HAVE WIND DESIGN PROVISIONS BECOME TOO COMPLICATED?

A Look at the Progression of Design Provisions for Mid-rise Buildings

by

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Abstract

Wind pressures affect buildings of all shapes and sizes. Standards and codes have been published that instruct engineers and designers how to account for the wind loads interacting with structures. As further research on wind interaction with buildings is completed, more provisions and requirements are added to the codes and standards. At what point do the provision modifications and additions become more complicated than they need to be for a safe, effective building design?

This report evaluates the progression of wind provisions through codes and standards since the early 1900's. Then a detailed review of the current ASCE 7-05 Analytical Procedure design provisions is completed. Specifically, this report focuses on mid-rise structures 60 feet to 180 feet in height, located in the Midwest region of the United States. Following this in depth review of the ASCE 7 Standard, two studies are carried out. The studies were developed in order to assess the following two ideas: Have the wind load provisions become too complicated? Should there be a simplified procedure for mid-rise buildings?

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Dedication

I dedicate this report first and foremost to my major professor Kimberly Kramer for allowing me to research a topic that was slightly atypical and for guiding me successfully through the research process. I think we both learned a great deal about this topic, more than we realized. She always made time to sit down and have discussions with me regarding parts of my research and report.

I also dedicate this report to Ryan; for understanding when I had to spend hours and hours researching and writing instead of spending time with him. He continually pushed me forward when I was feeling discouraged.

SECTION 1.0: Introduction

Buildings and structures are constantly subject to wind loads and pressures as it is an innate phenomenon of nature. Wind is defined as the flow or movement of air in the atmosphere that occurs because of atmospheric pressure differentials caused by solar radiation. It is fascinating to wonder how the wind is actually interacting with various buildings and structures. Is it pushing, pulling, causing suction, and/or causing inflation? What pressure should the structure be designed for to ensure safety? Other people have wondered these same questions, which is proven by the fact that research is continually taking place, that building codes and standards have been created, and that the codes and standards change in accordance with completed research.

Since the early 1900's and earlier, engineers have been designing buildings with wind pressures in mind. Prior to that, it was known that wind had an effect on structures, but there were not specific methods in which to design for the wind. The methods used today have progressed significantly and are much different than what has been employed in the past as indicated in Section 2. This report first examines how the design provisions for determining wind pressures on buildings have evolved over the years through codes and standards such as the Uniform Building Code, American National Standards Institute publications, International Building Code, and American Society of Civil Engineers publications. While a new edition of each code or standard is generally published every three years or so, there are not always additions or changes made. It is often large-scale, destructive weather events that generate the need and desire for research, which then produces certain changes or additions to the building codes and standards.

Many factors are considered in regards to wind pressures acting on buildings, known as Design Considerations; some examples include geographical location for terrain and weather considerations, shape of building, and height of building. Section 3 presents these design considerations. The method of establishing a design wind pressure has progressed from a code-given pressure to equations in which the wind velocity and other coefficients are used to determine an applied pressure. In both cases, type and location of building must be known in order to being the design process. This report focuses on a specific location and type of building in order to limit the scope of the design process so a more detailed account can be shown.

The focus of this report is mid-rise buildings located in the Midwest region of the United States. In this region of the United States, the vast majority of existing buildings and those being constructed are low-rise and mid-rise structures, defined in this report as 60 feet or less and 60-180 feet, respectively. High-rise buildings, those greater than 180 feet, are also being constructed but at a relatively smaller quantity than mid-rise and low-rise buildings. In order to show a more detailed evaluation of the effect of wind pressures on buildings, a specific category of building was selected. This report investigates the wind pressures associated with the Main Wind Force Resisting System (MWFRS) of mid-rise structures, five to thirteen stories high. Mid-rise was selected for two main reasons: First, this type of building is very common in the Midwest and second, the wind pressures are more complex to evaluate than a low-rise building. Wind pressures increase non-linearly as the height of a structure increases and can be modeled in various ways.

As mentioned previously, building codes and standards have been around for about a century. In this time many changes have occurred with the provisions for wind pressure design. This report uses a simple base structure in order to compare older wind pressure design methods with the current provisions. The base structure, or control group, is rectangular in plan with no structural irregularities and it is examined as both an enclosed structure as well as a partially enclosed structure. Structural building material is not significant at this point in the design process. An analysis is conducted to determine how the design wind pressures changed from the base structure, and conclusions are presented. Through these design studies, the simplicity of the wind design provisions is also examined.

With multiple codes in existence many years ago, to only one model code and standard that exist in the present day, it is a wonder how engineers are able to consistently design buildings across the United States. As codes were compiled together, more wind research conducted, and requirements added every few years, the design process has become more complex. The question at hand: Have the codes and standards become more complex than needed for the safe design of structures? As a final point, this report discusses the complexity and/or simplicity of the current codes and standards using the analytical method of wind analysis.

SECTION 2.0: History and Background Information

Building Standards and Building Codes are two separate entities; yet can have much in common. Building standards such as the American Society of Engineers (ASCE) 7 *Minimum Design Loads for Buildings and Other* Structures establishes technical standards for loads applied to buildings and other structures. Standards are written for almost any and everything in the United States, from building design to energy resources to business matters, and these standards are written based on research and testing done all over the country. For example, a standard is written specifically about wind design procedures for structures. Building Codes are a set of rules that specify the minimum acceptable level of safety for constructed buildings. Code becomes law of a particular jurisdiction when formally enacted by the appropriate authority (city, state, etc.). A model building code can be revised by a jurisdiction to be the local building code. Codes cover a wide variety of topics; however multiple related topics are included in a code. For example, a building code includes not only wind design provisions, but also requirements for mechanical and electrical design, building materials, site conditions and more. The basic distinction between codes and standards is that code committees can adopt various standards to be a part of the model building code if the committee members are in agreement with the provisions set forth in the standards being adopted, as well as the research that was conducted for the standards. The general method for adopting new information into standards and codes is as follows:

- Standards Committees: research a new or ongoing area and write or revise a standard for it
- Code committees: write and revise previous codes, adopt standards

Both Standards and Building Codes are created and reformed by professional associations that include such people as code officials, engineers, architects, contractors, vendors and others in the building industry and profession. For the United States, the existence of Standards and Codes for the building and construction industry dates back over 100 years. The early codes, now referred to as "legacy" codes, were written for specific regions of the country: one primarily for the southeast, one for the east/Midwest, and one for the Midwest/west. An engineer needed to be able to interpret and understand multiple codes based on where a structure was being built. The local governing body for a specific state, city, township, etc. chooses which code they want to adopt.

Each city, state, and government locality has the authority to adopt a code or standard of their choice, or they may choose to make use of their own building code. In addition, stand-alone sections instead of an entire code can be adopted as well. Upon adoption by the local governing authority, a standard or code becomes law. Furthermore, any government has the ability to amend any sections in order to better depict what they felt was necessary for building safety.

This report section provides information on the two primary Standards that are related to wind provisions and how they have developed over the years. Subsequently, this report section discusses the various model Building Codes that have existed in the United States and how the wind design provisions have progressed.

2.1 Building Standards

As mentioned previously, a standard can be written about a specific topic or related topics. These are highly based on research and testing done by professionals and researchers. Standards have existed in the United States for many years. One of the earliest standards with requirements for the design of structures for wind pressures was in 1924, written by the U.S. Department of Commerce, Building Code Committee and published by the National Bureau of Standards. These requirements later transferred to another standard, written and published by a standards association holding the title, *Minimum Design Loads in Buildings and Other Structures*. Transfer of the design provisions occurs three times throughout the 1900's and includes publications by the American Standards Association, American National Standards Institute, and the American Society of Civil Engineers. The title for the requirements has remained unchanged over the years. Each standard and the changes made to the wind design provisions are discussed in the following sections.

2.1.1 U.S. Department of Commerce, Building Code Committee

1924 Publication

The wind provisions in the 1924 document are the following:

"All vertical plane surfaces of all buildings and structures shall be taken not less than 10 psf when h<40ft and not less than 20psf when h>40ft." (U.S Dept. of Commerce, 1924) These provisions are very straightforward and make the design process simple. Only the height of the building needs to be known. General provisions for wind pressures on signs and tanks are equally simple.

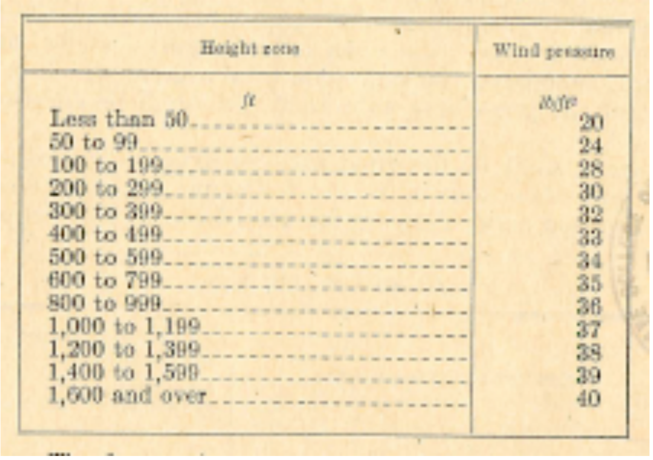
Further background information found in the appendix of the document gives rhyme and reason to where the pressure values originated. The wind provisions in the 1924 publication were based on wind velocities measured as five- minute averages (anemometers, a device used to measure wind speeds, were located at various stations, or cities, and managed by the Weather Bureau). These wind velocities are eventually translated into design pressures; however, certain considerations such as gust speeds, terrain exposures, and the increase in height of surrounding buildings are also taken into account. Through experimentations completed at the time, a design equation that converts velocity into a pressure was developed. Rectangular plates of specified sizes were utilized in the wind pressure experiments. The wind pressure equation is as follows:

$$P = 0.004(B/30)SV^2 \qquad \text{Equation 2.1.1-1}$$

V is the velocity of the wind, measured in miles per hour for a 5-minute interval. The term S is for the surface area of the plate (building surface), measured in squared feet. The barometric pressure, B, is also factored into the equation. While this relationship is just an estimate, many other experiments were taking place at the same time. For example, the constant at the beginning of the equation, 0.004, was thought to be very conservative due to the lack of accurate instrumentation. In Paris, M. Eiffel completed tests and analyses with more accurate appliances that led him to the conclusion of a constant equaling 0.0033 (U.S Dept. of Commerce, 1924).

1945 Publication

In 1945, the United States Department of Commerce, under the sponsorship of the National Bureau of Standards, published an updated document for design loads in buildings named, “Building Code Requirements for Minimum Design Loads in Buildings”. This code was composed and approved by the American Standards Association as American Standard A58.1-1945. Design wind pressures within this document are provided in table format for the engineer and it is noted all pressures should be assumed to come from any horizontal direction. For buildings or other structures less than 50 feet in height, a standard 20 psf is applied as the design pressure. The pressure increases slightly as the height of the building increases. A copy of this table is illustrated in Figure 2-1 below.



Height zone	Wind pressure
ft	*lb/ft*^{2}
Less than 50	20
50 to 99	24
100 to 199	28
200 to 299	30
300 to 399	32
400 to 499	33
500 to 599	34
600 to 799	35
800 to 999	36
1,000 to 1,199	37
1,200 to 1,399	38
1,400 to 1,599	39
1,600 and over	40

Figure 2-1: Design Wind Pressure for Buildings – A58.1-1945

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Factors involved in determining the design wind pressure include wind velocity pressures, building shape coefficients, and height increases of the building or structure. The wind velocity pressures are provided in a map format. The difference between the design wind load pressures and the wind velocity pressures is as follows: (1) The design wind load is the product of the velocity pressure and a shape coefficient determined by the geometrical form of the structure and (2) The velocity pressure is influenced by factors such as geographical location, height above the ground, and the surrounding exposure (ASA, 1945). The velocity pressure corresponding to the 20 psf design wind pressure for buildings less than 50 feet high, is 15.4 psf This was measured at a height of 30 feet and a shape coefficient of 1.3 was applied. Also included in the commentary is the equation used in determining the velocity pressures and an explanation of each term.

2.1.2 American Standards Association

1955

After the 1945 publication of the standard for Minimum Design Loads for Buildings and Other Structures, there was another revision published in 1955. This revision continued to take on the reference of being the A58.1 standard. The wind provisions remained unchanged with the exception of the addition of a wind pressure map for the determination of design wind pressures. Previously, design wind pressures were only tabulated based on the height of the building above ground. In the 1955 publication, wind pressures are shown to vary based on different regions within the United States. These resultant pressures are illustrated in a map labeled, Minimum Allowable Resultant Wind Pressures Map.

