

PROCEEDINGS

# RCI INTERNATIONAL CONVENTION AND TRADE SHOW

## WIND PRESSURES ON LOW-SLOPE ROOFS: ASCE 7-16 STANDARD AND FOURTH EDITION OF RCIF MONOGRAPH

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## ABSTRACT

The standard published by the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI), titled *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, is used for designing building structures and their components. The standard is revised periodically. Its latest revision, which was scheduled for publication in 2016, became available in 2017 and is known as ASCE/SEI 7-16. The next edition of the monograph is scheduled for 2022.

ASCE/SEI 7-16 contains a number of revisions in the wind load chapters of the standard. This presentation examines these revisions and how they impact low-slope roof assembly design in resisting wind uplift. It also describes wind uplift design of roof assemblies in accordance with ASCE 7-16, with several illustrative examples.

As the fourth edition of the RCIF monograph *Wind Pressures on Low-Slope Roofs*, which is keyed to ASCE/SEI 7-16, has just been published and is available for purchase, this presentation addresses the topics covered in the monograph, with particular focus on the fundamentals of wind uplift on low-slope roofs. The use of wind pressure tables included in the monograph, which allow the selection of wind pressure values without detailed calculations and converting them to FM Global wind uplift ratings, is explained. The paper examines the use of ultimate strength design-safety provisions in wind uplift design of roof assemblies in place of the commonly used allowable stress design provision.

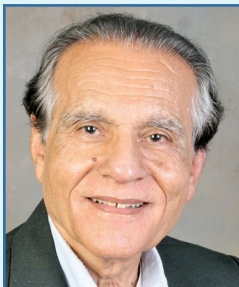
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# WIND PRESSURES ON LOW-SLOPE ROOFS: ASCE 7-16 STANDARD AND FOURTH EDITION OF RCIF MONOGRAPH

The standard published by the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE), titled *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, is used for designing buildings and other structures. The standard is revised periodically to keep abreast of the developments in this important field because the determination of loads on a building is fundamental to ensuring the building's safety and performance.

Various editions of this standard, designated as the ASCE/SEI 7 standard (but commonly known as ASCE 7) are distinguished from each other by a two-digit number at the end of each designation, which refers to the year of the standard's revision. For example, ASCE 7-98 standard implies that it was revised in 1998. Similarly, ASCE 7-10 implies the standard's revision occurred in 2010.

The current edition of the standard was released in March 2017 but is designated as ASCE 7-16 standard because the target year for its release was 2016. The revision immediately preceding 2016 was in 2010, called ASCE 7-10 standard. The next revision of the standard is targeted for 2022, to be known as ASCE 7-22 standard.

An ASCE 7 standard is a comprehensive document that deals with all types of loads, such as dead loads, live loads, rain loads, snow loads, wind loads, seismic loads, and so on. Its revision is accomplished through a transparent, consensus-based process by a group of ASCE 7 committees, where each committee is composed of experts and stakeholders for a particular load type. The most important part of the ASCE 7-16 standard of interest to roofing professionals is that related to wind pressures on roofs. This part is covered in the wind load chapters of the standard.

## ROOFING ASSEMBLY AS PART OF COMPONENTS AND CLADDING (C&C) IN ASCE 7 STANDARD

In dealing with wind pressures on buildings, it is important to distinguish between wind pressures on individual building com-

ponents and the building as a whole. A building is an assemblage of its components that are connected together with nails, screws, bolts, welds, adhesives, and so on. For safety and performance reasons, each component must have the necessary strength to resist the design wind pressure.

In addition to each component having sufficient strength, the building as a whole must also be adequately strong to resist wind loads. Even if all components of the building are strong against wind, the building as a whole may not be. For example, wind may cause a building to become skewed in shape (rack), slide, or overturn as a whole, without causing any or major failure of its components.

The wind resistance of a building as a whole is provided by the structural interaction between its vertical and horizontal assemblies (walls, structural frame, floor, and roof diaphragms) that work collectively as a system to provide the required strength and stability to the building while transferring all loads to the ground. ASCE 7 standard refers to this structural system as the main wind-force resisting system (MWFRS).

The elements of the building that receive wind pressure directly and transfer it to MWFRS, such as roof deck, insulation, cover board, fasteners, adhesive beads, etc., are referred to as components and cladding (C&C). Note that some elements, though loaded individually as C&C, can also be part of MWFRS, if they are part of a vertical or horizontal diaphragm, such as the roof deck or roof joists as part of the roof diaphragm.

The two of the six chapters in the wind load section of ASCE 7 relevant to wind-resistant roofing design are Chapter 26 (General Wind Load Requirements) and Chapter 30 (Wind Loads on Components and Cladding). Chapters 27 to 29 deal with MWFRS, and Chapter 31 with wind tunnel testing.

## WHAT THIS PAPER ADDRESSES AND ITS TWO-PART FORMAT

The foregoing discussion briefly underlines that although a roof assembly is a small part of a building as a whole,

the determination of wind pressures on it requires an understanding of wind-building interaction in addition to some grasp of the structural engineering fundamentals. In fact, a flip through wind load chapters of ASCE 7-16 reveals how complex the subject is, as it deals with such unwieldy topics as the statistical aspects of extreme wind speeds, atmospheric boundary layers, ground roughness, the building's exposure classification, building envelope types, local topography, building geometry, and so on.

**Part One:** The complexity just stated is aggravated by periodic revisions of the standard. Therefore, the first part of this paper presents various revisions made in ASCE 7-16 over its previous (ASCE 7-10) version that relate specifically to low-slope roofs. This part also summarizes the possible impact of these revisions on the current design and construction practices for low-slope roofs.

**Part Two:** The second part of this paper introduces the fourth edition of the monograph, titled *Wind Pressures on Low-Slope Roofs* published by the RCI Foundation (RCIF). This edition of the monograph is keyed to the ASCE 7-16 version and, hence, it includes all the revisions mentioned in Part One and illustrates their application with several numerical examples.

## PART ONE: CHANGES IN ASCE 7-16 FOR LOW-SLOPE ROOFS

One of the major revisions incorporated in wind load chapters of ASCE 7-10 was to reorganize them in six chapters (Chapters 26 to 31) in place of the one-chapter organization in ASCE 7-05 and the standard's prior versions.<sup>1,2</sup> The multiple-chapter organization substantially improved the clarity and accessibility of the provisions. The six-chapter organization of ASCE 7-10 has been retained in ASCE 7-16.<sup>3</sup> However, while the standard's provisions and the commentary were bound in a single volume in ASCE 7-10, they have been separated into two separate volumes in ASCE 7-16. This separation allows simultaneous reading of the provisions and commentary for those using the standard's print version, further improving

its accessibility. The digital version of the standard, through its website, which can be found at [asce7.online](http://asce7.online), includes several other useful features.

Another helpful (formatting) change in ASCE 7-16 relates to transferring the velocity pressure equation and velocity pressure exposure classifications in one chapter (Chapter 26) in place of duplicating the information in four other chapters (Chapters 27 to 30). The changes (from ASCE 7-10 to ASCE 7-16) that impact wind pressures on low-slope roofs are described in the following sections.

### 1. Ground Elevation Factor New to ASCE 7-16

The wind pressure on building surfaces is due to the kinetic energy contained in moving air, which is a function of wind speed and the density of air. The density of air, assumed in ASCE 7-10 and all its previous versions, is the one for air at standard temperature and pressure (15°C at mean sea level). The constant (0.00256) in velocity pressure equation is based on air density at sea level. The reduction in air density at higher elevations (and the resulting lower wind pressure) was ignored in all previous versions of ASCE 7.

This fact has been recognized in ASCE 7-16, and a new factor, called ground elevation factor (symbolized by  $K_e$ ) has been introduced in ASCE 7-16. The factor  $K_e$  modifies the constant 0.00256 so that ASCE 7-16 velocity pressure equation is shown in Equation 1.

$$q_z = 0.00256 K_e K_d K_z K_{zt} (V^2)$$

#### Equation 1

Where:

$q_z$  = velocity pressure at height  $z$  above ground in psf;

$K_e$  = ground elevation factor;

$K_d$  = wind directionality factor;

$K_z$  = height and site exposure factor;

$K_{zt}$  is the topography factor; and

$V$  = basic wind speed for the site in mph.

ASCE 7-16 gives a simple equation for  $K_e$  as a function of elevation above sea level, shown in Table 1.<sup>4</sup>

For determining pressures on a low-slope roof,  $q_z$  in Equation 1 is replaced by  $q_h$ , where  $h$  = eave height of roof (ASCE 7-16 allows setting  $h$  = eave height of roof if roof slope  $\leq 10^\circ$ , i.e.,  $\leq 2.1:12$ ). See Equation 2.

$$q_h = 0.00256 K_e K_d K_h K_{zt} (V^2)$$

#### Equation 2

With the use of a ground elevation factor, wind pressures on buildings at high altitudes will be lower than those used previously. For example, for Santa Fe, New Mexico (altitude of 7200 ft.),  $K_e = 0.77$ , giving a reduction in wind pressures of approximately 23% from that of ASCE 7-10.

As Table 1 shows, the reduction in wind pressures at higher elevations is fairly gradual, which may be ignored for elevations up to 1000 ft. or so. In fact, ASCE 7-16 permits setting  $K_e = 1.0$  for all elevations.

### 2. Clarification on Wind Directionality Factor in ASCE 7-16

ASCE 7-16 provides an important clarification with respect to the wind directionality factor. Although the value of wind directionality factor,  $K_d$ , for components and cladding (to which low-slope roofing belongs) is mentioned as 0.85 in ASCE 7-10, Table 26.6-1, the note under the table confused the issue. This note reads “Directionality Factor  $K_d$  has been calibrated with combination of loads specified in Chapter 2. This factor shall only be applied when used in conjunction with load combinations specified in Sections 2.3 and 2.4.”

