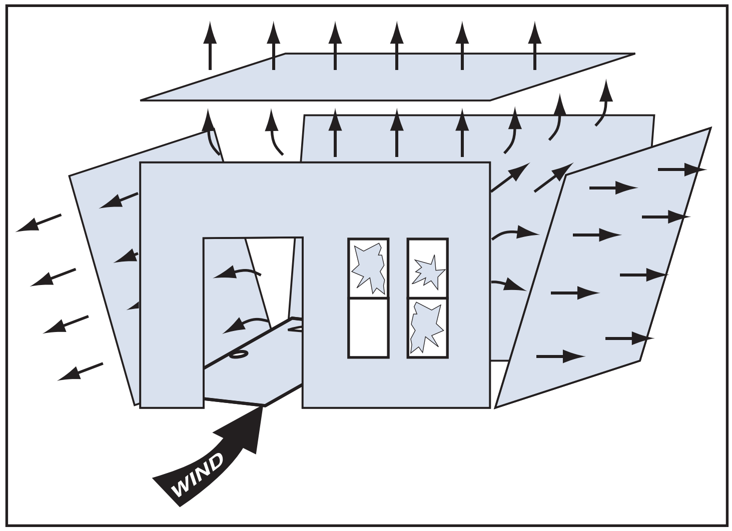


Figure 4-4. Internal pressurization and resulting building failure due to design winds entering an opening in the windward wall

The magnitude of internal pressures depends on whether the building is "enclosed," "partially enclosed," or "open" as defined by ASCE 7-05. The internal pressures in a building are increased when a building changes from an "enclosed" to a "partially enclosed" building (e.g., when a building envelope is breached). The design criteria presented in Chapter 3 (and discussed in detail in Chapters 5, 6, and 7) state that safe room designs to provide occupants with life-safety protection be based on the partially enclosed internal pressures or on enclosure classifications outlined in the ICC-500, Chapter 3. The walls and the roof of the safe room 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 a conservative approach because of the life-safety issues involved in safe room design.

4.3.3 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 6 of this publication and Section 6 of ASCE 7-05 provide information on calculating the direction and magnitude of the wind forces acting on a building once the design wind speed and types of openings in the building envelope have been determined.

Building failures can be independently categorized by one or a combination of the four failure modes illustrated in Figure 4-5. Winds moving around a building or structure may cause sliding, overturning, racking, and component failures. 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 extreme-wind events (and typically a contributing factor 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.

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. The beginning of this chapter identified the concept that, under extreme-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 loads may cause a partial failure or propagate into a total failure of the primary structural system. Uplift or downward forces (depending on roof pitch and wind direction) may act upon the roof of the building and cause overturning, racking, or failure of components.

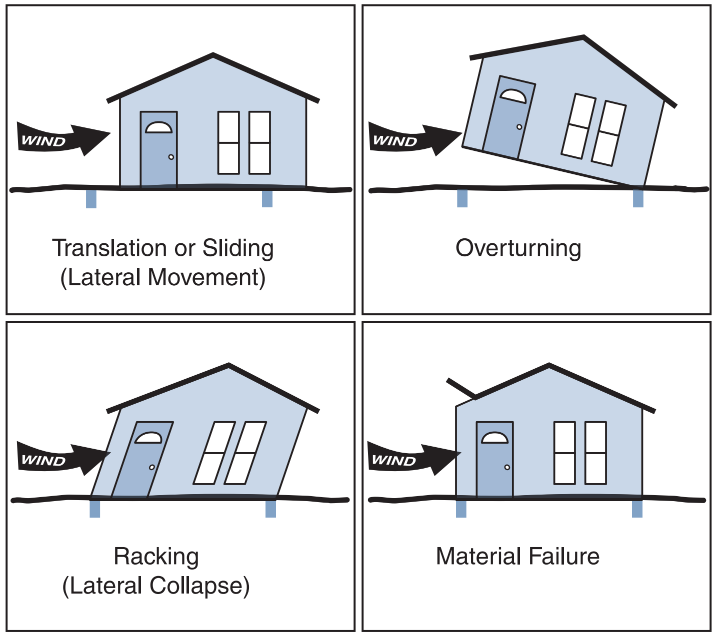


Figure 4-5. Forces on a building due to wind moving around the structure

4.3.4 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 safe rooms for cyclic loads is not required.