The resultant wind pressure values are based on fastest mile velocity data recorded by the U.S. Weather Bureau. Using power-law formulas known at the time, the recorded velocities are decreased assuming a 30-foot height above ground. Multiplying factors accounting for gust effects, typical building shape, and inward and outward pressure are also applied to the recorded velocities (ASA, 1955). Following these steps, the outcome is a resultant wind pressure, which varies in different areas of the U.S. due to varying wind velocities. Aside from coastal areas, the Midwest region has the highest resultant wind pressures. Figure 2-2 below shows the Minimum Allowable Resultant Wind Pressures map.

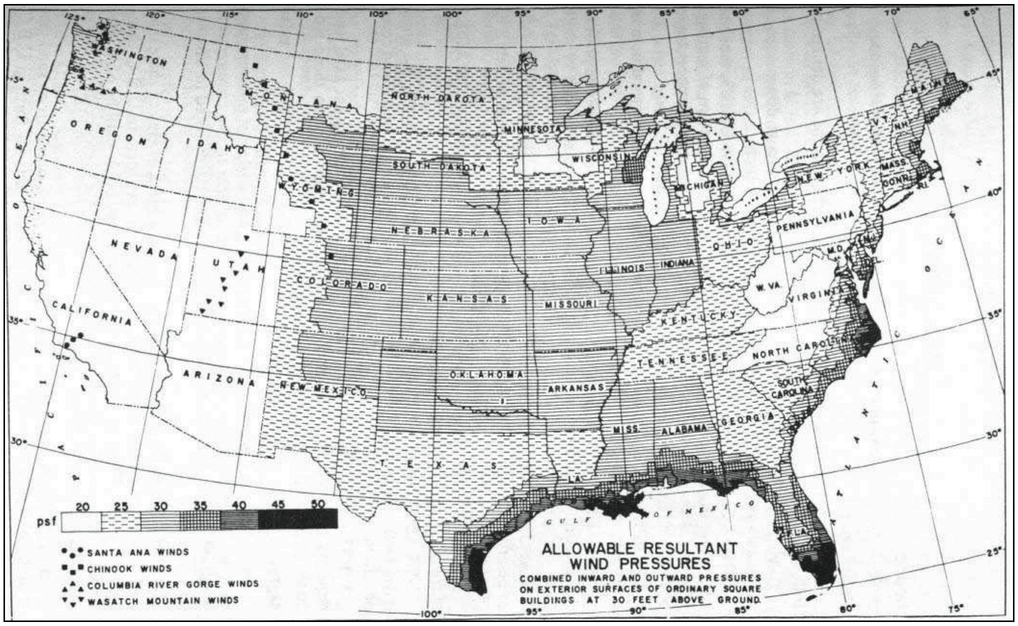
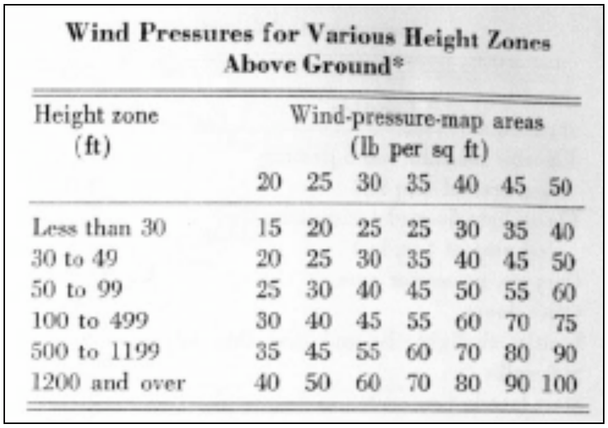


Figure 2-2: Minimum Allowable Resultant Wind Pressures (pounds per square foot)

With permission from ASCE

Similar to the previous publication in 1945, design wind pressures are tabulated based on building height above the ground; however the height increments specified are different. The

20psf minimum pressure for all buildings less than or equal to fifty feet (regardless of location) previously assumed in the 1945 provisions is now separated into two height increments with different design pressures: less than 30 feet gives 15 psf, and 30 feet to 49 feet gives 20 psf. It is important to note that these are the design wind pressures for the smallest resultant wind pressure of 20 psf. The Midwest region has a resultant wind pressure of 30 psf, which can be seen in the Figure 2-1 above. This results in a design wind pressure of 30 psf for buildings 30 feet to 49 feet in height (shown in table within the standard); an increase of 10psf from previous requirements for the same building height.



Wind Pressures for Various Height Zones Above Ground*

Height zone (ft)	Wind-pressure-map areas (lb per sq ft)						
	20	25	30	35	40	45	50
Less than 30	15	20	25	25	30	35	40
30 to 49	20	25	30	35	40	45	50
50 to 99	25	30	40	45	50	55	60
100 to 499	30	40	45	55	60	70	75
500 to 1199	35	45	55	60	70	80	90
1200 and over	40	50	60	70	80	90	100

Figure 2-3: Design wind pressures for various heights (psf) – A58.1-1955

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From the changes within the 1955 standard provisions, it can be concluded that there was more awareness of the effect of wind pressure on buildings. Thus, a more detailed pressure map was introduced into the standard. Following the 1955 publication by the American Standard Association, the American National Standards Institute takes on the task of modifying and publishing future provisions.

2.1.3 American National Standards Institute

1972

The next revision to the A58.1 Standard occurred in 1972 and was published under the author, American National Standards Institute (ANSI). This revision included several additions and updates to the previous standard publication.

The ANSI A58.1-1972 standard can be broken down into three major categories regarding the main wind force resisting system. The categories include 1) the basic data, such as wind speed, needed for design, 2) pressure coefficients, both internal and external, and 3) the final design wind pressure. Each category will be discussed with respect to the most relevant design information as it has changed from the previous standard.

A basic procedure for calculating wind loads is provided and includes determining the following three items: mean recurrence interval (MRI), basic wind speed, V, and an effective velocity pressure, p. Most buildings and structures employ a standard 50-year MRI; however the 1972 edition also includes means for a 100-year MRI and a 25-year MRI. These last two correlate to buildings with a high degree of hazard to human life and property, and a negligible risk to human life, respectively (ANSI, 1972). Having the three options to choose from is similar to applying an Importance Factor, I, to the design (which had not been introduced to the standard yet). After selection of the proper MRI, the engineer selects a basic wind speed from the basic wind speed maps of the United States based on both MRI and location within the country. The basic wind speeds make use of a fastest-mile speed measurement that is recorded at a height of 30 feet off the ground in open, level country (ANSI, 1972). The final component in the basic design procedure is to calculate an effective velocity pressure. First, wind speeds are converted to a velocity pressure using the provided equation:

$$q_{30} = 0.00256(V_{30})^2 \qquad \text{Equation 2.1.3-1}$$

This equation for velocity pressure is very similar to the one mentioned in the commentary of the 1945 publication. The only difference is the value of the conversion factor, 0.00256 – this one is more precise than the previous coefficient. Next, this velocity pressure is converted into separate effective velocity pressures for two categories: (1) the Buildings and Structures, q_F, (MWFRS) and (2) the Parts and Portions, q_P, (components and cladding). It is important because it utilizes two new variables that were not present in the previous standard.

$$q_F = K_z G_F q_{30} \qquad \text{Equation 2.1.3-2}$$

The velocity pressure coefficient, K_z, accounts for the type of exposure the building or structure is in as well as the height of the building. The gust factor, G_F, also is dependent on the type of exposure, as well as any dynamic response characteristics of the structure. Three exposure categories are described in the standard; A, B and C. Category A is for centers of large cities and very rough, hilly terrain. Category B is for suburban areas, towns, city outskirts, wooded areas, and rolling terrain. Category C is for flat, open country, open flat coastal belts, and grassland. (ANSI, 1972) Values of q_F have been tabulated with respect to building height and exposure category.

The next category within the A58 standard is pressure coefficients. External and internal pressure coefficients are applied to determine the design wind pressure. The 1972 standard has a design procedure for Buildings and Other Enclosed Structures. In this case, enclosed refers to a typical, rectangular building with vertical walls that may have doors and operable windows, with approximately the same square footage of openings on all sides (ANSI, 1972). External pressure coefficients, C_P, are tabulated for windward walls, leeward walls, side walls, and other buildings. For the interior of a building or structure, an internal pressure must be calculated, which includes an effective velocity pressure, q_M, (at height z) and an internal pressure coefficient, C_{pi}. Each of these variables is given in tables within the standard according to exposure category, basic wind speed, and height of building. As a final note, local pressure coefficients are provided in the standard for the ends of external walls, where the wind will likely have a harsher affect on the structure. However, the local pressures should not be added to the other external pressures (ANSI, 1972). The two pressure types are not added together because the structure would be over-designed. The main external pressures are for the design of the structural system, whereas the local pressures are for the design of the building cladding.

After all variables have been determined, a final design wind pressure can be calculated. The 1972 standard includes a single equation for the design of enclosed structures, which incorporates the effective velocity pressure and pressure coefficients.

$$p = qC_p - q_M C_{pi} \qquad \text{Equation 2.1.3-3}$$

As can be concluded, this pressure is a net pressure for the entire structure. Both internal and external, and windward, leeward and sidewall pressures have been taken into account. The first ‘q’ term in the equation is substituted with q_F, used for the main wind force resisting system, which was discussed previously.

The ANSI A58.1-1972 had many major additions for the wind provisions. More information was presented directly into the standard rather than in a commentary. This is useful for engineers in understanding how the design wind pressure is calculated. Also, the wind pressures are able to be more exact based on the location of a building or structure due to the variables that are accounted for. This standard was revised and published again in 1982 with further changes to the wind provisions.

1982

The 1982 addition of the A58.1 standard included substantial modifications in regards to wind design. The most noticeable difference in the ANSI A58.1-1982 is the addition of specific methods for calculating wind loads to structures, the Analytical Procedure and the Wind-tunnel procedure, which requires specific testing of the building model. To design buildings and structures for wind using the Analytical Procedure, three design factors must be found: velocity pressure, gust response factor, and pressure or force coefficients. Each factor will be discussed with respect to the most relevant design information as it has changed from the previous standard.

Similar to the previous standard, the velocity pressure, q, incorporates the wind speed, along with other factors, and converts it to an effective pressure. As the design process continues, the velocity pressure will be multiplied by appropriate gust factors and force coefficients to eventually become a design wind pressure acting on the building surface. The equation given by ANSI A58.1 – 1982 for determining the velocity pressure is as follows:

$$q_z = 0.00256K_z(IV)^2 \qquad \text{Equation 2.1.3-4}$$

Also similar to the 1972 standard, the coefficient 0.00256 is used as the primary conversion factor of wind speed, measured in miles per hour (mph), to wind pressure, measured in pounds per square foot (psf). The terms for exposure, K_z, and importance, I, are both new to the equation; however K_z was accounted for in the previous standard, just later in the design process. The Importance factor is used to account for potential hazard or need of the building during emergency situations. Four importance categories are specified in the standard and an importance factor is selected based on which category the building or structure fits into best. Since an importance factor is contained in the equation, selecting the basic wind speed, V, has changed since the 1972 standard. Before, one would select the basic wind speed in regards to which MRI was desired; a longer MRI indicating a building is of lesser importance or harm to people and the environment. The current wind speed map is associated with an annual probability of 0.02, or a 50-year MRI (ANSI, 1982). A second difference in the two wind speed maps is the height at which the basic speed was measured; 30 feet for the first, and 33 feet for the latter. A measurement of 33 feet corresponds to the metric measurement of 10 meters. Velocities are measured in locations deemed Exposure Category C, such as at airports. Refer to Figures 2-2 and 2-3 for a comparison of the two basic wind speed maps.