With this note in the table,<sup>5</sup> it was not clear whether  $K_d$  can be assumed as 0.85 when combining positive wind pressures on low-slope roofs with other loads, such as rain and snow loads. Consequently, in some literature related to wind pressures on roofs, the effect of wind directionality was ignored; i.e.,  $K_d = 1.0$  was assumed. The stated note has been deleted in the corresponding table in ASCE 7-16, clarifying that the value of  $K_d = 0.85$  for buildings and components in all cases.<sup>6</sup>

### 3. An Additional Basic Wind Speed Map New to ASCE 7-16

Risk Category III and Risk Category IV, which were lumped together in ASCE 7-10 (for wind loads), have been separated in ASCE 7-16. This change recognizes the more widespread consequence of failure of Risk Category IV structures as compared

with that of Risk Category III structures from extreme wind events. Therefore, ASCE 7-16 has four different basic wind speeds for a location, in contrast with three basic wind speeds for a location in ASCE 7-10.

Risk Category III is defined in ASCE 7 as buildings whose failure could cause substantial risk to human life, such as occupancies with large occupant loads. Risk Category IV includes essential facilities, such as fire, ambulance, and police stations; power generating stations; emergency surgery and treatment facilities; and so on. In ASCE 7-10, the Risk Category III basic wind speed map was used for essential facilities. In ASCE 7-16, essential facilities require the use of the Risk Category IV wind speed map.

The mean return interval (MRI) for Risk Category IV in ASCE 7-16 is 3000 years.<sup>7</sup> The MRIs for Risk Category I, Risk Category II, and Risk Category III in ASCE 7-16 are the same as in ASCE 7-10 (i.e., 300 years, 700 years, and 1,700 years, respectively).

### 4. Reduction in Basic Wind Speeds for Non-Hurricane Region in ASCE 7-16

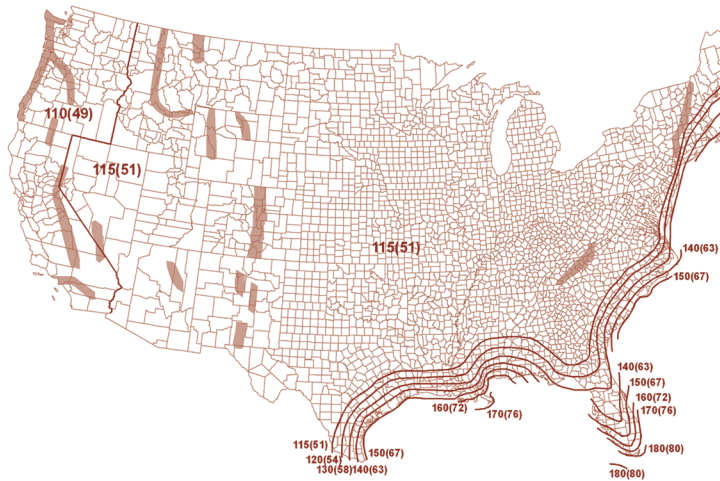
Based on new analysis of non-hurricane wind data and improvements in hurricane simulation models, the basic wind speeds for all risk categories have been revised in ASCE 7-16. In general, the basic wind speeds for non-hurricane regions in the continental United States for all risk categories are lower than those in ASCE 7-10. This fact is illustrated in Figures 1 and 2, which show basic wind speed maps (for Risk Category II) for ASCE 7-10 and ASCE 7-16, respectively.

For example, the basic wind speed for Risk Category II for Dallas, Texas, in ASCE 7-10 is 115 mph. In ASCE 7-16, the corresponding wind speed is 105 mph, reducing the velocity pressure to approximately 83% of ASCE 7-10 values—a reduc-

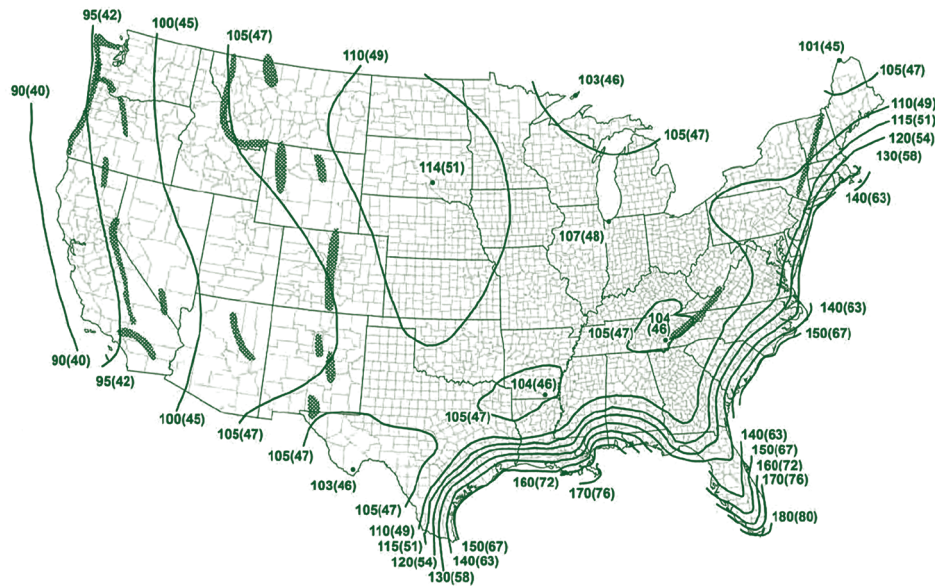
Elevation above sea level, $z$ (ft)	Ground elevation factor, $K_e$	
0	1.00	$K_e = e^{-0.0000362z}$ where $z$ = elevation above sea level (in ft)
1,000	0.96	
2,000	0.93	
3,000	0.90	
4,000	0.86	
5,000	0.83	
6,000	0.80	
10,000	0.70	

Table 1 – Ground elevation factor as a function of elevation above sea level.

**Figure 1 – ASCE 7-10 basic wind speed map for Risk Category II buildings (with permission of the American Society of Civil Engineers).**



**Figure 2 – ASCE 7-16 basic wind speed map for Risk Category II buildings (with permission of the American Society of Civil Engineers). Observe the reduction in basic wind speeds in non-hurricane regions of the continental United States as compared with those of ASCE 7-10, shown in Figure 1.**



tion of 17%. Note that  $(105/115)^2 = 0.83 = 83\%$ , as the velocity pressure is proportional to the square of wind speed.

The reduction in wind speed is more pronounced on the West Coast. Thus, while the ASCE 7-10 basic wind speed for San Francisco, California, is 110 mph (for Risk Category II), the corresponding value for ASCE 7-16 is 92 mph. Because  $(92/110)^2 = 0.7$ , it gives a reduction in velocity pressure of approximately 30%.

For many situations, the reduction in non-hurricane wind speeds in ASCE 7-16 has not resulted in corresponding decrease in wind pressures on low-slope roofs for buildings with roof height  $\leq 60$  ft. because of the higher values of external pressure coefficients ( $G C_p$ ) introduced in ASCE 7-16, as explained in Section 9 below.

The wind pressure values for low-slope roofs in non-hurricane regions with roof heights  $>60$  ft. have been reduced substantially in ASCE 7-16 because the  $G C_p$  values for such buildings have not changed in ASCE 7-16; i.e., they remain the same as in ASCE 7-10 (see Section 9 below).

### 5. Changes in Basic Wind Speeds for Hurricane-Prone Regions in ASCE 7-16

The definition of a hurricane-prone region in ASCE 7-16 remains the same as in ASCE 7-10; i.e., it is the region on the U.S. Atlantic Ocean and the Gulf of Mexico coasts where the basic wind speed for Risk Category II is greater than 115 mph. This region also includes the islands of Hawaii, Puerto Rico, Guam, the Virgin Islands, and Samoa. ASCE 7-16 wind speed contours in hurricane-prone regions of the continental U.S. are geometrically similar to those in ASCE 7-10, as shown in Figures 1 and 2. However, ASCE 7-16 contours have shifted

slightly outward (toward the Atlantic Ocean) for the continental U.S. for some locations. Consequently, the land mass covered by the hurricane-prone region has contracted a little.

This has resulted in a small reduction in basic wind speeds of some locations along the Atlantic Ocean as compared with those in ASCE 7-10, while for the other locations, the basic wind speeds have not changed. For example, the basic wind speed for Boston, Massachusetts, in ASCE 7-10 (Risk Category II) is 128 mph, while that in ASCE 7-16 is 120 mph. For Miami, Florida, ASCE 7-16 basic wind speed is the same as for ASCE 7-10—170 mph.

The outward shifting of hurricane wind speed contours (in some locations of the continental U.S.) has resulted in a few locations shifting from the hurricane-prone region into a non-hurricane-prone region. For example, for Tallahassee, Florida, ASCE 7-10 basic wind speed for Risk Category II

was 118 mph, which places it in the hurricane-prone region. The corresponding value for ASCE 7-16 is 114 mph, placing it in the non-hurricane-prone region.

This change has implications on the use of aggregate-surfaced roofs, as the 2018 IBC (and its previous versions) imposes a blanket ban on the use of aggregate-surfaced roofs in a hurricane-prone region.<sup>8</sup> In a non-hurricane-prone region, there is no blanket ban, but the IBC restricts the use of such roofs above a certain roof height (Figure 3).