Hurricane winds typically affect a site for a much longer period of time, which 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 are precipitated under such 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 ICC-500, Chapter 8 (Protocols for Testing) for shelters and 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 more likely to resist hurricane cyclic loads.

4.3.5 Windborne Debris and the Selection of the Representative Missile

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 actual size, mass, and speed of missiles in tornadoes or hurricanes vary widely by storm type and event. Only a few direct measurements of debris velocity have been made; such measurements require the use of photogrammetric techniques to analyze videos of tornadoes that contain identifiable debris. For this reason, the choice of the missile, the impact of which a safe room should withstand, is somewhat subjective and relies upon the selection of a "representative" missile traveling at an assumed speed related to the safe room design wind speed. Tornadic winds tend to lift and accelerate debris (missiles) consisting of roof gravel, sheet metal, tree branches, broken building components, and other items. Large debris, such as cars, tends to tumble along the ground. The impact of this debris can cause significant damage to wall and roof components. The speed at which the representative missile travels is a function of the shelter design wind speed and was presented in Section 3.3.2.

2x6 missile penetrating a refrigerator, Midwest tornadoes of May 3, 1999

A plywood missile lodged in a palm tree, Hurricane Andrew

From over 38 years of post-disaster investigations after tornadoes and hurricanes, the WISE Research Center at TTU concluded that the missile most likely to perforate building components during a hurricane event is a 2x4 wood member, weighing up to 15 pounds. Other, larger airborne missiles do occur; for example, 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 resistance to the impact of a 15-lb 2x4 missile was a reasonable criterion for tornado safe room design.

The ICC-500 Shelter Standard Committee worked to define the appropriate representative missile and speed for hurricane hazards although the data and research on windborne debris associated with both hurricanes and tornadoes are limited at best. As a result, little data are available from the field, wind tunnel tests, or empirical studies to discuss this topic in detail. The committee concluded that, based on construction in coastal areas, it was appropriate that the representative, large missile need not be larger than the 9-lb 2x4 board member. However, a notable point is that the FEMA safe room publications review committee examined the ICC-500 proposed debris impact criteria and testing methods and supporting data, and ended with a different determination as to the appropriate speed at which the representative missile travels during a hurricane. As a result, the FEMA criteria will utilize the same 9-lb 2x4 board member as the large, representative missile, but will test the impact resistance of a safe room at a higher speed than the ICC-500. The speed at which the representative missile travels is a function of the shelter design wind speed and was presented in Section 3.3.2. More detail on this topic is provided in Chapter 7.

CROSS-REFERENCE

Chapter 7 presents additional information about cyclic loading for missile impact protection and for code compliance in specific regions of the country.

4.4 Multi-Hazard Considerations

Most safe rooms are built with a single purpose in mind: to protect the local population against the dangers inherent to extreme-wind events. This singular objective, however, should not divert the designers' and local decision-makers' attention from the all too real presence of other hazards, both natural and manmade. For this reason, designers and local officials alike should adopt a multi-hazard approach from the very beginning of their safe room deliberations. Multi-hazard approach to building design has gained prominence and the support of FEMA and other government agencies and professional associations that have long promoted this approach. This is not only because a multi-hazard approach ensures a comprehensive risk analysis and appropriate mitigation responses, but because it is able to optimize building design and produce the most cost-effective design solutions over a life-cycle of a building.