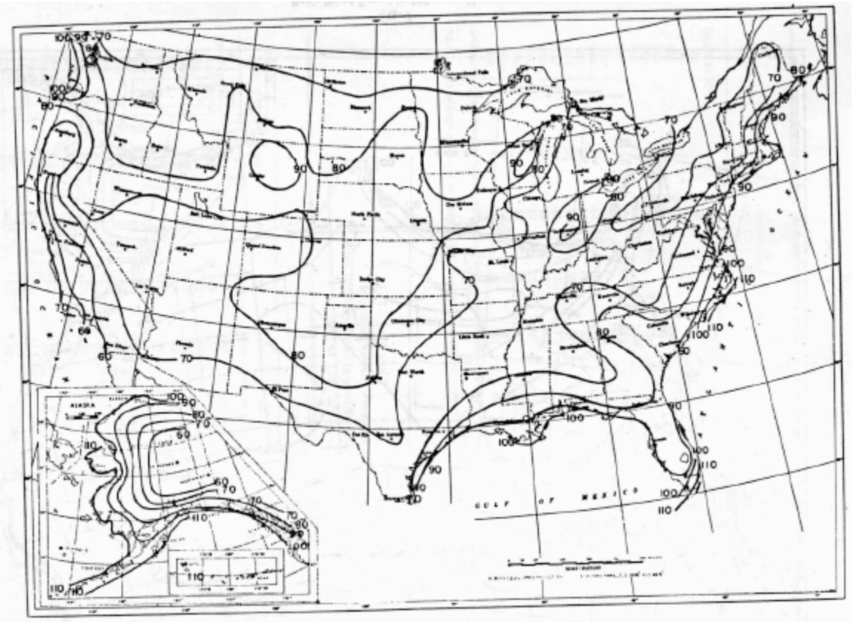
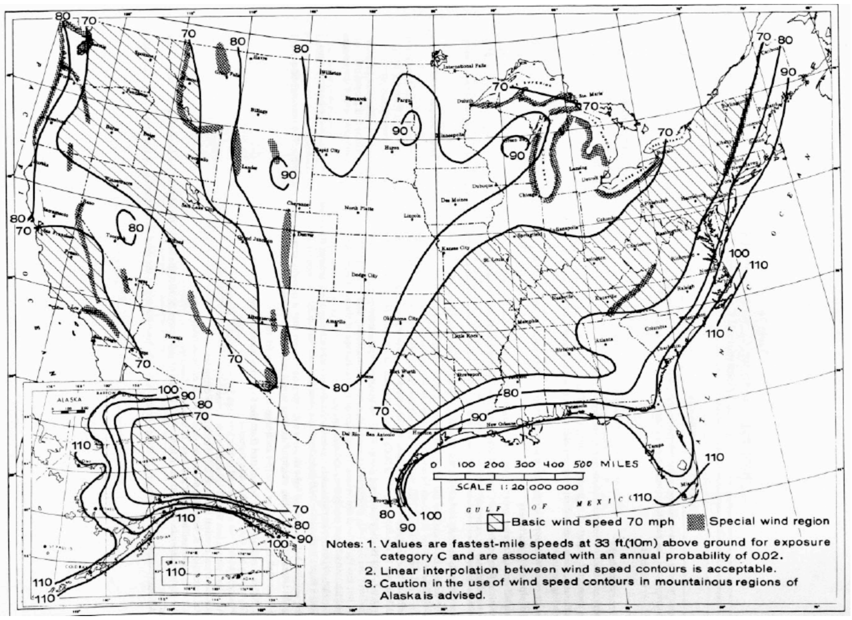


Figure 2-4: Basic Wind Speed (miles per hour) in ANSI A58.1-1972 standard, 50-year MRI

With permission from ASCE



Notes: 1. Values are fastest-mile speeds at 33 ft.(10m) above ground for exposure category C and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is acceptable.
3. Caution in the use of wind speed contours in mountainous regions of Alaska is advised.

Figure 2-5: Basic Wind Speed (miles per hour) in ANSI A58.1-1982 standard

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Exposure Categories is the final topic that needs to be discussed for determining the Velocity Pressure. Four exposure categories are specified in the standard; Exposure D is an addition to the previous standard. This category is for flat, unobstructed coastal areas that are directly exposed to the wind flowing over large bodies of water (ANSI, 1982). The inclusion of category D allows for more efficient wind design in the southern states, as well as those near the Great Lakes. The next step in the design process is to determine the Gust Response Factors.

The concept of including a Gust factor is new in the 1982 version of the standard. This factor is utilized in order to account for the variable nature of wind and the additional loading effects it can have on buildings and other structures (ANSI, 1982). The wind speed used to determine the value of the gust response factor is the fastest-mile wind speed. All gust factors have been tabulated based on Exposure category and building height. Occasionally, these factors are combined with the pressure coefficients, which will be covered next.

As in the previous standard, both external and internal pressure coefficients are applied to the design wind pressure. External pressure coefficients, C_P, are tabulated for windward walls, leeward walls, and side walls. The values within the table have been updated slightly since the 1972 publication; instead of only one value for leeward walls, there are three and they are based on Length-to-Width ratios. A figure has also been included for reference. It denotes how the external pressure coefficients should be applied to the building or structure. Similarly, the interior surfaces of a building or structure require an internal pressure coefficient, C_{pi}, which accounts for the area of doors and windows present on the surface. This term is only used in the design of C&C, not the MWFRS. Different from the previous code, the internal pressure coefficients are paired directly with the gust factors and should not be separated (ANSI, 1982).

After all variables (velocity pressure, gust response factor, and pressure or force coefficients) have been determined, a final design wind pressure can be calculated. The 1982 standard provides a table that signifies various building types and denotes which equations should be utilized for the various cases. This is new since the 1972 version. For the Main Wind Force Resisting System (MWFRS) of buildings, only one design wind pressure equation is given. Components and Cladding (C&C) differs for heights less than or greater than 60 feet. The design wind pressure for the MWFRS is defined by ANSI A58.1 – 1982 as:

$$p = qG_hC_p \qquad \text{Equation 2.1.3-5}$$

The design pressure is calculated for each wall, with a different velocity pressure, q, being utilized for the various element types. Once the pressure for each surface is known, the pressures are added together to determine the governing net loading case. For one-story buildings and possible other frames, including the internal pressure as part of the net pressure design may give the most critical load (ANSI, 1982). This equation appears as such:

$$p = qG_hC_p - q_h(GC_{pi}) \qquad \text{Equation 2.1.3-6}$$

As in previous standards, a minimum design wind pressure requirement of 10 psf is specified as well. Finally, this Analytical Procedure has limitations. While it can be applied to the majority of buildings and structures, it cannot be applied to those with unusual geometric shapes or those located in certain terrain areas (ANSI, 1982). For buildings and structures in these cases, the Wind Tunnel method must be employed instead.

The ANSI A58.1-1982 had one major modification for the wind provisions – the addition of the Analytical Procedure. Prior to this, basic equations were provided in order to determine the design wind pressure on a building. The commentary also has valuable information that further explains the requirements of the standard. This aids designers in understanding how the factors for wind pressure design are calculated. The 1982 publication of this standard was the final version produced by the American National Standards Institute. In 1988, when the next revision was published, the American Society of Civil Engineers (ASCE) sponsored it.

2.1.4 American Society of Civil Engineers, ASCE 7

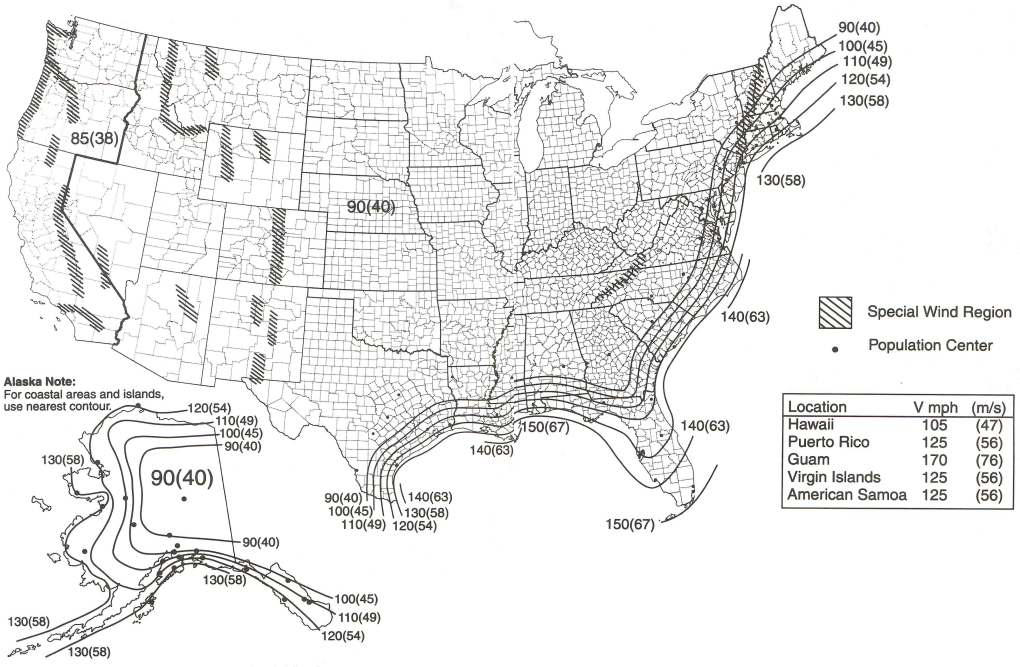
The year 1988 marked the first year that the American Society of Civil Engineers (ASCE) published the standard, "Minimum Design Loads for Buildings and Other Structures". Subsequent editions were published in 1993, 1995, 1998, 2002, and 2005. It was not until the 1995 publication that any modifications were made to the standard since the ANSI A58.1-1982.

1995

The ASCE 7-95 included numerous changes and additions to the wind load provisions. Noticeable changes to how the design wind pressure is determined include: added definitions, measure of basic wind speed, low-rise and all heights building provisions, an updated velocity pressure equation with many new terms, a standard gust effect factor, and overall re-organization to the design procedure. Each modification will be discussed as it is presented within the design process.

For the first time, a distinction is made for building type. A building or structure can be classified as Enclosed, Partially Enclosed, or Open. The classification type will have an impact on the internal pressure coefficients that are selected for the structure. Also, a low-rise building type is defined and set apart. Buildings and structures are low-rise if their height is less than or equal to 60 feet and if the mean roof height does not exceed the least horizontal dimension (ASCE, 1995).

The Basic Wind Speed, V, is now measured as a 3 second gust wind speed versus a fastest-mile wind speed. Measurements are still taken at 33 feet above ground as in previous standards. Wind speeds within the standard are based on data from the National Weather Service (NWS), and they decided to phase out fastest-mile wind speed measurement. The 3-second gust method measures the peak gust speed and is associated with an averaging time of 3 seconds. Measurements from over 400 NWS locations throughout the United States were considered in this update. (ASCE, 1995) Due to the change in how wind speed was being measured, the basic wind speed map within the standard was also changed. Figure 2-6 below shows the basic wind speed map with speeds measured in miles per hour.



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

FIG. 6-1. Basic Wind Speed

Figure 2-6 Basic Wind Speed (miles per hour) in the ASCE 7-95 Standard

With permission from ASCE

In the ANSI A58.1 – 1982 version of the standard, design provisions were given for the main wind force resisting system and for components and cladding. The ASCE 7-95 has now differentiated between low-rise buildings and buildings of other heights, providing separate design equations. The same is true for the design of components and cladding. The primary difference can be seen in the velocity pressure with the use of q_z for windward walls, measured at height z above the ground, versus q_h for leeward walls, which is measured at the mean roof height. In the new low-rise provisions, q_h is considered for both windward and leeward walls. Also, a new form of the gust effect factor is used for the low-rise design provisions and will be discussed subsequently. The velocity pressure equation has been slightly modified since the previous standard and will be discussed next.

As new research has been completed, variables and factors have been modified and added to the velocity pressure equation. The latest equation, as specified in the ASCE 7-95 is:

$q_z = 0.00256K_zK_{zt}V^2I$ Equation 2.1.4-1

Previously, the basic wind speed and importance factor were one term that was squared. Now, only the velocity term is squared. The new factor, K_{zt}, is called the topographic factor and takes into account abrupt changes in the landscape that are not considered in the terrain exposure categories. An equation is provided and values are tabulated for the determination of the topographic factor. Generally, this value will be taken as 1.0. A quick comparison between the calculation of velocity pressure in the 1982 standard and the 1995 standard shows that the latter is slightly more conservative. Next, the adjustment of the gust effect factor will be discussed.

Instead of finding values of a gust effect factor in a table based on exposure category, the standard now assigns one specific value for each exposure category. Exposures A and B have G equal to 0.8 and exposures C and D have G equal to 0.85. These values are for rigid buildings. New to the standard is a requirement to determine a gust effect factor for flexible buildings and structures. As mentioned previously, there are now design provisions for low-rise buildings. The equation given incorporates a variation of the velocity pressure as well as a combined gust effect factor and pressure coefficient. This new combined factor is tabulated and therefore, the gust effect factor should not be determined separately. (ASCE. 1995)

In the ASCE7-95, both the design procedure and how the standard is organized have changed significantly from previous standards. Many new figures and tables are provided for the designer; however they are not placed in such a way so as to guide one through the design process easily. For example, the tables for determining K_{zt} are placed several pages before reaching the equation and section that refers the designer to the appropriate tables. The organization of the standard has evolved in future versions, which will be discussed.