**2018 IBC Section 1504.8: Surfacing and Ballast Materials in Hurricane-Prone Regions**  
 “For a building located in a hurricane-prone region as defined in Section 202, or any other building with a mean roof height exceeding that permitted by Table 1504.8 based on the exposure category and basic wind speed at the site, the following materials shall not be used on the roof:  
 1. Aggregate used as roof coverings.  
 2. Aggregate or gravel or stone used as ballast.”

**Figure 3 – Section 1504.8 of the 2018 International Building Code.**

## 6. Effective Basic Wind Speed Maps for the Islands of Hawaii New to ASCE 7-16

Microzoned “effective basic wind speed” maps, not provided in ASCE 7-10, have been added in ASCE 7-16 for the islands of the state of Hawaii for all four risk categories.<sup>9</sup> One such map for the island of Kauai for Risk Category II is shown in Figure 4. The effective wind speed refers to the basic wind speed modified by large-scale topographical features lying beyond 650 ft. (200 m) of the building’s location. The provision of the effective wind speed maps is a simplification that allows ignoring the large-scale topographical features because they have been accounted for in the maps. In other words, the topographic factor for such features,  $K_{zt}$ , equals 1.0. Local topography (finer-scale terrain conditions), however, must be considered to determine the corresponding value of  $K_{zt}$ .

## 7. New Website for Location-Specific ASCE 7-16 Basic Wind Speeds

ASCE has created a website that gives location-specific ASCE 7-16 basic wind speeds for all four risk categories. Referred to as the ASCE 7 Hazard Tool, it not only provides ASCE 7-16 basic wind speeds,

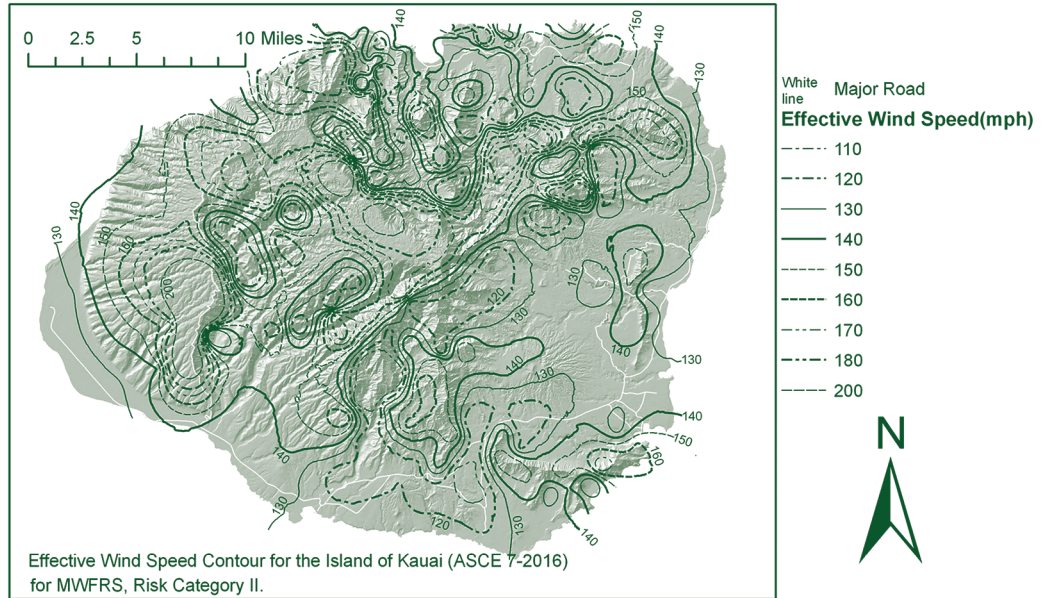


Figure 4 – ASCE 7-16 micro-zoned effective basic wind speed map (Risk Category II) for the island of Kauai in Hawaii (with permission of the American Society of Civil Engineers).

but also ASCE 7-10 basic wind speeds and other building loads-related hazard data, such as seismic acceleration, ground snow load, rain load, and so on. At the time of writing this paper, access to basic wind speed data was free of cost from this tool. Its address is <https://asce7hazardtool.online/>.

## 8. Building Enclosure Classifications Refined in ASCE 7-16

As wind strikes a building, its envelope surfaces are subjected to toward-the-surface pressure (positive pressure) or away-from-surface pressure (negative pressure; i.e., suction). For a rectangular building with a low-slope roof, the windward wall is subjected to positive pressure, while all other walls and the roof are under negative pressure (Figure 5).

As no building can be perfectly airtight (particularly under an extreme wind event), the positive pressure on the windward wall causes the air to enter the building interior through it and exit from the other walls. The infiltrating air pressurizes the building interior, causing outward pressure on the walls and uplift on the roof (Figure 6).

The magnitude of interior pressure is a function of the porosity of the walls of the building. ASCE 7 classifies buildings’ porosity under different types and refers to it as the building’s enclosure classifications. ASCE 7-10 (and the prior versions) had three enclosure classifications: (i) enclosed buildings, (ii) partially enclosed buildings, and (iii) open buildings.

The classification is based on the quantitative description of the porosity of walls. A simple-to-understand, qualitative interpretation of this description, commonly used in day-to-day practice, is given in Figure 7.

The three enclosure classifications of ASCE 7-10 did not cater to multistory parking buildings with a low-slope roof, the windward wall is subjected to positive pressure, while all other walls and the roof are under negative pressure (Figure 5). Because a “partially enclosed” building is essentially one that has large opening(s) in one wall with no (or small) openings in other walls, a multistory parking garage does not belong to this classification either.

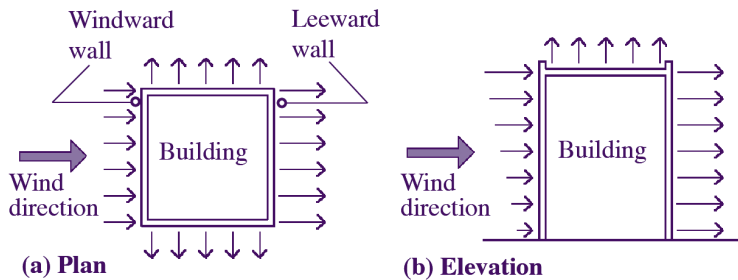


Figure 5 – Exterior pressurization of building envelope surfaces by wind.

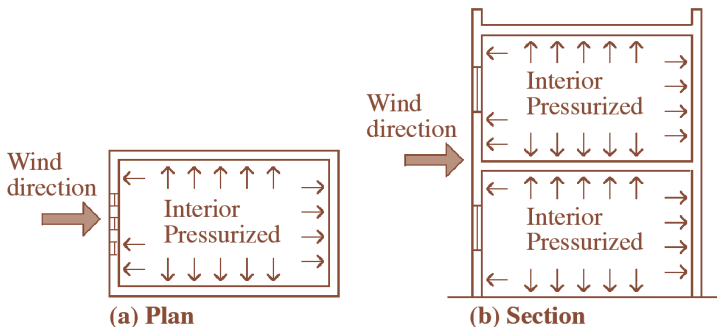


Figure 6 – Interior pressurization of building spaces by wind.

### ASCE 7-10 Enclosure Classifications

**1. Enclosed Building** has closed doors and windows; Porosity of walls is due to: gaps between walls and door and window frames, glass panes and gaskets, under door threshold, and so on. Most contemporary buildings belong here. *Interior pressurization is small.*

**2. Partially Enclosed Building** has large opening(s) in one wall with small or no openings in other walls. The air, entering through the wall with large openings, is unable to exit quickly because of small openings in other walls. Aircraft hangars and warehouses with open roll-on doors belong here. *Interior pressurization is substantial.*

**3. Open Building** has all walls that are at least 80% open. Air entering the building is able to exit quickly. *No interior pressurization.*

A building that does not meet the requirements of anyone of the three classifications is to be assigned to “enclosed” building classification.

### ASCE 7-16 Enclosure Classifications

**1. Enclosed Building:** same definition as in ASCE 7-16.

**2. Partially Enclosed Building:** same definition as in ASCE 7-16.

**3. Open Building:** same definition as in ASCE 7-16.

**4. Partially Open Building:** A building that does not meet the requirements of the above three classifications. *Level of interior pressurization is same as in an enclosed building.*

**Figure 7 – Enclosure classifications of ASCE 7-10 and ASCE 7-16.**

To overcome this deficiency, ASCE 7-16 has added a fourth enclosure classification called “partially open,” shown in *Figure 7*. The definitions of the three classifications of ASCE 7-10 (enclosed, partially enclosed, and open) have been retained in ASCE 7-16, and the “partially open” classification does not have an independent (quantitatively specified) definition. It is a default classification so that if a building does not meet the requirements of “enclosed,” “partially enclosed,” or “open” classification, it belongs to a “partially open” classification.<sup>10</sup>

In the absence of the “partially open” classification in ASCE 7-10, did a multistory parking garage not get assigned to any classification? Because the default classification in ASCE 7-10 was the “enclosed” classification, a parking garage was assigned to the “enclosed” classification.

*Figure 7* indicates that in terms of the magnitude of interior pressurization, there is no difference between the “enclosed” and “partially open” classifications. In terms of exterior pressure coefficients, the “enclosed” and “partially open” classifications are also identical. Thus, for all practical purposes, there has been no change in ASCE 7-16 with respect to enclosure classifications except that the type of enclosure classification for parking garages has been recognized as a distinct classification.