4.4.1 Multi-Hazard Risk Assessment

Once it is established that extreme winds represent a sufficient threat to the community, it is recommended that a multi-hazard approach be used in assessing the multitude of risks. The potential adverse effects of other hazards on the functionality of safe rooms should be identified, evaluated, and documented. The final risk analysis should include these multi-hazard considerations in order to produce as comprehensive a list of design requirements as possible.

4.4.2 Multi-Hazard Design

Multi-hazard design (i.e., the design of buildings that may be exposed to more than one hazard) can be both an advantage and a disadvantage for the designer. This is because, on the one hand, two or more hazards may pose design requirements that reinforce each other, thus reducing costs and improving protection. On the other hand, design requirements for some hazards may be conflicting, thereby making them extremely difficult to reconcile. Many recommended features of wind-resistant design, for example, are detrimental for earthquake-resistant design and vice versa. In such circumstances, it is extremely important to conduct a careful risk analysis and identify all design constraints and prioritize all design parameters.

4.4.3 Flood Hazards

The designer should investigate all sources of flooding that could affect the use of the safe room. It should be remembered that the functionality of the safe room can be affected by flooding in many different ways. The building itself may be under water or surrounded by water, but it can also be affected indirectly when access to the safe room is disrupted or blocked as a result of flooding in the area.

The sources of flooding include floods up to and including the 500-year flood, any flood of record, flooding from storm surge (in coastal areas), and flooding from local drainage. If it is not possible to locate a community safe room on a site outside an area subject to the flooding defined in the hazard design criteria provided in Chapter 3, special precautions should be taken to ensure the safety and well-being of anyone using the safe room. The lowest floor of the safe room should be elevated above the flood elevation from any of the flooding sources described. All utilities or services provided to the safe room should be protected from flooding as well. Additionally, the planning and design of the proposed safe room should be conducted according to the 8-step process mandated by the Executive Order 11988, Floodplain Management.

A safe room in a flood-prone area should be properly equipped to meet any emergency medical, food, and sanitation needs during the time the occupants could be isolated by flooding. Access to the safe room should be maintained during flooding conditions. If access is not possible by ground transportation during flooding, alternative access should be provided. An example of how alternative access can be achieved is the installation of a helicopter pad that is above the flood levels. In all cases, both the designer and the owner will need to work with local and state emergency managers to ensure that these special requirements are met, both in the safe room design and construction and in emergency operation procedures.

For residential safe rooms, the design criteria are more stringent than for the community safe rooms (and also when compared to the ICC-500). Residential safe rooms cannot be placed in any area that may be affected or inundated by coastal storm surge for any category hurricane. Potential safe room owners should be aware that flood design criteria for residential safe rooms is provided to guide the appropriate design and construction of safe rooms that may be exposed to these hazards.

Whether constructing a community or residential safe room, the safe room developer should remember that FEMA provides policy statements and guidance separate from the design criteria in this publication for both wind and flood hazards associated with extreme-wind shelter projects. The FEMA HMA Safe Room Policy, and associated guidance, should be consulted for the latest information from FEMA regarding implementation of safe room design criteria and how much of the design criteria may be eligible for federal funding.

4.4.4 Seismic Hazards

When a safe room is in a seismically active area as defined by the IBC, ASCE 7-05, or FEMA's National Earthquake Hazards Reduction Program (NEHRP) provisions, a seismic risk assessment of the structure should be conducted. New facilities will also require the assessment of risks for the selected site conditions. Seismic design requirements should be reviewed for compatibility with other design parameters and prioritized according to the design program.

As mentioned earlier, wind and earthquake (seismic) loads differ in the mechanics of loading (i.e., the way the load is applied). In a wind event, the load is applied to the exterior of the envelope of the structure. Typically, internal building elements that are not part of the MWFRS of the building will not receive loads unless there is a breach of the building envelope. Earthquakes induce loads based on force acceleration relationships. These relationships require that all objects of mass develop loads. Therefore, all structural elements and all non-structural components within, and attached to, the structure will be loaded. As a result, seismic loading requires both exterior building elements and internal building elements (including non-load-bearing elements and fixtures) to be designed for the seismically-induced forces.