1998

The 1998 publication of the ASCE 7 standard brought both minor and significant changes from the previous edition. The most prominent change was the addition of the Simplified Procedure. In the ASCE 7-95 provisions were added for low-rise buildings, which have now been given a designation, namely the Simplified Procedure. All wind pressures are tabulated based on Enclosure type and Basic Wind Speed. According to the foot notes, multiplication factors should also be included for the various Exposure Categories (these are tabulated) and for

Importance Factors other than 1.0. There are also a few minor changes to the design process for low-rise buildings, which is noticeable in the various factors that must be determined.

The next significant change was the addition of a wind directionality factor, K_d. This factor takes into account that wind can come from multiple directions and that it will not always be at its highest intensity. Previously, these aspects were taken into account with just the load factors shown in figures provided in the standard. The load factors have been adjusted accordingly, and K_d should only be used in conjunction with the load factors.

In addition to the significant changes were multiple minor modifications, which are mostly seen in new definitions and revised requirements in the design process. For example, the topographic graphic has five checks to complete prior to selecting a value from the table, whereas previously it was only two or three checks. Also, the values internal pressure coefficients have been modified and re-tabulated based on new research.

The gust response factor was present in the last revision of the ASCE 7 standard, both in the main text as well as in the commentary. For the ASCE 7-98, equations for calculating a gust response factor for flexible buildings and structures has been moved from the commentary and placed in the main text of the wind provisions. The equations are slightly different from before, most likely due to continued research and findings.

Finally, the overall organization of the wind design provisions has been updated. The design pressure equations were previously listed in a table; categorized by building height, rigidity, and system being designed (main wind force resisting system or components & cladding). The equations are now provided as each particular design process is presented within the wind provisions. All figures and tables for any portion of the design process are located at the end of the wind provisions section.

2002

The ASCE 7-02 expanded on the previous provisions of the ASCE 7-98. First, the Simplified Procedure can now be used for buildings up to 60 feet in height, but the structure must be categorized as enclosed. There is now an equation provided for determining the design wind pressures. It is very similar to the provisions that were previously included in the footnotes. The adjustment factor that accounted for Exposure Category now accounts for Exposure as well as the height of the building. The design equation from ASCE 7-02 is as follows:

$p_s = \lambda I p_{s30}$ Equation 2.1.4-2

Where, p_{s30} = standard wind pressure for Exposure B, $\lambda = 1.0$ and $h = 30$ft

In previous editions of the ASCE 7 standard, there were four Exposure Categories. As of the 2002 publication, Exposure Category A has been dropped. This category was meant for large city centers where at least 50% of the buildings were greater than 70 feet in height. Exposure Category B will now be used for these conditions as well as the others prescribed within the standard. (ASCE, 2002) For each of the exposure categories, the prevailing distance requirements for wind coming in a particular direction were increased.

Another new consideration of the ASCE 7 standard is for torsional effects on the structure. Considerations are present for both the Low-Rise and All Heights provisions. According to the commentary, research on wind tunnel models showed that torsional effects needed to be accounted for in certain building types because it was significant to the overall design of the structure. There are four load cases discussed in the standard, just as were present in the two previous publications. The difference is that two of the load cases also require a torsional moment to be calculated. Various magnitudes of the design wind pressure are applied to each face either separately or simultaneously to give the worst-case scenarios. Illustrations and requirements are provided in the standard.

Finally, some of the figures and illustrations have been updated or changed slightly in the ASCE 7-02. For the most part, the updated figures give a clearer understanding of the overall wind design process and structural design process.

2005

After comparing the ASCE 7-02 to the ASCE 7-05, it appears that there are many changes and additions overall. Most of these are minor and include wording changes and formatting. There are three significant changes that have occurred; one of which make the provisions more complicated and one that simplifies the understanding of the provisions.

First, there is an added stipulation for using the Simplified Procedure. The building must be exempt from torsional cases as noted in Figure 6-10. Essentially, only buildings less than two stories in height or that have a flexible diaphragm are exempt from being designed for torsion. (ASCE, 2005) Therefore, the majority of buildings being designed must use the All Heights provisions. Second, thick black lines have been incorporated along the margins to indicate that a change or modification has been made to a particular part since previous standard. These lines may span an entire paragraph or a single sentence depending on what has changed.

Other modifications within the 2005 version are related to areas other than the main wind force resisting system, which is the scope of this report. A more detailed discussed of the design requirements for the MWFRS can be found in Section 3.

2.2 Model Building Codes

The United States was, to some extent, divided into regions as three primary professional associations were created and began to publish Model Building Codes. These three organizations were Building Officials and Code Administrators International (BOCA), Southern Building Code Congress International (SBCCI), and International Conference of Building Officials (ICBO). For over 80 years, the three aforementioned groups held discussions about building practices, code publications, and code revisions. Finally, in the early 1990's, leaders from the organizations made the decision to come together and form a new association, and produce one model building code with the hopes of it being accepted nationwide. (ICC, 2009) This new, non-profit organization is called the International Code Council (ICC) and it publishes the International Building Code, among others. The three older codes are now referred to as the "legacy codes". Beyond these professional associations and organizations, many cities, states and other government localities choose to write and revise their own building code instead of adopting the International Building Code (IBC). Other cities and states have their own code for certain aspects of building and construction, but have adopted the International Building Code as a primary or secondary reference.

This report addresses the three building code organizations that eventually came together and formed a single group. Knowing the history of these organizations will provide a better understanding of the combined group and its efforts in creating a single model building code. Along with the brief history of each group, the progression of the wind provisions within each building code will also be examined as was done previously for the Standards. The majority of the focus is placed on the Uniform Building Code, the code primarily used in the Midwest in the last century (Premier Steel, 2009), and the IBC, which is the current model building code. Figure 2-7 illustrates the approximate locations that each legacy code was used - exact use varied by state.

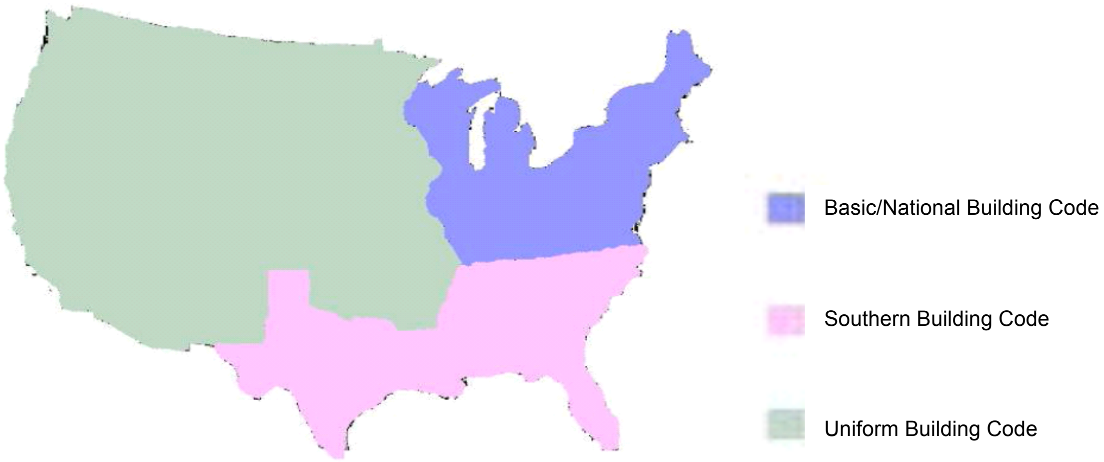


Figure 2-7: Approximate Legacy Code Regions

2.2.1 Basic/National Building Code - BOCA

The Building Officials and Code Administrators International, hereafter referred to as BOCA, was established in 1915. Officials from nine states and Canada founded the organization. Their purpose was “to provide a forum for the exchange of knowledge and ideas about building safety and construction regulation” (BOCA, 1950). It was not until 1950 that the organization published its first model code, the BOCA Basic Building Code. They published revisions of the code in 1965, 1970, 1978, and 1981. In 1984, BOCA published another revision of the Basic Building Code, however it was also labeled as the National Building Code (NBC). The BOCA NBC was revised and published on three other occasions; 1987, 1990, and 1996. Each of the BOCA codes includes comprehensive standards for all phases of building construction. The provisions for wind design are present in the 1950 Basic Building Code as well as in the codes that followed.

The BOCA codes were implemented in parts of the Midwest and, therefore, this report will examine the development of the wind provisions within these codes. The 1950, 1965, and 1978 wind provisions are discussed below.

1950 Basic Building Code

The Basic Building Code designs for wind pressures with the assumption that wind can come from any horizontal direction. Also, all buildings and structures must, “be designed to resist the torsional moment due to eccentricity of the resultant load with respect to the center of rigidity of the structure” (BOCA, 1950). The center of rigidity of a structure is only calculated and used when there is a rigid diaphragm transferring the loads to the vertical load resisting elements. For a structure with a flexible diaphragm, tributary areas are used for calculating force transfer. The diaphragm deforms and there is no torsional rigidity.

For wind in the horizontal direction acting on vertical surfaces, there are three categories for buildings. According to the 1950 Basic Building Code, the following terms apply (BOCA, 1950):

- For buildings/structures ≤ 50 ft, the load due to wind can be generally neglected unless the following is true:
  - Height > 4x(minimum width)
  - Adequate transverse bracing is not provided
- For building/structures ≤ 100 ft, the portion of the building from 50-100ft should be designed for 20psf wind pressure. The portion from 0-50ft is still generally neglected.
- For buildings/structures > 100 ft, the wind pressure will increase linearly 0.025psf every 1ft in height beyond the 100ft height mark. Still, from 0-50ft is generally neglected, and 50-100ft is designed for 20psf.

Other conditions for the vertical surfaces are that the wind pressures need to be distributed with 2/3 of the design wind pressure acting normal to the external windward surface and 1/3 of the design wind pressure acting normal to the interior leeward surface (causing outward suction). If a building or structure has more than 1/3 of its surface area as openings, there needs to be an internal pressure of 10 pounds per square foot applied simultaneously with the external pressures on all surfaces.

These basic requirements are very general and do not account for any items such as location, ground roughness, or known wind speed. The requirement that is of most interest is that the lower fifty feet of any building or structure is not actually being designed for wind pressures. It is unclear what the code means when it uses the term “generally neglected” for applying wind loads to low-rise structures, but it can be assumed to mean that a value of zero pounds per square foot need to be applied. Wind is present everywhere and in any direction, even within fifty feet from the ground surface. Perhaps it was common knowledge or practice at the time that gravity loads would always govern the design. After the vertical surfaces, the Basic Building Code has provisions for roof surfaces, an element that can be either horizontal or slightly non-horizontal.

Three different roof types are noted in the 1950 code: pitched roofs, curved roofs, and integral curved walls and roof. The code also provides information about wind loads on signs, tanks, radio towers, and chimneys. Each is given a wind pressure design requirement based mostly on height and net area that is exposed to the wind. The provisions for roofs and other structures are straight-forward and require minimal calculation beyond square-footage (area).

Section 717.0 of the 1950 code discusses cases when unusual wind exposures for buildings and structures may occur. For buildings and structures located in unusually exposed positions or in geographical regions subjected to higher wind loads than specified previously in the code, "the design wind load shall be determined by the prevailing conditions" (BOCA, 1950). *Prevailing conditions* is likely to mean that if another wind pressure is known to exist in the area based on previous measurements, then that pressure should be used in the design of the building or structure. However, it is still unclear whether or not a known wind pressure or velocity should be applied to the lower fifty feet of a structure, in regards to section 714.1 of the code.

1965 Basic Building Code

In the 1965 Basic Building Code, a distinction is made between primary and secondary members, which was not in the 1950 code. The primary and secondary members are referring to the MWFRS and the C&C, respectively. Another addition since the 1950 code excludes any type of large storm from the consideration of wind loads. Specifically, the code mentions that, "hurricanes, cyclones, tornadoes, and similar extraordinary wind pressures" are not considered in the wind pressure design provisions of the code (BOCA, 1965).

For wind in the horizontal direction acting on vertical surfaces, the following terms apply (BOCA, 1965):

- For buildings/structures ≤ 50 ft, the load due to wind pressure is 15psf
- For building/structures ≤ 100 ft, the portion of the building from 50-100ft should be designed for 20psf wind pressure.
- For buildings/structures > 100 ft, the wind pressure will increase linearly 0.025psf every 1ft in height beyond the 100ft height mark.

The requirements for distribution of wind loads onto the vertical surface are unchanged from the 1950 code, with the exception that the load is referred to as a pressure instead of a force. These two terms, pressure and force, can go hand-in-hand, but generally force indicates that the surface area has already been taken into account and it is being applied to a specific primary member.