### 9. Low-Slope Roof Pressure Coefficients and Roof Zones Redefined

In determining wind pressures on low-slope roof surfaces, ASCE 7 gives the following equation (see *Equation 3*):

$$p = q_h (GC_p - GC_{pi})$$

**Equation 3**

**Where:**

$q_h$  = velocity pressure at roof height  $h$ , determined from *Equation 2*, where  $h$  = eave height.

$GC_p$  = exterior pressure coefficient, and  $GC_{pi}$  = interior pressure coefficient, representing interior pressurization.

ASCE 7-16 values for  $GC_{pi}$  are given in *Table 2*.<sup>11</sup> Note that they are the same for the “enclosed” and the “partially open” classification.

For  $GC_p$  values, ASCE 7 divides roofs into two categories based on roof height  $h$ :<sup>12</sup>

1.  $h \leq 60$  ft.
2.  $h > 60$  ft.

### No Change in Roof Zones and $GC_p$ Values for Roof Height $h > 60$ ft.

$GC_p$  values are not constant over an entire roof area but vary according to roof zone, being highest at roof corners, lower on roof perimeter, and lowest in the field-of-roof. For  $h > 60$  ft., the three roof zones (corner, perimeter, and field-of-roof) are shown in *Figure 8*.

There has been no change in the layout of roof zones or their dimensions from ASCE 7-10 to ASCE 7-16.<sup>13</sup> The beneficial effect of a parapet (3 ft. or higher) on roof pressures, which assumes pressures on corners

Enclosure classification	$GC_{pi}$
Enclosed building	0.18
Partially enclosed building	0.55
Open building	0.00
Partially open building	0.18

**Table 2 –  $GC_{pi}$  values for various enclosure classifications.**

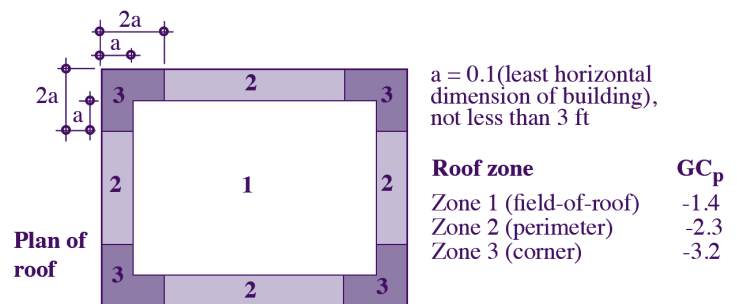
the same as the perimeter pressures, also remains unaltered in ASCE 7-16.

### Major Changes in Roof Zones and $GC_p$ Values for Roof Height $h \leq 60$ ft.

As a result of the analysis (published in 2014) of an extensive wind tunnel test data database obtained in 2005, the layout of roof zones and their dimensions has been modified substantially from ASCE 7-10 to ASCE 7-16. ASCE 7-16 can have up to four roof zones (corners, perimeter, exterior field-of-roof, and interior field-of-roof) in place of three roof zones in ASCE 7-10. The actual number of roof zones is a function of roof height and its plan dimensions, as shown in *Figures 11A* and *11B*. The dimensions (length and width) of zones are also different in ASCE 7-16.<sup>14</sup>

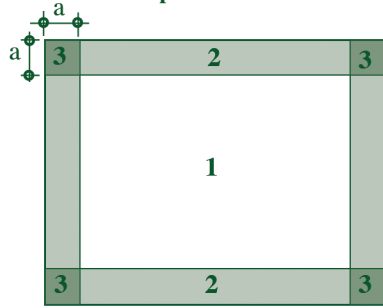
A comparison between  $GC_p$  values of ASCE 7-16 and ASCE 7-10 and the corresponding roof zone layouts (for  $h \leq 60$  ft.) is illustrated in *Figure 9*. Note that there is an increase in  $GC_p$  values in ASCE 7-16 over those of ASCE 7-10. The increase has made  $GC_p$  values (for perimeter and corner in ASCE 7-16) consistent with corresponding  $GC_p$  values for  $h > 60$  ft. For example,  $GC_p$  values for corner and perimeter in ASCE 7-16 (for  $h \leq 60$  ft.) from *Figure 9* are -2.3 and -3.2, respectively. They are exactly the same in ASCE 7-16 for  $h > 60$  ft. (shown in *Figure 8*).

**ASCE 7-16 Wind Pressure Zones on Roof and  $GC_p$  Values for  $h > 60$  ft**



**Figure 8 – Roof zones and  $GC_p$  values for roof height,  $h > 60$  ft. in ASCE 7-16 (applicable to roofs with a slope  $\leq 7^\circ$ , i.e.,  $\leq 1.5:12$ ). These have not changed from ASCE 7-10.**

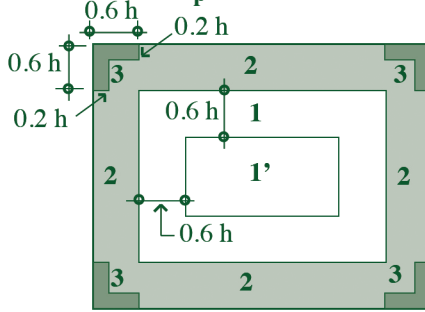
**ASCE 7-10 Wind Pressure Zones on Roof and  $GC_p$  Values for  $h \leq 60$  ft**



$a$  = smaller of  $(0.1D)$  and  $(0.4h)$  but  $a \geq (0.4D)$  and  $\geq 3$  ft  
 $D$  = least horizontal dimension of building  
 $h$  = eave height of roof

Roof zone	$GC_p$
Zone 1 (field-of-roof—interior)	-1.0
Zone 2 (perimeter)	-1.8
Zone 3 (corner)	-2.8

**ASCE 7-16 Wind Pressure Zones on Roof and  $GC_p$  Values for  $h \leq 60$  ft**



$h$  = eave height of roof

Roof zone	$GC_p$
Zone 1' (field-of-roof—interior)	-0.9
Zone 1 (field-of-roof—exterior)	-1.7
Zone 2 (perimeter)	-2.3
Zone 3 (corner)	-3.2

**Figure 9 – ASCE 7-10 and ASCE 7-16 roof zones and  $GC_p$  values for roofs ( $h \leq 60$  ft.) (applicable to roofs with a slope  $\leq 7^\circ$ , i.e.,  $\leq 1.5:12$ ).**

In ASCE 7-10,  $GC_p$  values for  $h \leq 60$  ft. (-1.8 and -2.8) were much lower than for  $h > 60$  ft. (-2.3 and -3.2). This used to result in a substantial and an unexplainable abrupt increase in the calculated pressure for a roof height,  $h = 61$  ft. against that of  $h = 60$  ft.

The increase in  $GC_p$  values in ASCE 7-16 for  $h \leq 60$  ft. is compensated for by the reduction in wind speeds for most locations in non-hurricane regions. In the case of Dallas, Texas, for example, the field-of-roof pressures have increased in ASCE 7-16 but the corner and perimeter pressures are essentially the same (Figure 10). For instance, ASCE 7-16 pressures for Dallas, Texas, on roof perimeter (for an enclosed building, Exposure B, and  $h = 60$  ft.) is 50.8 psf—just a little higher than ASCE 7-10 pressure of 48.7 psf. For the western United States, where ASCE 7-16 basic wind speeds are much lower than ASCE 7-10 speeds, roof pressures in ASCE 7-16 are lower than ASCE 7-10 pressures (see Example 3 in Section 11).

In hurricane-prone regions, where ASCE 7-16 wind speeds are essentially the same as ASCE 7-10 wind speeds, the pressures for  $h \leq 60$  ft are higher for all roof zones because ASCE 7-16 wind speeds are the same as in ASCE 7-10, but  $GC_p$  values have increased (see Example 2 in Section 11 below).

The roof zone layout pattern, shown in

roof zones present; smaller roofs may have three zones, two zones, or only one zone. As a major change, it will impact wind design and construction of low-slope roofs substantially for  $h \leq 60$  ft.<sup>15</sup>

**Beneficial Effect of Roof Parapet  $\geq 3$  ft. High Retained in ASCE 7-16**

The beneficial effect of a parapet (3 ft. or higher) on roof pressures, which assumes pressures on corners the same as the perimeter pressure, remains unaltered in ASCE 7-16 for all roof heights.

**Revision in Velocity Pressure Exposure Coefficient for Roof Height  $\leq 30$  ft.**

In ASCE 7-10, the velocity pressure exposure coefficient,  $K_z$ , for Exposure B and roof height  $\leq 30$  ft. was constant. In ASCE 7-16, this has been revised so that the revised values vary with roof height—as they do for Exposure C and Exposure D.