Another important seismic consideration for the designer is the assumed response of the structure during an event. Buildings are designed to remain elastic during a wind event – elastic in the sense that no permanent deformation of any of the structural members will occur. For earthquakes, this is not the case. Design for earthquakes is based on a two-earthquake scenario. The first earthquake is the common earthquake that can occur many times in the life of a structure and the second is the larger, rare earthquake. The design process requires that the structure remain elastic for the common earthquake. But, for the rare earthquake, permanent deformation is allowed as long as it does not result in structural collapse of the building. Building elements that can "stretch and bend" give a structure the ability to withstand a large earthquake without the economic penalty of having to accommodate the rare earthquake without any permanent deformation.

Design Methods

After earthquakes in the 1920s and 1930s in California, engineers began to recognize the need to account for the lateral seismic-induced loads on structures. The first seismic codes calculated lateral seismic-induced loads using a percentage of the weight of the structure. This allowed common analysis procedures to be used. This method has been retained and is seen in today's building codes. It is commonly called the equivalent static force method. Over the years, this percentage coefficient has been refined and put on a more rational basis derived from the dynamic analysis of structures.

There are cases in which a more complicated dynamic analysis procedure is required. This dynamic analysis is common in the design and construction of very tall, irregular structures. The structures are considered irregular if they are not cube-like or do not have a rectangular footprint. They may have wings or appendages like an "L" or they may be "cross-shaped" structures. Figure 4-6 shows examples of buildings with regular and irregular shapes.

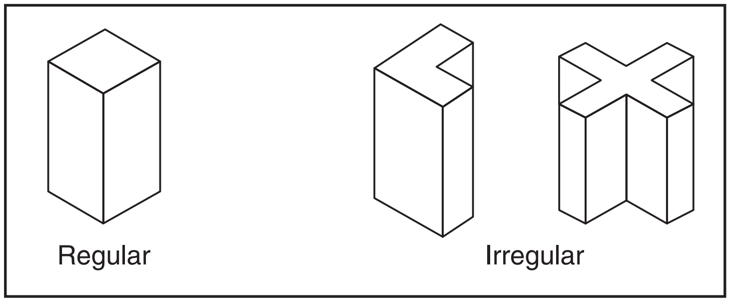


Figure 4-6. Examples of buildings with regular and irregular shapes

The dynamic analysis procedure for these types of structures consists of three parts:

1. A time history analysis is conducted.
2. A response spectrum is developed.
3. A modal analysis of the final structure is performed.

Unless a seismic event has occurred and is documented at the exact building site, some sort of computed ground movement should be developed. This can be done in several ways. One is to use the existing earthquake records and average several of them to produce a composite ground motion. Figure 4-7 is an actual graphical representation of a time response of the ground during a seismic event.

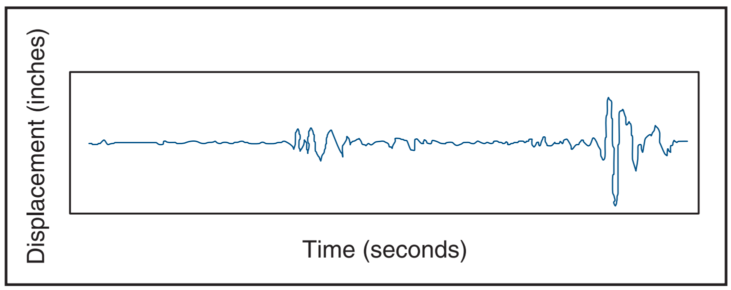


Figure 4-7. Time response of ground during a seismic event

Another way is to synthetically generate this motion using models of geologic phenomena and soil conditions. In either case, the result is a description of the movement and acceleration of the ground. Once this acceleration is defined, the acceleration is used as input in a single-degree-of-freedom system, illustrated in Figure 4-8. The single-degree-of-freedom system is a model of the building system with mass from floors and roof systems consolidated together to represent the building as a mass (M) supported by vertical building elements, with stiffness (k), acted upon by a lateral force (F) representative of the ground acceleration.