Also new to the 1965 code are sections regarding external and internal pressures. Both sections are for the design of secondary members, namely the wall framing and wall panels and their connections. Along with the framing secondary members, C&C, a design requirement for glass pieces that are greater than or equal to four square feet is noted. This holds true for vertical sections as well as those less than or equal to 20 degrees off the vertical (BOCA, 1965).

1978 Basic Building Code

The 1978 Code includes both a Basic Wind Speed map and a table for effective velocity pressures of wind to be applied in design, based on the height of the building. The map, seen in Figure 2-6, divides the United States in to various regions and a basic wind speed is assigned. Wind Speeds are based on an annual extreme fastest-mile speed measure 30 feet above ground, for a 50-year mean recurrence interval. The pressure table, shown as Table 2-1 then translates the basic wind speed into an effective pressure based on geographic locations such as suburban areas, towns, outskirts, wooded areas, and rolling terrain (BOCA, 1978). The pressures increase as the building height increases. Heights range from less than 30 feet up to 825 feet.


Note a. This figure applies to all types of storms except tornadoes.
Note b. 1 foot = 304.8 mm; 1 mph = 0.447 m/s.

Figure 2-8: Basic Wind Speed map from Basic Building Code, 1978 (miles per hour)

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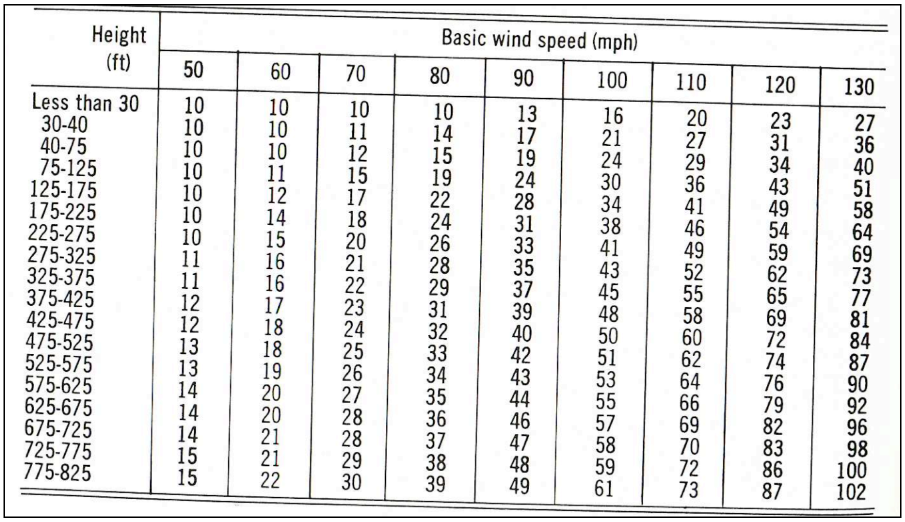

Height (ft)	Basic wind speed (mph)								
	50	60	70	80	90	100	110	120	130
Less than 30	10	10	10	10	13	16	20	23	27
30-40	10	10	11	14	17	21	27	31	36
40-75	10	10	12	15	19	24	29	34	40
75-125	10	11	15	19	24	30	36	43	51
125-175	10	12	17	22	28	34	41	49	58
175-225	10	14	18	24	31	38	46	54	64
225-275	10	15	20	26	33	41	49	59	69
275-325	11	16	21	28	35	43	52	62	73
325-375	11	16	22	29	37	45	55	65	77
375-425	12	17	23	31	39	48	58	69	81
425-475	12	18	24	32	40	50	60	72	84
475-525	13	18	25	33	42	51	62	74	87
525-575	13	19	26	34	43	53	64	76	90
575-625	14	20	27	35	44	55	66	79	92
625-675	14	20	28	36	46	57	69	82	96
675-725	14	21	28	37	47	58	70	83	98
725-775	15	21	29	38	48	59	72	86	100
775-825	15	22	30	39	49	61	73	87	102

Table 2-1: Basic Wind Speed table from the Basic Building Code, 1978

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Designed winds loads to buildings may be increased or decreased as well, depending on the location. For buildings to be located in flat, open country, design wind pressures should be increased per local data; whereas for buildings to be located in large cities or near hilly terrain, wind pressures can be decreased upon approval (BOCA, 1978). It is important to note that by mid-1970, engineers knew terrain conditions had an impact on the wind velocity, and thus wind pressure, acting on a building.

Similar to the 1965 Code, provisions for the primary framing members, and secondary framing members are included. The primary framing members, those responsible for providing stability for the building, are to be designed for external and internal pressures. For the external pressures, the windward pressure is applied inward on the wall while the leeward and side wall pressures are applied outward. On the other hand, all internal pressures are applied outward on the walls. According to the code, external and internal pressures should not be combined as a net pressure for the primary members, but need to be individually considered in the design process (BOCA, 1978). This is due to the fact that wind can cause a suction affect or ballooning affect on a building. Structural members must be able to resist either extreme. The 1978 code includes separate modification factors for external pressures on primary members that are positioned at an incline. This includes members that are a part of wall or roof surfaces.

In summary, the 1978 code included major changes since the 1965 code in terms of the design pressures applied to buildings. Instead of a pre-determined value that the 1965 code used for buildings in any area of the country, the 1978 code makes use of wind speed maps and effective velocity pressure which include considerations for geographic location.

Basic Building Codes in the 1980's

Three years after the 1978 code was published, another revision occurred - the 1981 Basic Building Code. In this edition no significant changes to the wind provisions occurred. Again, three years later a 1984 revision was published now bearing the name Basic/National Building Code. No further changes occurred in this version either. Following the 1984 code, subsequent codes would be listed under the name National Building Code only.

1993

The next available National Building Code was published in 1993. Since the 1984 edition, many modifications have been made. From an organization standpoint, a section of Definitions of terms has been incorporated, which is a helpful tool for designers. All other modifications are found within the design process and included changes to the Basic Wind Speed map, revisions to the Exposure Categories, and explicit design equations provided for the calculation of wind pressures.

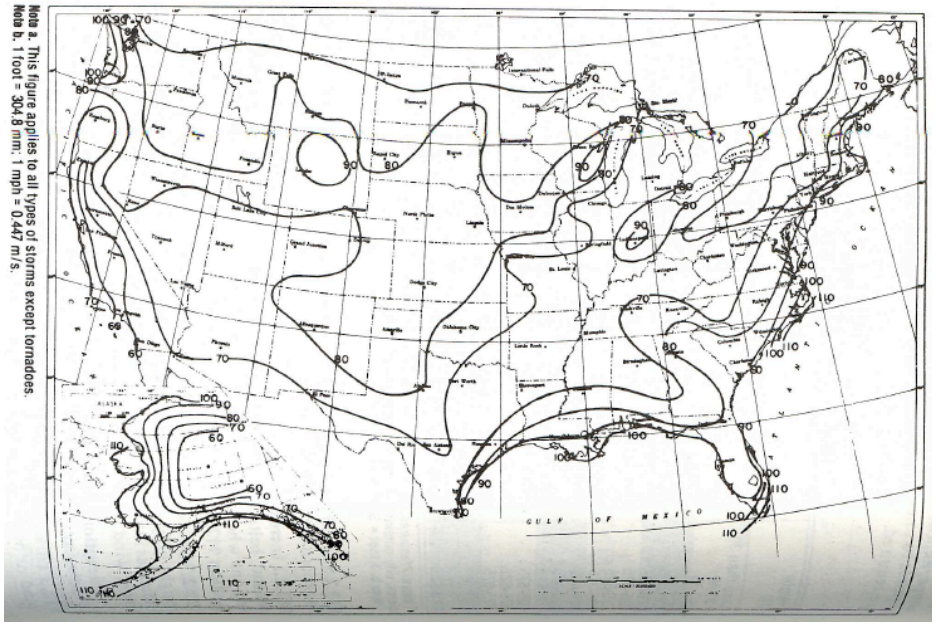
In the previous code edition, there were general statements and considerations for the topography surrounding a building. The 1993 NBC includes four specific Exposure Categories, which are an elemental part of the design process. Exposure A is designated for buildings within large city centers, Exposure B is designated for buildings located in urban and suburban areas, Exposure C is required for buildings located on open terrain, and Exposure D is designated for building located where the wind would flow over the water surface (BOCA, 1993). With the selected exposure, the gust effect factor and velocity pressure exposure coefficient are determined from tabulated values. These latter two terms are part of the design pressure equation, which will be discussed next.

Previously, pressures were determined by multiplying a basic wind pressure with tabulated coefficients. This was all written in paragraph format for the designer. New to the 1993 code, designs equations have been provided to facilitate in the design process. There are equations for the main wind force resisting system as well as components and cladding. Those for the MWFRS are shown below.

$$P = P_v\, I\, [K_z G_h C_p - K_h(GC_{pi})] \qquad \text{Equation 2.2.1-1}$$

$$P = P_v\, I\, [K_h G_h C_p - K_h(GC_{pi})] \qquad \text{Equation 2.2.1-2}$$

The first equation presented is for the design of windward walls, while the second equation is for the design of leeward and sidewalls. As can be seen, the only difference is in regards to the velocity pressure exposure coefficients, the use of K_h instead of K_z. The subscript z stands for any height above ground that is being evaluated, whereas h is defined as the mean roof height. Wind pressures are assumed to increase with increasing height above the ground on the windward face of a building. P_v is the basic velocity pressure and is tabulated within the code based on the basic wind speed, V (BOCA, 1993). The basic wind speed is determined from the map provided in the code and has been modified slightly since the 1984 code revision. Figures 2-5 and 2-6 below show the 1984 and the 1993 Basic Wind Speed maps, respectively. Both are based on a fastest-mile wind speed measured at 33 feet above the ground and with a 50-year mean recurrence internal. The modified contours can be seen from the two maps.



Note a. This figure applies to all types of storms except tornadoes.
Note b. 1 foot = 304.8 mm, 1 mph = 0.447 m/s.

Figure 2-9: Basic Wind Speed map from Basic/National Building Code, 1984 (miles per hour)

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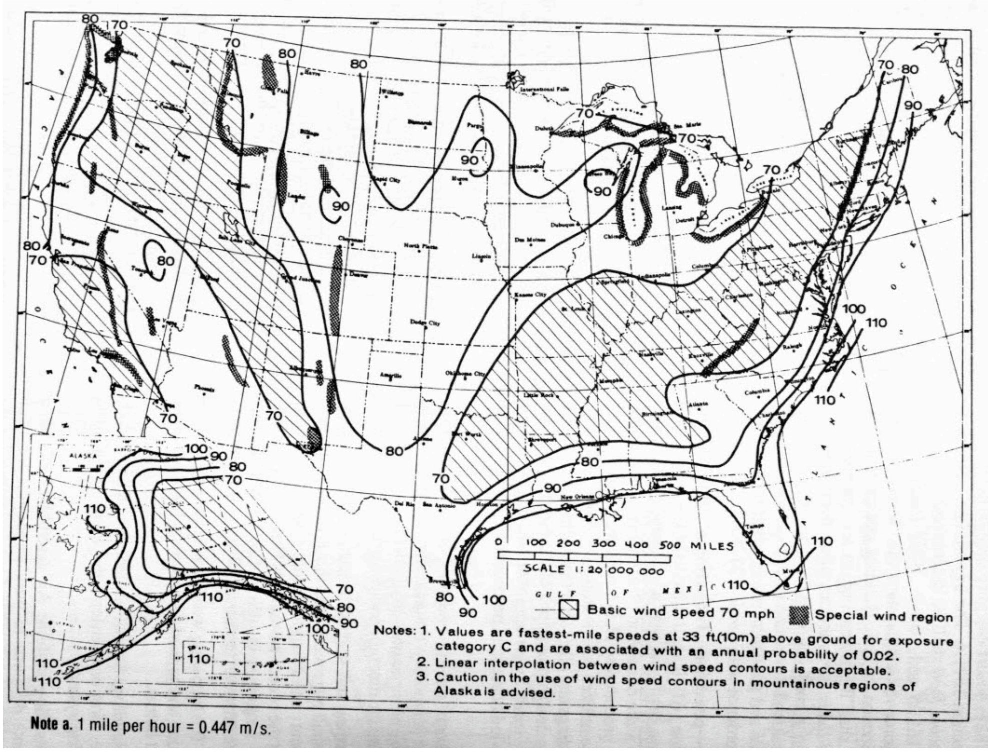

Notes: 1. Values are fastest-mile speeds at 33 ft(10m) above ground for exposure category C and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is acceptable.
3. Caution in the use of wind speed contours in mountainous regions of Alaska is advised.

Note a. 1 mile per hour = 0.447 m/s.