**Wind Pressures on Rooftop Equipment**

A few other revisions that pertain to rooftop equipment, including photovoltaic (PV) panels, have been either revised or included for the first time in ASCE 7-16.<sup>16</sup>

Figure 9 (for  $h \leq 60$  ft.), leads to five different possibilities, depending on the relative dimensions of roof height and the plan dimensions of the building, as shown in Figures 11A and 11B. A large roof (compared with building height) has all four

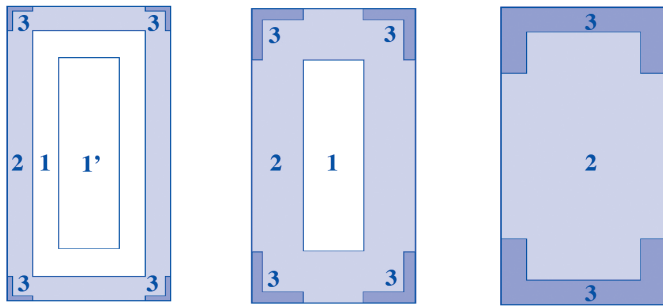
**ASCE 7-16 Low-Slope Roof Wind Pressures,  $h \leq 60$  ft, Dallas, Texas,  $V = 105$  mph**

Eave ht. (ft)	EXPOSURE B				EXPOSURE C				EXPOSURE D			
	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.
15	-14.9	-25.9	-34.2	-46.6	-22.0	-38.3	-50.5	-68.8	-26.7	-46.5	-61.3	-83.5
20	-16.2	-28.1	-37.1	-50.6	-23.4	-40.7	-53.7	-73.1	-28.1	-48.8	-64.4	-87.8
30	-18.2	-31.6	-41.7	-56.8	-25.4	-44.3	-58.4	-79.6	-30.1	-52.4	-69.1	-94.2
40	-19.7	-34.3	-45.3	-61.7	-27.0	-47.1	-62.1	-84.6	-31.7	-55.1	-72.7	-99.1
50	-21.0	-36.6	-48.2	-65.7	-28.3	-49.3	-65.1	-88.7	-32.9	-57.3	-75.6	-103.0
60	-22.1	-38.5	-50.8	-69.3	-29.4	-51.3	-67.6	-92.2	-34.0	-59.1	-78.0	-106.3

**ASCE 7-10 Low-Slope Roof Wind Pressures,  $h \leq 60$  ft, Dallas, Texas,  $V = 115$  mph**

Eave ht. h	EXPOSURE B			EXPOSURE C			EXPOSURE D		
	Fie	Per	Cor	Fie	Per	Cor	Fie	Per	Cor
15	-23.8	-39.9	-60.1	-28.8	-48.4	-72.8	-35.0	-58.7	-88.3
20	-23.8	-39.9	-60.1	-30.6	-51.4	-77.3	-36.8	-61.7	-92.9
30	-23.8	-39.9	-60.1	-33.4	-56.0	-84.2	-39.5	-66.2	-99.7
40	-25.8	-43.3	-65.2	-35.4	-59.5	-89.5	-41.5	-69.6	-104.8
50	-27.5	-46.2	-69.5	-37.1	-62.3	-93.8	-43.1	-72.4	-108.9
60	-29.0	-48.7	-73.2	-38.6	-64.8	-97.5	-44.5	-74.7	-112.4

**Figure 10 – A comparison of wind pressure values (enclosed building) for Dallas, Texas, on roofs ( $h \leq 60$  ft.) of ASCE 7-16 and ASCE 7-10. This illustration takes into account the difference in wind speeds for Dallas, Texas (105 mph for ASCE 7-16 and 115 mph in ASCE 7-10). Note that ASCE 7-16 wind pressures have increased for the field-of-roof but remain almost the same as in ASCE 7-10 for perimeter and corner.**



(a) A roof with smaller horizontal dimension > 2.4h; all four zones present.  
 (b) A roof with smaller horizontal dimension > 1.2h but < 2.4h; zone 1' does not exist.  
 (c) A roof with smaller horizontal dimension < 1.2h and larger horizontal dimension > 1.2h; zones 1' and 1 do not exist.

**Figure 11A – Five possible roof zone layout patterns based on ASCE 7-16 for  $h \leq 60$  ft. shown in Figure 9. Three patterns are shown here and the other two in Figure 11B.**

**PART TWO: ASCE 7-16-BASED RCIF WIND PRESSURE MONOGRAPH**

As mentioned at the beginning of this paper, the RCIF publishes a monograph titled *Wind Pressure on Low-Slope Roofs*. The current (fourth) edition is keyed to ASCE 7-16. It functions as a handbook for roofing professionals as it includes wind pressure tables from which wind pressure values for various roof zones may be read.

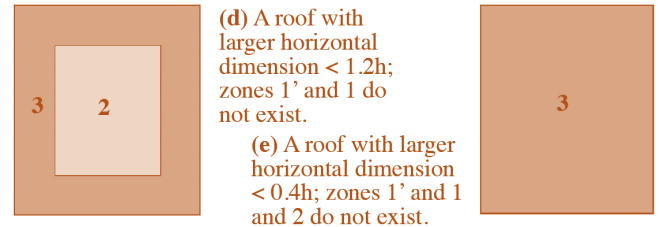
In addition to serving as a handbook, the monograph also serves as a primer on wind pressures on low-slope roofs. It provides roofing professionals with a simplified explanation of how wind affects buildings. It covers the fundamentals of wind pressures, wind loads, the difference between ultimate and nominal (allowable stress design) wind pressures, basic wind speed, mean recurrence intervals of basic wind speed, risk categories, and so on.

The fundamentals covered give roofing professionals a theoretical background so that they are able to comprehend how the monograph tables have been arrived at and apply that information to situations beyond those covered by the tables. It comprises five chapters and a number of appendixes over 160 pages and consolidates all provisions of ASCE 7-16 applicable to low-slope roofs in a single publication.

**10. Wind Pressure Tables in RCIF Monograph**

The tables have been formulated for three (out of four) building enclosure classifications:

- 1. Enclosed
- 2. Partially open
- 3. Partially enclosed



(d) A roof with larger horizontal dimension < 1.2h; zones 1' and 1 do not exist.  
 (e) A roof with larger horizontal dimension < 0.4h; zones 1' and 2 do not exist.

**Figure 11B – Five possible roof zone layout patterns based on ASCE 7-16 for  $h \leq 60$  ft. shown in Figure 9. Two patterns are shown here and the other three in Figure 11A.**

“Enclosed” and “partially open” classifications are grouped together because their  $GC_p$  and  $GC_{pi}$

< 3 ft. high. If the site’s topography requires its consideration, reference to the relevant monograph appendix is required. If ground elevation is to be considered, its value can be obtained from Table 1.

To read the values of wind pressure on a roof, a roofing professional needs the following information:

- 1. Basic wind speed for the location, which can be obtained accurately from the website mentioned in Section 7.
- 2. Building’s enclosure classification: enclosed building, partially enclosed building, partially open building, or open building.
- 3. Site exposure: B, C, or D.

A partial snapshot (for roof height,  $h$  up to 80 ft.) of a typical monograph table is shown in Figure 12. An actual table extends to  $h = 500$  ft. As previously mentioned, table values give ultimate pressures ( $P_{ult}$ ), which implies that the load factor of 1.6 (applied separately

values are identical.

The “open” enclosure classification (all walls  $\geq 80\%$  open) is not included in the tables because of its rarity, but it is covered in the monograph. The basic wind speeds included in the tables are 85 mph to 210 mph in steps of 5 mph (i.e., 85 mph, 90 mph, 95 mph, etc., to 210 mph). This covers all possible wind speeds for the U.S. and its territories. Note that the basic wind speeds in the tables are ultimate wind speeds. Therefore, the resulting wind pressures on a roof are ultimate pressures.

Local topography, ground elevation factor, and effect of a parapet are not included in the tables. In other words,  $K_{zt} = 1.0$ ,  $K_e = 1.0$  and parapet is assumed to be absent or

**Appendix E**

**Ultimate Wind Uplift Pressures (psf) on a Low-Slope Roof**

Wind Speed = 160 mph  
 Enclosed Building or Partially Open Building  
 Topographic Factor,  $K_{zt} = 1.0$   
 Ground Elevation Factor,  $K_e = 1.0$   
 Parapet height < 3 ft  
 Roof without Overhangs

Eave ht. (ft)	EXPOSURE B				EXPOSURE C				EXPOSURE D			
	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.	Fie. (Int.)	Fie. (Ext.)	Per.	Cor.
15	-34.6	-60.2	-79.4	-108.2	-51.1	-88.9	-117.3	-159.8	-62.0	-107.9	-142.3	-194.0
20	-37.5	-65.3	-86.2	-117.5	-54.3	-94.5	-124.6	-169.8	-65.2	-113.4	-149.6	-203.9
30	-42.1	-73.4	-96.8	-131.9	-59.1	-102.9	-135.7	-184.9	-69.9	-121.7	-160.6	-218.8
40	-45.8	-79.7	-105.1	-143.2	-62.8	-109.3	-144.2	-196.5	-73.5	-128.0	-168.8	-230.1
50	-48.8	-84.9	-112.0	-152.6	-65.8	-114.5	-151.1	-205.9	-76.4	-133.0	-175.5	-239.2
60	-51.4	-89.4	-118.0	-160.8	-68.4	-119.0	-157.0	-214.0	-78.9	-137.3	-181.1	-246.9
	Fie.	Per.	Cor.		Fie.	Per.	Cor.		Fie.	Per.	Cor.	
61	-75.5	-118.5	-161.6		-100.4	-157.6	-214.7		-115.7	-181.7	-247.6	
70	-78.6	-123.3	-168.0		-103.3	-162.2	-221.1		-118.5	-186.1	-253.6	
80	-81.6	-128.1	-174.6		-106.3	-166.8	-227.4		-121.3	-190.4	-259.5	

**Figure 12 – A snapshot of a part of a typical monograph table. Note that while this table ends at  $h = 80$  ft., the monograph tables extend to  $h = 500$  ft.**

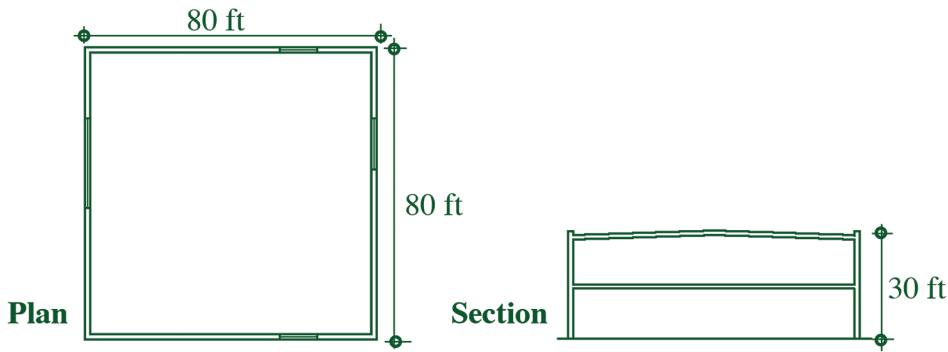


Figure 13 – Plan and section of the office building in Example 2.

in ASCE 7-10) is embedded in the ultimate pressures of ASCE 7-16, as further explained in Section 12.