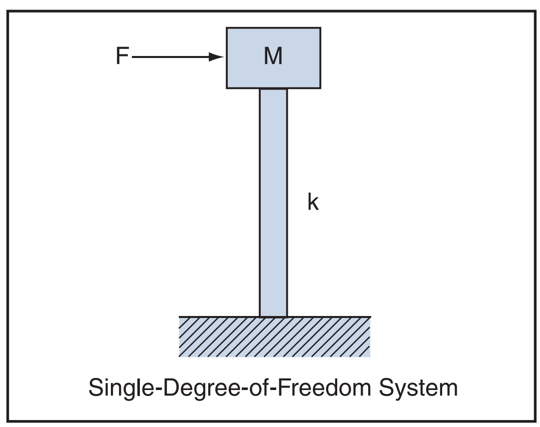


Figure 4-8. Example of a single-degree-of-freedom system

The stiffness (k) of the system can be varied to change the period of the building response to the applied lateral force. When this is done, a plot is made of the acceleration versus the period of the structure (see Figure 4-9). This type of plot is known as a Response Spectrum for the induced earthquake motion and illustrates the elastic structural system response to a particular earthquake motion.

The last step in the dynamic analysis is to perform a modal analysis on the actual building. This type of analysis provides the motion of the building in terms of a single-degree-of-freedom system. Therefore, the response spectrum can be input into the modal analysis to give the building's response to the earthquake.

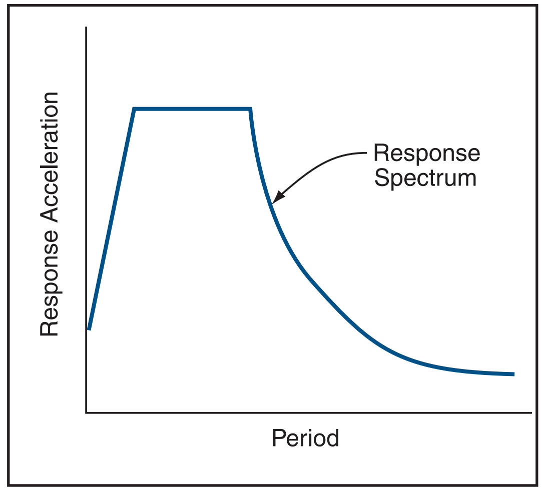


Figure 4-9. Acceleration vs. period of structure

Both the static method and the dynamic method determine the lateral forces acting on the structure. The geographic region of the country in which the safe room is located will dictate which analysis should be used. Once the forces are calculated, they can be input into the load combinations (as seismic load E) used for the design of the safe room.

Code Development

Earthquake codes are under continual refinement as new data become available. This continual refinement attempts to give more accurate models of how a structure responds to ground motion. Seismic events, like wind events, are constantly occurring and continue to test buildings constructed to recently improved codes and standards. An earthquake provides a test for the current procedures; after every event, those procedures are reviewed to ensure they are acting as intended.

An example of code development is the recent acknowledgment that seismic events occurring on the west and east coasts are not expected to be the same type of seismic event. On the west coast, the difference between the common earthquake and the rare earthquake is small. Design codes assume that the rare earthquake is only 50 percent larger than the common earthquake. On the east coast, this is not the case. In this region, the rare earthquake can be as much as 400 percent larger than the common earthquake. Therefore, prior to the release of the 2000 IBC, western U.S. design codes did not fit well to eastern U.S. earthquake requirements.

This poor fit has led to refinements in seismic design procedures. The new procedures attempt to provide a process for evaluating the response of a building when it begins to deform from seismic loads. This approach is needed to ensure that the structure can stretch and bend to resist the rare earthquake. In the western U.S., this is ensured because of the minimal difference between the two different earthquakes; however, this cannot also be assumed in the eastern U.S.