Figure 2-10: Basic Wind Speed map from the National Building Code, 1993 (miles per hour)

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Another modification since the prior edition of the code is related to the Internal and External pressure coefficients. Unlike the previous code, the pressure coefficients are applied simultaneously to each wall instead of separately. This can be seen in how the design equation is written: a net value is determined before multiplying it by the basic velocity pressure and importance factor, I. Also new are the Gust Effect factors. External pressure coefficients are multiplied by a corresponding gust effect factor, which is tabulated in terms of height and exposure category. Internal pressure coefficients are tabulated as a combined term with the gust effect factor. Meanings for each of these terms are similar to the current ASCE 7-05 terms and will be further discussed in Section 3 of this report

2.2.2 Uniform Building Code - ICBO

The International Conference of Building Officials, hereafter referred to as ICBO, is the author and publisher for the Uniform Building Code (UBC). The UBC was first established in 1927 at an annual business meeting held in Phoenix, Arizona. According to the Preface within each edition of the code, the UBC is, "dedicated to the development of better building construction and greater safety to the public by uniformity in building laws." (ICBO, 1943, et. al.) Further editions of the UBC are updated and published on a three-year cycle. Any person is permitted to suggest changes or revisions that should be incorporated into the code and these are reviewed in public hearings. Primarily, the UBC was adopted by states west of the Mississippi river (Ghosh, 2007) and its 1997 edition is still in use in some states today.

The earliest code available for research in this report was published in 1943 and code editions up to 1997 have been referenced in this report. Due to the considerable number of codes published, not all are referenced in this report. Code modifications and revisions related to the wind design provisions have been generalized based on the decade they were published in, focusing on major changes that occurred.

1940's

The 1943 version of the UBC includes specific values of wind pressures for various structure types. These design wind pressures are to be applied to all vertical surfaces. For buildings, the conditions for wind pressure magnitude were as follows: height < 60 ft, p=15psf; height > 60 ft, p=20psf (ICBO, 1943). If a building was going to be 100 ft in height, the lower 60 ft would be designed for 15psf wind pressure, while the remaining 40 ft would be designed for 20psf wind pressure.

The wind design provisions of the 1949 UBC did not change from the 1943 version. This means that the 1946 UBC also saw no modifications. However, a precursor was added prior to the design provisions. The general notes states that, “Buildings and structures and every portion thereof shall be designed and constructed to resist the wind pressure specified…All bracing systems shall be designed and constructed to transfer the wind loads to the foundations” (ICBO, 1949).

Also within the 1949 UBC, a section dedicated to the design of open framed structures was added (ICBO, 1949). This is the first time that a distinction is made between typical buildings and open structures.

1950’s

Before the 1958 version of the UBC was published, two other versions (one in 1952 and the other in 1955) were published, following a three-year cycle. Similar to the 1949 version, there only slight modifications occurred during these years. The only design modification was in regards to building type. Greenhouses, lath houses, and agricultural buildings were thought of differently than typical buildings. These facilities were required to be designed for a wind pressure not less than 10 psf (ICBO, 1958). This requirement is the first time a distinction is made in regards to the importance of a building or structure. Greenhouses, lath houses, and agricultural buildings did not have great numbers of occupants inhabiting them each day.

1960’s

The 1967 UBC brought multiple changes from the previous versions. Since the 1958 version, editions were also published in 1961 and 1964. The initial noticeable change is the statement regarding that wind could come from any direction and should be designed as such (UBC, 1967). While this fact may have been common practice in previous years, it is now a minimum requirement for all building designs. Also new since the 1958 version of the UBC is a definition for an enclosed building; which requires the building to be enclosed at the perimeter with solid exterior walls. Openings are allowed in the exterior walls if they are glazed or protected with door assemblies (ICBO, 1967). The reason that a distinction is made between enclosed and unenclosed buildings is for the purpose of designing the building for uplift wind pressures.

For the first time, tables and maps are present in the code as a design aid for the wind pressure provisions. The map, called “Allowable Resultant Wind Pressure” separates the United States in regions and assigns a basic design wind pressure. The map is shown as Figure 2-11. The majority of the Midwest region falls into the category of 40 psf, with some of the northern states as low as 25 psf (ICBO, 1967). The pressure from the map is then applied to a table that gives revised design wind pressures based on the height of the building. This table is called, “Wind Pressures For Various Height Zones Above Ground” and ranges from less than 30 ft up to 1200 ft and over. A footnote associated with the table reminds designers that the pressures are recommended as minimums and that the minimum requirements do not provide for tornadoes (ICBO, 1967).

Many updates occurred during the 1960’s for the UBC. The most prominent being the wind pressure map and table design aids. These design aids allow buildings and structures located in different regions of the United States to be designed accordingly, and not over- or under-designed. Similar maps, tables and other design aids continue to be a part of the wind design provisions in future codes.

1970’s

Following the three-year cycles, UBC revisions during the 1970’s were published in 1970, 1973, 1976 and 1979. After close study and comparison of the 1976 and 1979 versions to the 1967 version of the UBC, it is seen that no changes in regards to the main wind force resisting members were made. The only update occurred in the 1976 version and involved an increase in the height condition for minimizing wind pressures on miscellaneous structures (greenhouses, lath houses and agricultural buildings) from 10 ft to 20 ft (ICBO, 1976).

1980’s

Three code revisions were published throughout the 1980’s decade, occurring in the years 1982, 1985, and 1988. Most changes can be seen in the 1982 version, with minor additions and changes thereafter. It is in the 1982 version that a clause is now included about adjacent structures to the building under design. The clause reads, “No reduction in wind pressure shall be taken for the shielding effect of adjacent structures” (ICBO, 1982). By the 1970’s and 1980’s, the population was growing which meant an increase in the need for more buildings and structures. The “shielding effect” of nearby buildings would be accounted for by an Exposure factor, which will be described subsequently.

Two primary design aspects are introduced in the 1982 UBC: The first is an equation in which to determine the design wind pressure for a building, the second is a description of two different design methods for applying the wind pressures to the building. First, the design equation will be examined and discussed. The equation given in the 1982 UBC is as follows:

$$p = C_e C_q q_s I \qquad \text{Equation 2.2.2-1}$$

Four factors are in the equation, some of which are new considerations to the wind pressure design provisions. The first factor, C_e, is the coefficient for combined height, exposure and gust factor. The value is provided in a table with respect to height and exposure factor. The idea of an Exposure Factor is also new to the UBC. Two exposure categories described, Exposure C and Exposure B. Per the code, “Exposure C represents the most severe exposure and has terrain which is flat and generally open, extending one-half mile or more from the site. Exposure B has terrain which has buildings, forest or surface irregularities 20 feet or more in height covering at least 20 percent of the area extending one mile or more from the site” (ICBO, 1982). Both of these exposure factors, with very similar definitions, exist in the current building standards and model building codes.

The second factor, C_q, is the coefficient for the type or portion of structure that is being designed. The various values are listed in a table, separated according to what part of the building it is. Some of the categories include primary frames and systems, elements and components, and chimneys, tanks and solid towers. The table indicates if the factor should be applied inward or outward based on which element is being designed (i.e. windward or leeward).

The wind stagnation pressure is the third element in the equation and is denoted by q_s. This pressure is measured at a standard height of 30 ft as the C_e factor already accounts for the building height. Similar to previous versions of the UBC, a map of the United States shows the effect of wind in various regions. Different from those previous codes, however, is the fact that the map shows basic wind speeds instead of wind pressure. The basic wind speeds are obtained from 50-year wind speed records. As a convenient design aid, the wind speeds are converted into pressures (q_s) and are located in a table. The former wind pressure map, first illustrated in the 1967 UBC, and the basic wind speed map first incorporated in the 1982 UBC are shown for comparison in Figures 2-11 and 2-12, respectively.

The final element in Equation 2.2.2-1is the importance factor, I. Generally, this factor will always be equal to 1.0, except when designing an essential facility. This type of facility is one that must be safe and usable for emergency purposes, and includes hospitals, medical facilities, fire and police stations, municipal government disaster operation centers, and buildings where 300 or more people could assemble. For these, an importance factor of 1.15 is specified (ICBO, 1982). The four factors described herein make up the design wind pressure equation, *p*, the first of two primary design aspects newly introduced in the 1982 version of the UBC. Next the two design methods will be discussed.

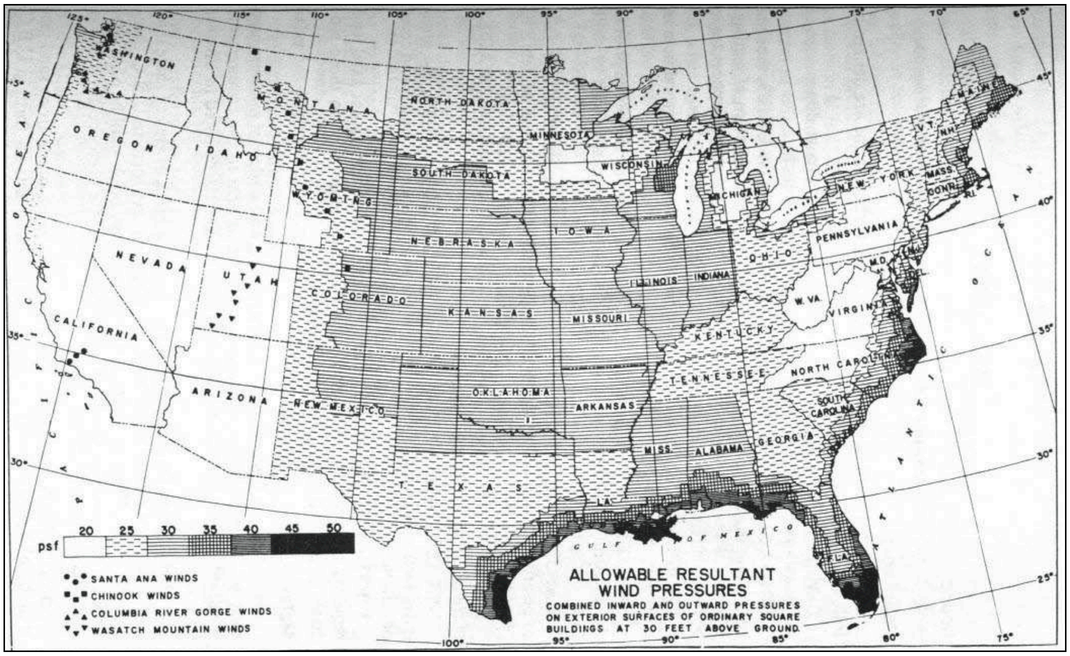

Figure 2-11: Allowable Resultant Wind Pressure in pounds per square foot (psf), 1979 UBC

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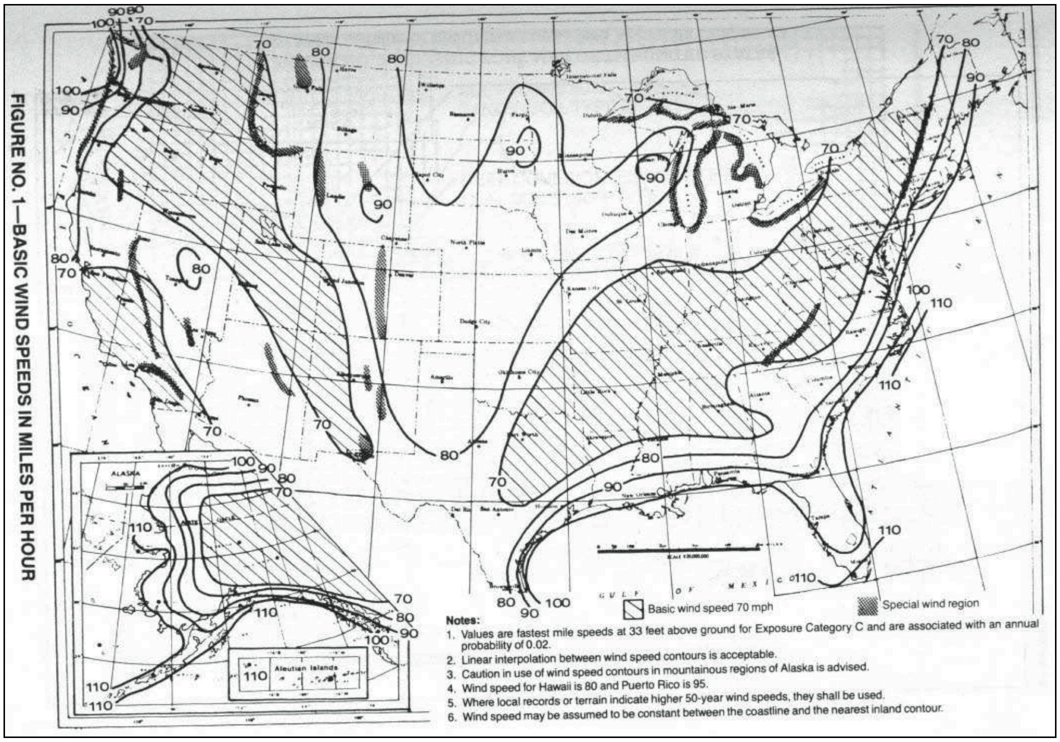

Notes:

1. Values are fastest mile speeds at 33 feet above ground for Exposure Category C and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is acceptable.
3. Caution in use of wind speed contours in mountainous regions of Alaska is advised.
4. Wind speed for Hawaii is 80 and Puerto Rico is 95.
5. Where local records or terrain indicate higher 50-year wind speeds, they shall be used.
6. Wind speed may be assumed to be constant between the coastline and the nearest inland contour.