### Wind Pressures for Roof Height and Wind Speed and Other Than Table Values

A simple interpolation between adjacent roof heights in a table is acceptable if the roof height of the actual building is different from those included in the table. The same applies to wind speed. For example, if the wind speed for a location is 113 mph, one can obtain the values by averaging the values from the tables for 110 mph and 115 mph. But if a precise estimate of pressures is needed, it can be obtained from any table for the given enclosure classification.

For example, Figure 10 gives ASCE 7-16 pressures for wind speed,  $V = 105$  mph (“enclosed” building). This table can be used to obtain uplift pressure for  $V = 160$  mph (“enclosed” building) by simply multiplying the pressures shown in the table for  $V = 105$  mph to obtain the values for  $V = 160$  mph. The multiplier =  $(160/105)^2 = 2.322$ .

For example, the perimeter pressure given in Figure 10 ( $V = 105$  mph) for  $h = 50$  ft. and Exposure B = 48.2 psf. The corresponding pressure for 160 mph =  $48.2(2.322) = 111.9$  psf. In Figure 12, this value is 112.0 psf. The difference between 111.9 psf and 112.0 psf is due to the rounding off in the table values and the multiplier.

### 11. Wind Pressure Calculations on a Roof From First Principles

Most roofing professionals will use the monograph as a handbook to read wind pressure values from the tables. In some situations, however, calculating wind pressures from basic fundamentals and using ASCE 7-16 provisions may become necessary. To serve that end, the monograph includes a step-by-step procedure with sev-

eral examples explaining the procedure’s use. A few examples given in the monograph are presented here.

#### Example 1

Using the step-by-step procedure, determine the ultimate wind uplift pressures per ASCE 7-16 on the roof of a two-story office building in downtown Galveston, Texas, which measures 80 x 80 ft. in plan. The roof is a low-slope roof (roof pitch  $\leq 1.5:12$ ), and the roof’s eave height is 30 ft. (Figure 13). Glazed fenestration has been designed to be impact resistant and safe against failure from wind pressure. Assume  $K_{zt} = 1.0$ .

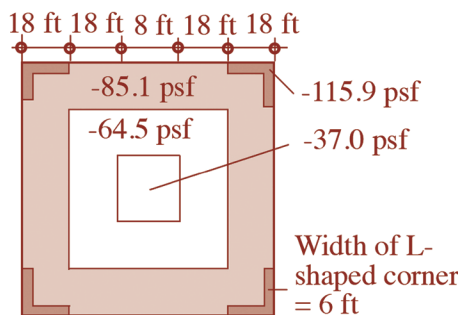
#### Solution

**Step 1.** Office building belongs to Risk Category II (explained in the monograph).

**Step 2.** From the ASCE 7 website (<https://asce7hazardtool.online>), the basic wind speed for downtown Galveston, Texas,  $V$ , for Risk Category II building per ASCE 7-16 = 150 mph.

**Step 3.** Exposure category of site is B (downtown area).

**Step 4.**  $h = 30$  ft.



(a) Roof zones and pressures per ASCE 7-16

**Step 5.**  $K_h = (2.01)[30/1200]^{(2/7)} = 0.7006$ ; the algebraic form of this expression is from ASCE 7-16 and included in the monograph.

**Step 6.**  $K_{zt} = 1.0$  (given).

**Step 7.**  $K_e = 1.0$  (Galveston is at sea level).

**Step 8.**  $K_d = 0.85$  (see Section 2).

**Step 9.**  $q_h = 0.00256(K_h)(K_{zt})(K_e)(K_d)(V)^2$  (From Equation (2))

$$= 0.00256(0.7006)(1.0)(1.0)(0.85)(150)^2 = 34.3 \text{ psf.}$$

**Step 10.** Galveston, TX lies in a windborne debris region (because basic wind speed for Risk Category II  $> 140$  mph). However, because the glazing is impact resistant and safe against wind pressure, we bypass this step and go to Step 11.

**Step 11.** Because the glazing is impact resistant and safe against breakage by wind pressure, it is classified as “non-opening.” Hence, the building’s enclosure classification is “enclosed.” (Note that ASCE 7 requires that a glazing below 60 ft. in a windborne region must be impact resistant. If the glazing were not impact resistant, it would be considered as having openings and the building would be classified as a “partially enclosed.”)

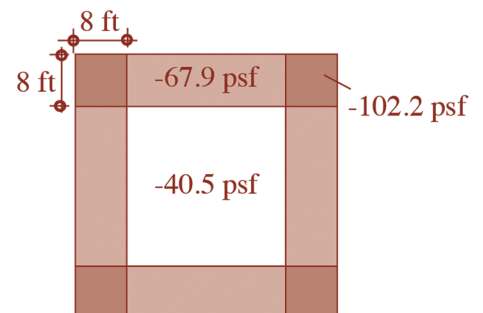
**Step 12:**  $h = 30$  ft. ( $< 60$  ft.). Therefore, from Figure 9:

$$\begin{aligned} GC_p \text{ (field-of-roof—interior)} &= -0.9 \\ GC_p \text{ (field-of-roof—exterior)} &= -1.7 \\ GC_p \text{ (perimeter)} &= -2.3 \\ GC_p \text{ (corner)} &= -3.2 \end{aligned}$$

**Step 13.**  $GC_{pi} = 0.18$  (Table 2)

**Step 14.** Since no information is provided about roof parapet, we will assume that the parapet height is  $< 3$  ft.—a conservative assumption.

$$\text{Step 15. } p = q_h [(GC_p) - (GC_{pi})]$$



(b) Roof zones and pressures for the same building per ASCE 7-10

Figure 14A – Wind pressure on the office building in Example 2. These are per ASCE 7-16. B – Wind pressures on the same building per ASCE 7-10. Note the substantial increase in ASCE 7-16 wind pressures as compared with ASCE 7-10 pressures for reasons explained in Step 16 of this example.

$$\begin{aligned}
 p \text{ (field-of-roof—interior)} &= 34.3[-0.9 - 0.18] = -37.0 \text{ psf} \\
 p \text{ (field-of-roof—exterior)} &= 34.3[-1.7 - 0.18] = -64.5 \text{ psf} \\
 p \text{ (perimeter)} &= 34.3[-2.3 - 0.18] = -85.1 \text{ psf} \\
 p \text{ (corner)} &= 34.3[-3.2 - 0.18] = -115.9 \text{ psf}
 \end{aligned}$$

**Step 16.** In Figure 14A, various roof zones are identified and the corresponding wind pressures are shown. Figure 14B shows the wind pressures on the same building per ASCE 7-10. Observe the significant increase in ASCE 7-16 pressures for all roof zones. This is because of the increase in  $GC_p$  values in ASCE 7-16. The basic wind speed for Galveston, TX (being in a hurricane-prone region) has not changed in ASCE 7-16 from ASCE 7-10.

Additionally, note that the roof zone under a pressure of -37.0 psf is only 8 x 8 ft. (= 64 sq. ft.)—a mere 10% of the total roof area. For ease of construction, a roof designer will most likely assume this zone as being under -64.5 psf—a huge increase from ASCE 7-10 pressure of -40.5 psf.

### Example 2

Using the step-by-step procedure, determine the ultimate wind uplift pressures on the roof of the office building of Figure 13, which is located in downtown San Francisco, California. Assume no topographical features at the site. The windows, although resistant to wind pressure, are not resistant to wind-borne debris.

### Solution

**Step 1.** Risk Category II building

**Step 2.** From ASCE 7 website (<https://asce7hazardtool.online>), the basic wind speed for San Francisco, V, for Risk Category II building per ASCE 7-16 = 92 mph.

**Step 3.** Exposure of site is B (downtown area).

**Step 4.**  $h = 30$  ft.

**Step 5.**  $K_h = (2.01)[30/1200]^{(2/7)} = 0.7006$ ; the algebraic form of this expression is from ASCE 7-16 and included in the monograph.

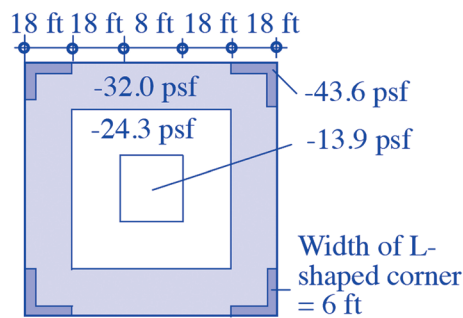
**Step 6.**  $K_{zt} = 1.0$  (given).