Other Design Considerations

All the elements of the structure should be evaluated for earthquake forces. Not only are the exterior walls loaded, but the interior walls can also receive substantial out-of-place loads. For wind loading, these interior building components are not usually considered, although most codes require interior walls to be designed for some lateral pressures. Seismically-induced forces may be larger than the code-specified lateral wind pressures and, as a result, govern the design in seismically active areas. For areas that may have both wind and seismic activity, the careful evaluation of which forces may govern the design is an important step in the design process. Therefore, the design of these elements and their connections to the main structure are essential to a complete design – one in which both structural and non-structural elements are considered.

Earthquake requirements considered in the design of a safe room can enhance the lateral resistance of the structure to wind loads. For example, seismic loads tend to govern the designs of "heavy" structures constructed with concrete or masonry walls and concrete slab or roofs. In "lighter" structures constructed from framing and light structural systems supporting lightweight (metal or wood) roof systems, wind loads tend to govern. But even if wind loads govern, consideration should be given to the calculated seismic loads to allow the structure to deform without immediate failure. This ability gives the structure reserve capacity that can be useful in extreme-wind events.

Earthquake requirements will also govern the design of all interior non-structural building components, fixtures, and equipment. For exterior-mounted equipment, both seismic and wind loads must be considered, as either may govern the design of the exterior component.

4.5 Other Hazards

It is important that the designer consider other hazards at the building site, in addition to the wind, flood, and seismic hazards already mentioned. One such consideration is the location of a safe room on a building site with possible physical hazards (e.g., other building collapses or heavy falling debris). These siting and location issues are discussed in Chapter 5.

Another consideration is the presence of a hazardous material (HAZMAT) on a site. Older buildings that are retrofitted for safe room use should be inspected for hazardous materials that may be stored near the safe room (e.g., gasoline, chlorine, or other chemicals) or that may have been used in the construction of the surrounding building (e.g., lead paint or asbestos). For example, asbestos may become airborne if portions of the surrounding building are damaged, resulting in the chemical contamination of breathable air. Live power lines, fire, and gas leaks are also safe room design concerns that may need to be addressed at some safe room sites. For example, the case study in Appendix D (Sheet P-1) shows how a gas line, required for gas service to the safe room area when in normal daily use, was fitted with an automatic shutoff valve. This precaution greatly reduces the risk of a gas-induced fire occurring while the safe room is occupied.

4.6 Fire Protection and Life Safety

The safe room should comply with the fire protection and life-safety requirements of the model building code, the state code, or the local code governing construction in the jurisdiction where the safe room is constructed. For single-use extreme-wind safe rooms, the model building codes, life-safety codes, and engineering standards do not indicate square footage requirements or occupancy classifications. For multi-use extreme-wind safe rooms, the codes and standards address occupancy classifications and square footage requirements for the normal use of the safe room. The designer is advised to comply with all fire and life-safety code requirements for the safe room occupant load and not the normal use load; the safe room occupancy load is typically the controlling occupancy load. Chapter 3 presented the recommended square footage requirements for tornado and hurricane safe rooms.

Guidance and requirements concerning fire protection systems may be found in the model building codes and the life-safety codes. Depending on the occupancy classification of the safe room (in normal use), automatic sprinkler systems may or may not be required. For many safe rooms, an automatic sprinkler system will not be required. However, when automatic sprinkler systems are not required and fire extinguishers are used, all extinguishers should be mounted on the surface of the safe room wall. In no case should a fire extinguisher cabinet or enclosure be recessed into the interior face of the exterior wall of the safe room. This requirement is necessary to ensure that the integrity of the safe room walls is not compromised by the installation of fire extinguishers. Finally, any fire suppression system specified for use within safe rooms should be appropriate for use in an enclosed environment with human occupancy. If a fire occurs during a tornado or hurricane, it may not be possible for occupants of the safe room to ventilate the building immediately after the discharge of the fire suppression system.