Figure 2-12: Basic Wind Speed in miles per hour (mph), 1982 UBC

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The second primary design aspect is the inclusion of two design methods for applying wind pressures to a building. Previously, the practice was to apply wind pressures normal to all vertical surfaces and horizontal to all other surfaces in completing the design process. The two methods referenced in the 1982 UBC are Method 1, Normal Force Method and Method 2, Projected Area Method (ICBO, 1982).

The normal force method (Method 1) can be used for any structure type. With this method, all wind pressures are assumed to act simultaneously on all exterior surfaces. The projected area method (Method 2) can only be used in the design of structures less than 200 feet, and cannot be used for gable rigid frames. For this method, both vertical and horizontal surfaces are considered. Horizontal pressures acting on the full area of vertical surfaces and vertical pressures acting on the full area of horizontal surfaces are assumed to act simultaneously. (ICBO, 1982) Both methods are very similar to one another. In conjunction with the two design methods are stipulations about the use of the coefficient, C_q. All building elements are designed for two loading cases: over the entire tributary area and at local areas of discontinuity such as corners, ridges and eaves. These conditions, when compared to current standards and codes, are referring to the central portion of a wall and the end zone of a wall, respectively.

Beyond these two major design aspects, other minor changes occurred in the 1982 version of the UBC as well. One notable change is the definition of an open structure. It is defined in the code, as, “A structure with more than 30% of any one side open Nonimpact-resistant glazing shall be considered as an opening" and is listed as a footnote to the pressure coefficient table (ICBO, 1982). The second notable change is the inclusion of a statement regarding structures that are or could be sensitive to dynamic effects. The designer is instructed to use approved national standards when designing these types of structures.

Significant changes were made to the wind design provisions in the early 1980’s, but in the code revisions published in 1985 and 1988 only subtle modifications were made. No changes to the design process occurred in the 1985 UBC, however the 1988 version had some definition modifications.

Once again, the definition for an Open Structure was adjusted, this time in the 1988 version of the UBC and as a stand-alone section instead of as a footnote to a table. While a building or structure used to be considered “open” if 30% of one side of was open, now the condition was reduced to 15%. This new requirement can be applied to buildings, structures or stories within a building or structure. Similar to previous codes, windows and doors may or may not be considered as openings. To qualify and non-openings, all windows, doors or other openings located in exterior walls must be specifically detailed and designed to resist the design wind loads and pressures applied to a building (ICBO, 1988).

1990’s

Three code revisions were published throughout the 1990’s decade, occurring in the years 1991, 1994, and 1997. Changes can be seen in all three publications. The codes will be discussed chronologically so that changes made are easy to discern.

Revisions to the 1991 code include both organizational as well as design changes. The most prominent organizational update is the addition of a Definitions section. This new section is placed at the beginning of the wind design provisions. It allows designers to become familiar with the terms prior to design, as well as gives them a common place to turn to when looking for a definition of a term in the design process. Within the definitions are terms that are new to the UBC and will be discussed subsequently.

The same design equation that was introduced in the 1982 code is still utilized with the same coefficients, but with minor adjustments and additions to these coefficients. The first factor, C_e, is still used to describe the exposure the building is located in. In addition to Exposures B and C, there is now an Exposure D. It is defined as follows: "Represents the most severe exposure in areas with basic wind speeds of 80 mph or greater and has terrain which is flat and unobstructed facing large bodies of water over one mile or more in width relative to any quadrant of the building site…extends inland from the shoreline ¼ mile or 10 times the building height, whichever is greater" (ICBO, 1991).

The pressure coefficient, C_q, and the wind stagnation pressure, q_s, the second and third factors, respectively are unchanged in their meaning from previous codes. As before, in order to determine the wind stagnation pressure the basic wind speed must be determined and selected from the map provided in the code. The basic wind speed is now based on a fastest-mile wind speed that is associated with a 50-year mean recurrence interval, also known as an annual probability of 0.02, and is measured at a height 33 feet (10 meters) above the ground (ICBO, 1991).

The final element of the design equation is the importance factor. Now, there are multiple values for the importance factor, based on the occupancy category of the building. The use of Occupancy Categories is an addition to the 1991 UBC. There are four occupancy categories and each has an importance factor associated with it. Category 1 is reserved for Essential Facilities, which were described in present in previous codes. Hazardous Facilities are established in Category 2 and are given the same importance factor as Category 1 facilities. Category 3 and 4 are intended for Special Occupancy Structures and Standard Occupancy Structure, respectively. Both categories are assigned the same importance factor.

These changes within the 1991 UBC have improved the accuracy of the wind design process without bringing about unneeded complications. The next code revision, published in 1994, also incorporated improvements, which aids in the design process.

Similar to many of the previous codes, the definition for the openness of a building or structure has undergone alterations. The term Opening is defined separately from the description of the building type, but maintains the same meaning as before. The two terms used to describe the type of building are Partially Enclosed Structure or Story and Unenclosed Structure or Story. The first term was previously referred to as an Open Structure or Story and the latter term is unchanged. The names of the terms now more closely reflect their meaning and are beneficial to a designer.

A second change in the 1994 UBC has the addition of a fifth occupancy category. Category 5 is reserved for Miscellaneous Structures, but maintains an importance factor of 1.0. Although the code does not specify, this category may have been added for seismic design purposes instead of wind design.

The 1997 UBC was the final code revision published by ICBO. There were no changes or modifications made since the 1994 version of the UBC. This alludes well to the fact that the ICC had been formed in 1994 and was already working toward producing a common model building code that incorporated the three previous building codes used throughout the country.

2.2.3 International Building Code - ICC

The International Code Council, ICC, was established as a nonprofit organization in 1994. It is comprised of officials from three previous professional code organizations: Building Officials and Code Administrators (BOCA), Southern Building Code Conference International (SBCCI), and the International Conference of Building Officials (ICBO). When deciding to combine efforts, the primary goal of this new organization was to develop “a single set of comprehensive and coordinated national model construction codes” (ICC, 2009). In 2000, ICC published the first comprehensive code, the International Building Code (IBC). This code does not have regional limitations as the other codes did; any city, state or other government body can adopt this code, in full or in part, for use in the design and construction of buildings. The IBC is revised and republished on a three-year cycle. Each new edition must be adopted by a city and/or state to become the governing code.

The wind design provisions within the IBC are less extensive compared to the separate codes in the past. With the existence of a building standard, the ICC has referred to the ASCE 7 for much of the wind design process. Each new edition incorporates more changes, resulting in fewer design provisions directly from the Building Code. The IBC 2000, 2003 and 2006 will be discussed below as modifications were incorporated into the wind design provisions.

2000 IBC

2000 marked the first year of the combined model building code. Instead of pulling provisions from each of the previous codes – NBC, SBCCI, and UBC – the IBC refers to the ASCE 7 standard as a guide stating, "Wind loads on every building or structure shall be determined in accordance with Section 6 of ASCE 7" (ICC, 2000). However, the IBC does include provisions for low-rise structures that can be used in place of the ASCE 7 provisions. The low-rise provisions allow for buildings up to 60 feet in height versus only 30 feet in the ASCE 7. Beyond the height requirement, the provisions are very similar to one another.

Given that three codes were combined to create one model code, figures were updated as well. The figures and tables provided in the IBC 2000 are simple and easy to understand. The basic wind speed map has changed significantly since any of the previous codes. It is based on a three-second gust speed, similar to the ASCE 7 wind speed map, instead of a fastest-mile speed. This will be discussed in further detail in Section 3 of this report.

2003 IBC

The 2003 IBC followed the provisions of the ASCE 7 standard even more closely than the 2000 IBC. Changes include the removal of Exposure Category A, additional stipulations for the low-rise simplified procedure, and updated figures and tables. All of the changes correspond to the current ASCE 7 standard at the time. As in the previous code edition, the ASCE 7 wind design provisions are permitted to be utilized in place of those in the IBC. Finally, thick black lines have been included in margins to indicate changes from the previous IBC edition.

2006 IBC

The wind design provisions in the 2006 IBC are almost obsolete. All reference is given to the wind provisions of the ASCE 7-05 standard (Barbera, 2007). A noticeable update to this code is the increasing amount of definitions and other requirements. For example, there is a much more detailed description for what the American Society of Testing and Materials (ASTM) standards requires regarding opening and glazing specifications.

Other trivial modifications include an equation and table for the conversion of the three-second gust speed to a fastest mile wind speed, the addition of Surface Roughness categories and updated Exposure Categories to match those in the ASCE 7, and small black arrows in the margins to indicate that a something has been removed.

SECTION 3.0: Design Wind Pressures to Midrise Buildings

As shown in the previous chapter, the American Society of Civil Engineers (ASCE) publishes the ASCE 7 standard, *Minimum Design Loads for Buildings and Other Structures*. Every few years (usually 3 years, but no more than 5 years), the standard is revised and republished. The report makes use of the ASCE 7-05, the most recent standard available. The model building code, the IBC 2006, refers engineers and designers to the ASCE 7 for determination of structural loads and calculations. For wind load considerations, three methods of determining wind loads are presented in the standard: Simplified Procedure, Analytical Procedure, and the Wind Tunnel Procedure. The first two design methods encompass the vast majority of building designs; however the third method is also available to be applied in any design circumstance, given the designer has the available means. This report focuses on the Analytical Procedure as it is the primary means available for determining design wind loads to Mid-rise structures.

The ASCE 7 Analytical Procedure for determining wind loads on the Main Lateral (Wind) Force Resisting System may be used when a building is regular shape with no unusual geometrical irregularity in spatial form and the building does not have response characteristics making it subject to cross wind loading, vortex shedding, instability due to galloping or flutter; or does not have a site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special consideration. The Analytical Procedure takes into consideration the load magnification effect caused by gusts in resonance with along-wind vibrations of flexible buildings.

3.1 ASCE 7 Basic Design Considerations for the Analytical Wind Procedure

Fundamentally, determining design wind loads for a building is comprised of taking into account each factor that would effect how the wind interacts with a building. These factors are known as Design Considerations. The Design Considerations can be categorized: (1) the building constraints, (2) the site constraints, and (3) the combination of the two for final design. In category one, this report discusses the enclosure classification, geometry of the structure, the rigidity of the building – whether it is rigid or flexible, and the building occupancy classification as it relates to the Importance Factor, I, used in the basic wind pressure equation. In category two, this report discusses the various surface roughness and exposure categories, the relevance of the topographic factor, and the basic wind speed associated with the site. The last category focuses on factors related to both the building and site, or factors needed to determine the final design wind pressure which is discussed in Section 3.2.

3.1.1 Building Enclosure Classification

A building may be classified in three ways: Open, Partially Enclosed, or Enclosed. These classifications relate to the proper selection of the internal pressure coefficients used to determine the wind pressures on various building surfaces. A typical building is generally found to be Enclosed or Partially Enclosed depending on the percentage of openings in the building envelope. An Open Building is defined as, “a building having each wall at least 80 percent open.” (ASCE, 2005) In equation form:

$$A_o \geq 0.8A_g \qquad \text{Equation 3.3.1-1}$$

A_o represents the total area of openings in a wall, which receive positive external pressure, while A_g represents the gross area of the wall where A_o is identified (ASCE, 2005). Examples of open structures include a parking garage that has open sides or a picnic shelter at a park. A Partially Enclosed building has two conditions that must be met for classification. In both conditions, the wall that receives positive external pressure is compared to the remainder of the walls. First, “the total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of opening in the balance of the building envelope (walls and roof) by more than 10 percent,” and second, “ the total area of openings in a wall that receives positive external pressure exceed 4 ft^2 or 1 percent of the area of that wall, whichever is smaller, and the percentage of opening in the balance of the building envelope does not exceed 20 percent” (ASCE, 2005). In equation form:

$$A_o > 1.10A_{oi} \qquad \text{Equation 3.3.1-2}$$

$$A_o > 4ft^2 \text{ or } > 0.01A_g, \text{ and } A_{oi}/A_{gi} \leq 0.20 \qquad \text{Equation 3.3.1-3}$$

A_{oi} represents the sum of the areas of openings in the building envelope (walls and roof) not including A_o. A_{gi} represents the sum of the gross surface areas of the building envelope not including A_g. A_o and A_g were defined previously. All variables can be measured in ft^2 or m^2. If a building does not meet the criteria for an Open structure or a Partially Enclosed building, then it is classified as an Enclosed building. The flowchart provided below, Figure 3-1, gives a visual representation of the classification process.