**Step 7.**  $K_e = 1.0$

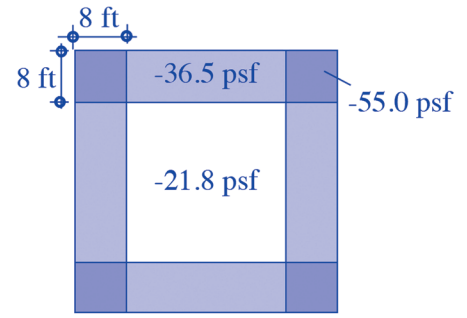
**Step 8.**  $K_d = 0.85$

**Step 9.**  $q_h = 0.00256(K_h)(K_{zt})(K_e)(K_d)(V)^2 = 0.00256(0.7006)(1.0)(1.0)(0.85)(92)^2 = 12.9$  psf

**Step 10.** San Francisco is not in hurricane-prone region and, hence, not in a wind-



(a) Roof zones and pressures per ASCE 7-16



(b) Roof zones and pressures for the same building per ASCE 7-10

**Figure 15A – Wind pressure on the office building in Example 3. These are per ASCE 7-16. B – Wind pressures on the same building per ASCE 7-10. Note that ASCE 7-16 pressures are lower than ASCE 7-10 pressures as explained in Step 16 of this example.**

borne debris region. Therefore, the glazed fenestration does not need impact protection.

**Step 11.** Because the windows are resistant to wind pressure, they are considered as “non-openings.” The enclosure classification of the building is “enclosed.”

**Step 12.**  $h = 30$  ft., which is  $< 60$  ft. Therefore:

$$GC_p \text{ (field-of-roof—interior)} = -0.9$$

$$GC_p \text{ (field-of-roof—exterior)} = -1.7$$

$$GC_p \text{ (perimeter)} = -2.3$$

$$GC_p \text{ (corner)} = -3.2$$

**Step 13.**  $GC_{pi} = 0.18$  (Table 2)

**Step 14.** Since no information is provided about a roof parapet, we assume that the parapet is  $< 3$  ft. high—a conservative assumption.

**Step 15.**  $p$  (field-of-roof—interior) =  $12.9[-0.9 - 0.18] = -13.9$  psf

$$p \text{ (field-of-roof—exterior)} = 12.9[-1.7 - 0.18] = -24.2 \text{ psf}$$

$$p \text{ (perimeter)} = 12.9[-2.3 - 0.18] = -32.0 \text{ psf}$$

$$p \text{ (corner)} = 12.9[-3.2 - 0.18] = -43.6 \text{ psf}$$

**Step 16.** In Figure 15A, various roof zones are identified and the corresponding pressures are shown. Figure 15B shows wind pressures on the same building per ASCE 7-10. Observe that ASCE 7-16 pressures are lower in corner and perimeter zones than those of ASCE 7-10 despite higher  $GC_p$  values of ASCE 7-16. The reason is that  $V_{7-16} = 92$  mph is much lower than  $V_{7-10} = 110$  mph because San Francisco is in a non-hurricane region. For ease of construction, here also, a roof designer will likely assume the 8- x 8-ft. roof zone (shown to be under a pressure of -13.9 psf) as being under the pressure of -24.3 psf.

### Example 3

Using the step-by-step procedure, determine the ultimate wind uplift pressures on the low-slope roof of a high-rise office building measuring 100 x 150 ft. in plan. The envelope of the building consists of glass curtainwalls whose glazing is resistant to wind-borne debris and wind pressure. Roof height = 500 ft., and a 2-ft., 9-in. high parapet is provided. The building is located in downtown Miami, Florida.  $K_{zt} = 1.0$ . Assume no topographic features.

### Solution

**Step 1.** An office building is a Risk Category II building.

**Step 2.** From the ASCE 7 website (<https://asce7hazardtool.online>), the basic wind speed for downtown Miami, Florida, V, for a Risk Category II building per ASCE 7-16 = 169 mph.

**Step 3.** Exposure category of site is B (downtown area).

**Step 4.**  $h = 500$  ft. (given).

**Step 5.**  $K_h = (2.01)[500/1200]^{(2/7)} = 1.5652$ ; the algebraic form of this expression is from ASCE 7-16 and included in the monograph.

**Step 6.**  $K_{zt} = 1.0$  (given)

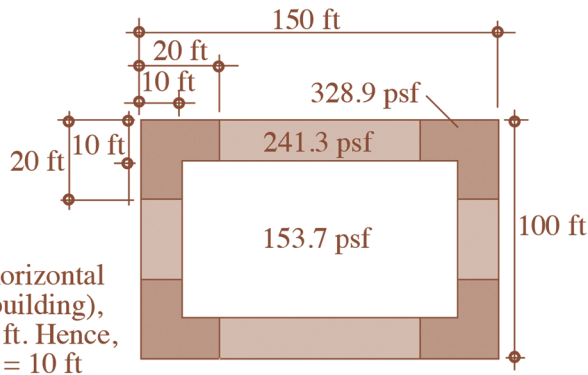
**Step 7.**  $K_e = 1.0$  (Miami, FL is at sea level).

**Step 8.**  $K_d = 0.85$

**Step 9.**  $q_h = 0.00256(K_h)(K_{zt})(K_e)(K_d)(V)^2 = 0.00256(1.5652)(1.0)(1.0)(0.85)(169)^2 = 97.3$  psf

**Step 10.** All fenestration is impact resistant and wind pressure resistant. Therefore, we proceed to Step 11.

**Step 11.** Because the glazing is impact and wind pressure resistant, and there are no



$a = 0.1$  (least horizontal dimension of building), not less than 3 ft. Hence,  $a = 0.1(100 \text{ ft}) = 10 \text{ ft}$

**Figure 16 – Wind pressures on the office building in Example 4 per ASCE 7-16. Note that ASCE 7-10 pressures on this building are the same as ASCE 7-16 pressures because  $GC_p$  values have not changed. The basic wind speed for Miami, FL, has also not changed, being in the hurricane-prone region.**

“openings” in the walls immediately below the roof, the enclosure classification is “enclosed.”

**Step 12:**  $h = 500 \text{ ft.}$ , which is  $> 60 \text{ ft.}$  Therefore, from Figure 8:

$$GC_p \text{ (field-of-roof)} = -1.4$$

$$GC_p \text{ (perimeter)} = -2.3$$

$$GC_p \text{ (corner)} = -3.2$$

**Step 13.**  $GC_{pi} = 0.18$  (Table 2)

**Step 14.** The parapet is  $< 3 \text{ ft.}$  high. Hence, no protective effect obtained from the parapet.

**Step 15.**  $p$  (field-of-roof) =  $97.3[-1.4 - 0.18] = -153.7 \text{ psf}$

$$p \text{ (perimeter)} = 97.3[-2.3 - 0.18] = -241.3 \text{ psf}$$

$$p \text{ (corner)} = 97.3[-3.2 - 0.18] = -328.9 \text{ psf}$$

**Step 16.** In Figure 16, various roof zones are identified and the corresponding uplift pressures are shown.

## 12. Safety Provisions in Roof Design

Despite the advances made in structural engineering, the current methods available to determine the loads on buildings are approximate. In other words, a perfect (100%) reliability in determining the loads on buildings or components does not exist. For example, as shown in the previous sections, the wind pressure on a roof zone is a function of several factors, such as the peak wind speed, building site’s exposure, building’s enclosure classification, ground elevation above sea level, and so on. There is a great deal of approximation in the numerical values assigned to these factors based on the assumptions that are only as close to reality as possible, but do not represent a 100% reality.

workmanship, construction site quality control, differences in the test specimen versus actual roof construction (despite both utilizing the same materials), age-related deterioration of assembly, and so on.

The imperfections (uncertainties) inherent in estimating the loads and resistance are dealt with by using two alternative design approaches: 1) allowable strength design (ASD) approach and 2) load and resistance factor design (LRFD) approach, also called ultimate strength design (USD) approach. Of the two approaches, ASD is older, and has been replaced by the more rational USD approach.

### ASD Approach in General

In the ASD approach, the estimation of loads (such as the dead load, live load, wind load, etc.) is based on peak values that are likely to occur during the structure’s service life (typically assumed as 50 years for Risk Category II structures). These loads are referred to as service loads or working loads.

All service loads that may act on a structure/component simultaneously are combined linearly (i.e., without any modification) to obtain the total load on it, and the resistance required to carry them is determined. We will call the required resistance the service load resistance,  $R_{SL}$ .

We then calculate the resistance of the structure/component that is furnished to carry the loads, based on material properties and structural analysis. We call this the nominal resistance,  $R_{NOM}$ . The term “nominal” is used to signify that the uncertainties in 1) estimating the loads and 2) computing the resistance of the structure/component

have not been accounted for. A similar lack of reliability prevails in estimating the resistance (i.e., strength) of the building/component. With respect to a roof assembly, the uncertainty in determining the resistance to wind uplift is due to such factors as

have not been accounted for.

To account for the uncertainties,  $R_{NOM}$  is divided by the factor of safety to obtain the practical, as furnished, resistance,  $R_{PR}$  so that:

$$R_{PR} = [R_{NOM}/FOS]$$

**Equation 4**

For safety considerations, the practical resistance,  $R_{PR}$ , must be  $\geq$  the required resistance,  $R_{SL}$ , that is:

$$R_{PR} \geq R_{SL}$$

**Equation 5**

From Equations 4 and 5:

$$R_{NOM} \geq (FOS)R_{SL}$$

**Equation 6**

A minimum  $FOS = 2.0$  was commonly used in most structural design using the ASD approach<sup>17</sup> and was adopted in wind-resistant design of roofs.

### ASD Applied to Wind Design of Low-Slope Roofs

Up until ASCE 7-05, wind-resistant design was based on service load pressures, obtained by using the service load wind speed for a location, defined as the peak wind speed that has a mean return interval (MRI) of 50 years (for Risk Category II). The 50-year MRI implies that the probability of the wind speed at a location equaling or exceeding the nominal wind speed in any one year =  $(1/50) = 0.02 = 2\%$ . This is similar to the probability of a fair cubical dice bringing up a certain number at any given throw =  $1/6 = 0.167 = 16.7\%$ .

However, the probability that the service load wind speed will be equalled or exceeded during the service life (of 50 years) of a building is:  $P_{50} = 0.64 = 64\%$ ;  $P_{25} = 0.4 = 40\%$ ;  $P_{10} = 0.18 = 18\%$ . These are fairly high probabilities of exceedance; and, therefore, the use of a high FOS, such as 2.0 (or greater) is reasonable in the light of several uncertainties just mentioned.

Because the only structural criterion to be satisfied with respect to wind design of a low-slope roof is the resistance to uplift pressure, its required resistance is simply equal to the uplift pressure on the roof. Thus,  $R_{SL} = P_{SL}$ , where  $P_{SL}$  = service load uplift pressure.

If  $R_{NOM}$  is the uplift resistance of the roof

assembly as furnished (based on laboratory testing), then from *Equation 6*:

$$R_{NOM} \geq FOS(P_{SL})$$

**Equation 7**

With minimum FOS = 2.0, *Equation (8)* becomes:

$$R_{NOM} \geq 2.0(P_{SL})$$

**Equation 8**

Thus, if the uplift pressure,  $P_{SL}$ , on a roof zone = 45 psf, then  $R_{NOM}$  for that zone must be  $\geq 2.0(45 \text{ psf})$ , i.e.,  $\geq 90 \text{ psf}$ .

Therefore, the generally accepted industry method for low-slope roof design, using ASD, involves the following steps:

1. Calculate the uplift pressure,  $P_{SL}$ , for each roof zone using the procedure given in ASCE 7.
2. Calculate the nominal uplift resistance,  $R_{NOM}$ , to be furnished for each zone using *Equation 8*.
3. Select a roof assembly that has been tested by an approved testing agency, such as Factory Mutual (FM) or Underwriters Laboratory (UL), whose uplift strength equals or exceeds the value obtained from Step 2.

### USD Approach in General

It has long been known that the nature of uncertainties in load and resistance are vastly different. Therefore, accounting for the two types of uncertainties (in load and the resistance) through one combined factor—FOS in ASD approach—is unsatisfactory. This is more evident when we consider that a typical building is subjected to a number of different load types—dead load, live load, wind load, earthquake load, and so on. The level of uncertainty in each load type is different. For example, the level of uncertainty in determining the dead load is much smaller than in live load or wind load. Therefore, the safety provisions for each load type have to be different.

Similarly, in dealing with the resistance of the member, one deals with a host of different strength types—compressive strength, tensile strength, bending strength, shear strength, pull-out strength—and so on. The level of uncertainty in their determination varies. Consequently, the safety provision for each strength type has to be different.

Thus, the fundamental difference between the ASD and USD approaches is

that in ASD, one single safety provision (FOS) is used, while in USD, there are two (partial) safety provisions—one for the loads on the structure/component and the other for its furnished resistance.

The factor that used to account for the uncertainty in load in USD has been called the load factor, which is greater than 1.0. For example, the load factor for dead load is 1.2; that for live load is 1.6. In other words, in USD, we magnify (i.e., multiply) the service loads by the respective load factors (LF). The product so obtained is called the ultimate load. Based on the ultimate load, we determine the required resistance of the structure/component, denoting it as  $R_{UL}$ .

Based on the structure/component's cross-sectional dimensions, material properties, and structural analysis, we determine the as-furnished resistance of the structure/component, calling it the nominal resistance,  $R_{NOM}$ . To account for the uncertainties (in analytical procedures and material properties), we multiply  $R_{NOM}$  by the strength reduction factor,  $\phi$ . The  $\phi$  factor is always  $< 1.0$ . In other words, we calculate the resistance of the structure/component and reduce it by multiplying it with  $\phi$ .

The resulting product [ $\phi (R_{NOM})$ ] is the practical, as-furnished resistance of the structure/component,  $R_{PR}$ . For a safe design:

$$R_{PR} = [\phi (R_{NOM})] \geq R_{UL}$$

**Equation 9**

### USD Applied to Wind Design of Low-Slope Roofs

From ASCE 7-10 onward, wind pressures are based on USD approach. The load factor for wind load in ASCE 7-05 was 1.6. In ASCE 7-10 and ASCE 7-16, the load factor is not applied separately (as was done in ASCE 7-05 and its earlier versions), but merged into the basic wind speed for the location. Consequently, the basic wind speed (in ASCE 7-10 and ASCE 7-16) is the ultimate wind speed, and the wind pressure obtained using this basic wind speed is called the ultimate pressure,  $P_{UL}$ . Thus:

$$P_{UL} = 1.6P_{SL}$$

**Equation 10**

Where:

$P_{SL}$  = service load pressure of ASCE 7-05 (and its earlier versions).

Note that  $P_{UL}$  signifies that all uncer-

tainties in determining the wind pressures (including that dealing with the uncertainty in estimating the wind speed) have been taken care of in the ultimate wind speed. In other words, the safety provision for loads is built into the wind speed.

As the load factor does not account for the uncertainties related to the roof's (uplift) resistance (strength as furnished), an additional safety factor is needed. From *Equation 10*:

$$P_{SL} = (1/1.6)P_{UL} = 0.625P_{UL}$$

**Equation 11**

The International Building Code allows the use of 0.6 in place of 0.625,<sup>18</sup> so that:

$$P_{SL} = 0.6P_{UL}$$

**Equation 12**

Substituting the value of  $P_{SL}$  from *Equation 12* in *Equation 8*, we get:

$$R_{NOM} \geq 2.0(0.6P_{UL}), \text{ i.e.,}$$

$$R_{NOM} \geq 1.2P_{UL}$$

**Equation 13**

*Equation 13* states that the nominal uplift resistance (i.e., the furnished uplift resistance) of the roof assembly should be  $\geq 1.2$  times the ultimate uplift pressure on it.

Because  $(1/1.6) = 0.83$ , *Equation 13* can also be written as:

$$(0.83)R_{NOM} \geq P_{UL}$$

**Equation 14**

The number 0.83 may be viewed as the  $\phi$  factor—the strength reduction factor. Because *Equations 13* and *14* are essentially identical, one can use either to design a roof assembly. However, the use of *Equation 13* is simpler, and the design of a roof assembly can be obtained from the following steps, as illustrated in Example 4:

1. Calculate  $P_{UL}$  for each roof zone using the ASCE 7-16 procedure (or read it from the monograph).
2. Calculate the (required) nominal uplift resistance for each zone,  $R_{NOM} = 1.2(P_{UL})$ .
3. Select a roof assembly that has been tested by an approved testing agency, such as FM or UL, whose uplift strength equals or exceeds the value obtained from Step 2).

It is important to emphasize that the number 1.2 in *Equation 13* is a safety factor that addresses the uncertainties in the materials and construction of roof assemblies. ASCE 7 does not deal with this issue. The roofing industry may consider revising it based on such parameters as: 1) mandated inspection of roof construction by third-party, qualified inspectors versus no mandated inspection, 2) differentiating between fully adhered roofing (where all roof components are fully adhered) and anchored roof assemblies, and others.

#### Example 4

Determine the ultimate wind uplift pressures ( $P_{UL}$ ) for various roof zones and then specify corresponding FM-rated assemblies for the low-slope roof of a building with eave height,  $h = 50$  ft. Basic wind speed for the location = 160 mph. The site lies in Exposure B, elevation above sea level = 500 ft. (assume  $K_e = 1.0$ ) and site topography is flat, i.e.,  $K_{zt} = 1.0$ . The roof has a 3-ft.-high parapet.

#### Solution

The ultimate pressures on the roof,  $P_{UL}$ , have been obtained from *Figure 12*, from which the uplift resistances of the assembly to be furnished,  $R_{NOM}$ , are:

Field-of-roof (interior):  $P_{UL} = -48.8$  psf;

$R_{NOM} = 1.2(-48.8) = -58.6$  psf

Field-of-roof (exterior):  $P_{UL} = -84.9$  psf;

$R_{NOM} = 1.2(-84.9) = -101.9$  psf

Perimeter:  $P_{UL} = -112.0$  psf;  $R_{NOM} = 1.2(-112.0) = -134.5$  psf

Corner: Same as perimeter  $R_{NOM} = -134.5$  psf (because of parapet  $\geq 3$  ft. high).

Because FM ratings are in steps of 15 psf, the required FM ratings for wind uplift are:

Field-of-roof (interior): FM 1-60

Field-of-roof (exterior): FM 1-105

Perimeter: FM 1-135

Corner: FM 1-135

## CONCLUSIONS


ASCE 7-16 includes several modifications from ASCE 7-10, such as the change in basic wind speed maps for the continental U.S. and its territories; the addition of microzoned, effective basic wind speed maps for the islands of Hawaii; the addition of a new ground elevation factor clarifying the definition of wind directionality factor; and the addition of one enclosure classification. The most significant change, however, is in relation to roofs with roof height,  $h \leq 60$  ft.

The paper makes a plea to the roofing industry to embrace the use of the USD approach and move away from the use of the ASD approach, realizing that the ultimate pressures include a (partial) safety provision incorporated into them. The additional safety factor of 1.2 is required to account for the quality of roof construction.

It should be noted that, in this approach, the overall safety provision remains unaltered from the “2.0 factor” used in the ASD approach, considered archaic in academia and the profession. It is the authors’ hope that the roofing industry will adopt the USD approach as presented.

The monograph has been updated to include all the modifications mentioned. Tables for ultimate pressures and various numerical examples, which explain how the table pressure have been arrived at, have been updated.

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