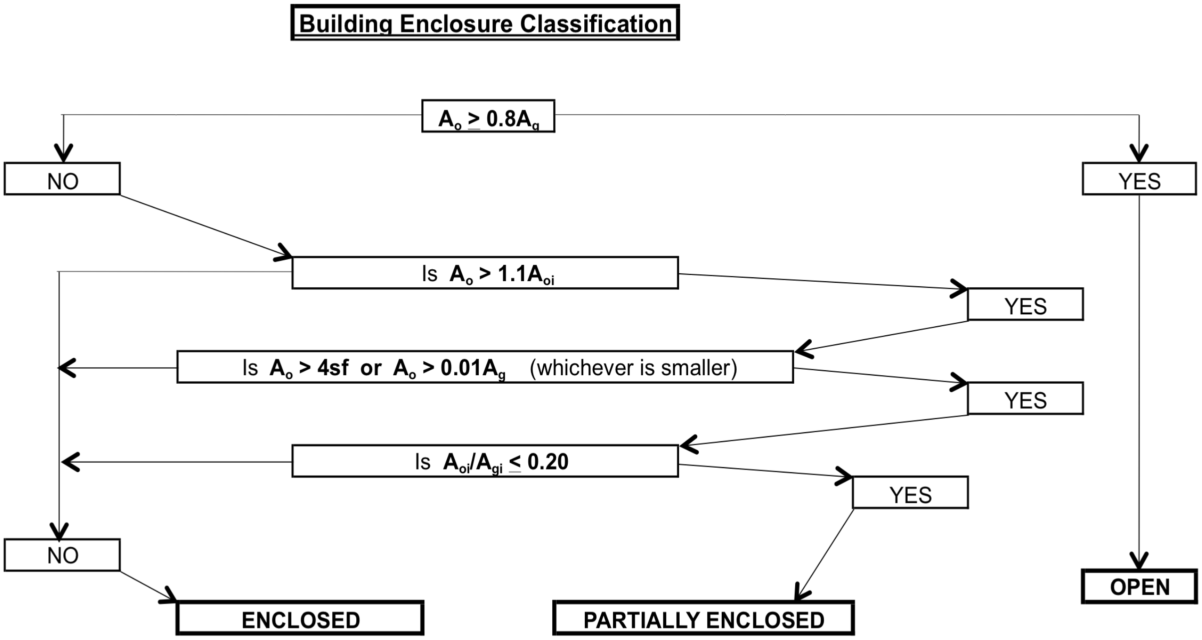


Figure 3-1: Building Enclosure Classification Flowchart

3.1.2 Geometry of Building

Building geometry refers to the plan dimensions, length, width and height. In conjunction with these three space dimensions, a building may have certain irregularities as well – not all buildings are rectangular in shape. The ASCE 7-05 refers to buildings that are "regular" shaped, meaning, "a building or other structure having no unusual geometrical irregularity in spatial form" (ASC, 2005). Of the three spatial dimensions (length, width and height), the height will have the greatest effect for wind pressures to buildings. The wind speed increases with height above the ground in accordance with the power law. The plan dimensions of the building factor into the final force, base shear or overturning moment that is acting on the structure.

Another factor associated with building geometry is the overall rigidity of a building. "To estimate the dynamic response of a structure, knowledge of the fundamental frequency (lowest natural frequency) of the structure is essential." (ASCE, 2005) Structures are classified as Rigid or Flexible. In most cases, low-rise structures are classified as rigid because the plan dimensions are larger than the overall height and they are less than 60 feet in height. Midrise structures require more consideration in determining their classification. The standard defines a rigid structure as, “A building or other structure whose fundamental natural frequency is greater than or equal to 1 Hz” (ASCE, 2005). Flexible buildings have a similar definition. “Slender buildings and other structures that have a fundamental natural frequency less than 1 Hz” are defined as Flexible (ASCE, 2005). According to the commentary on the ASCE 7, a slender building is one in which the building height exceeds four times the least horizontal dimension of the building.

The fundamental natural frequency and period of building are inverses of one another. The exact period of a building cannot be determined until after the building has been designed; therefore codes and standards provide empirical formulas. “The fundamental vibration period of a building appears in the equation specified in the building codes to calculate the design base shear and lateral forces. Empirical formulas are provided that depend on the building material (steel, reinforced concrete, etc.), building type (frame, shear walls, etc.), and overall dimensions.” (Goel, 1998)

For rigid and some flexible mid-rise structures, the wind-induced resonant vibrations are negligible and the fluctuating wind responses can be calculated using procedures applicable for static loads; such as the Analytical Procedure in the ASCE 7 standard. Determining if the structure is flexible or rigid is subjective unless a computer model of the structure is used to determine the fundamental frequency. In this case, a percent damping, selected at the engineer’s discretion, would need to be accounted for. If computer modeling/analysis is not applied, an approximate fundamental frequency may be used. In applications for wind design, it may be non-conservative to approximate the fundamental natural frequency of a building. “An estimated frequency higher than the actual frequency would yield lower values of the gust effect factor and likewise, a lower design wind pressure.” (ASCE, 2005)

For the parametric study in Section 4, the structure would need to be 400 feet tall to be classified as slender, which seems unreasonable. The commentary on the ASCE 7-05 also defines the approximate fundamental frequency for steel moment frames and concrete moment frames (MF) with equations C6-14 and C6-15, respectively. These are provided below:

$$n_1 = 22.2/H^{0.8} \qquad \text{Equation 3.1.2-1}$$

$$n_1 = 43.5/H^{0.9} \qquad \text{Equation 3.1.2-2}$$

Where n_1 = fundamental natural frequency (Hz)

In addition, the approximate fundamental natural frequency of a building may be determined by first calculating the period of the structure and then taking its inverse. Generally, this method is used in seismic consideration because the period of the building, as opposed to its natural frequency, has a greater impact on how the seismic forces are interacting with the structure. The fundamental period is defined by the ASCE 7-05 as:

$$T_a = C_t h^x_n \qquad \text{Equation 3.1.2-3}$$

This equation is found in the Seismic Provisions within the standard. C_t is one of the coefficients that accounts for the structural frame type. The exponent x also accounts for the structural frame type. Table 12.8-2 in the ASCE 7-05 provides the list of frame types and their requirements. Lastly, h_n is the height of the building or structure measured from the base to the highest level of the structure. As mentioned previously, the fundamental natural frequency is the inverse of the natural period, or $1/T_a$. Table 3-1 outlines the three methods available for determining the fundamental frequency of a building, as well as the heights (measured in feet) when a building changes from a rigid to flexible classification. Both steel and concrete moment frames are shown, in correlation to the parametric study in section 4.

Frequency Method Used	**Steel MF (ft)**	**Concrete MF (ft)**
Commentary Eqns C6-15 and C6-15	48.2	66.2
Seismic Period Eqn 12.8-7	87.3	99.0
4 x least horizontal dimension	400.0	400.0

Table 3-1: Natural Frequency Determination Methods and Heights when building changes from a rigid to flexible classification

Tables 3-2 and 3-3 show a more detailed breakdown of the building natural frequency at ascending heights and for various framing system types. Table 3-2 is based on Equations 3.1.2-1 and 3.1.2-2 for steel MF and concrete MF, respectively. Table 3-3 is based on Equation 3.1.2-3 from the seismic provisions.

Building Ht (ft)	Steel MF	Concrete MF
30	1.461	2.037
40	1.161	1.573
50	0.971	1.287
60	0.839	1.092
70	0.742	0.950
80	0.667	0.843
90	0.607	0.758
100	0.558	0.689
120	0.482	0.585
140	0.426	0.509
160	0.383	0.452
180	0.348	0.406
200	0.320	0.369

Table 3-2: Natural Frequency, Commentary method

Building Ht (ft)	Steel MF	Concrete MF	Steel BF	All other
60	1.350	1.569	1.546	2.319
70	1.193	1.366	1.377	2.066
80	1.072	1.211	1.246	1.869
90	0.976	1.089	1.141	1.711
100	0.897	0.991	1.054	1.581
120	0.775	0.841	0.919	1.379
140	0.685	0.732	0.819	1.228
160	0.616	0.649	0.741	1.111
180	0.561	0.584	0.678	1.017
200	0.515	0.531	0.627	0.940

Table 3-3: Natural Frequency, Seismic Period method

The upper portions of both tables have been shaded in orange to indicate a Rigid classification because the frequency, f, is greater than or equal 1.0 Hz. The lower portions of the tables have been shaded in blue to indicate a Flexible classification because the frequency, f, is less than 1.0 Hz. For the purpose of this report, the Steel MF and Concrete MF systems will be examined in the parametric study that is presented in a subsequent section of this report, as these are the typical framing systems used in Mid-rise buildings. Steel and Concrete MF systems are more flexible than other lateral force resisting systems and, therefore, are the most conservative cases and will interact with wind forces the greatest. It should be noted that although a building, based on its height, is classified as Rigid in Tables 3-2 and 3-3, it may still fall under the flexible category if the slenderness requirements are not met. The ASCE 7 standard states that any building with a height greater than four times its least horizontal dimension is classified as flexible. Only one of the two flexibility requirements needs to be met in order to classify a building as flexible. This will also be examined in the subsequent parametric study.

Upon examining the results of each of the three fundamental frequency methods for a structure, listed in Table 3-1, it was concluded that the natural period method from the Seismic Provisions should be utilized. First, the flexible height determined for each of the moment frames fell in the middle range of all approximations. The upper approximations of 400 feet, and the lower approximations of 48 feet and 66 feet, appear unreasonable for the parametric study. Second, only the natural period equations within the Seismic Provisions are actually part of the ASCE 7 standard. The other two approximation methods are referenced within the commentary on the ASCE 7-05. Finally, the purpose of the parametric study that follows is not to determine exact design wind pressures, but rather to establish how and why the design wind pressures changes for various building types; therefore, use of the natural period approximation will be sufficient for the scope of this report.

3.1.3 Importance Factor

Buildings and structures are built for a variety of functions. They can be used to house students at a school, to protect livestock on a farm, or as a warehouse holding products and goods. The ASCE 7 standard assigns an Importance Factor for each building based on its intended purpose, also referred to as occupancy category, and these values are tabulated. The importance factor is used to adjust the level of structural reliability of a structure to be consistent with the building classifications. Four building classifications are defined ranging from buildings housing goods, to buildings housing hazardous materials. The importance factors given in Table 6-1 of the ASCE 7-05 adjust the velocity pressure to different annual probabilities of being exceeded. Importance factor values of 0.87 to 1.15 are, for the non-hurricane winds, associated with annual probabilities of 0.04 and 0.01 (MRI’s of 25 and 100 years) of being exceeded, respectively. The mean return interval of 50 years is associated with an importance factor of 1.0 and a building classification of category II.

This report focuses on mid-rise structures in Occupancy Category II, which are often made use of as hotels or office buildings. For the purpose of the parametric study, an Importance Factor of 1.0 corresponding to an occupancy category II will be utilized. The building itself is not the only factor that is related to wind pressure design; consideration is also given to the surrounding terrain and the effects it has on the approaching winds.

3.1.4 Basic Wind Speed

Wind, is a fluid that flows at various velocities. It is defined specifically as the flow or movement of air in the atmosphere that occur because of atmospheric pressure differentials caused by solar radiation. The velocity of the air is dependent upon height above the ground, as well as the terrain that it is flowing over. The basic wind speed is the wind speed specified in the code as the fastest-mile wind speed associated with an annual probability of being exceeded of 0.02 (equivalent to 50-year return period). Eventually, the velocity is transformed into a pressure by means of a coefficient. This section will focus on how wind speeds are measured and on what basis, prior to being changed into an equivalent pressure.

The National Weather Service collects wind speed data from numerous locations throughout the United States (U.S.) using anemometers. Data locations are most often airports where the surrounding terrain has minor effect; categorized as Exposure C. Measurements are taken at 33 feet (10m) above the ground and are evaluated as a 3-second gust speed. The National Weather Service as redefined the basic wind speed to be the peak gust that is recorded and archived at each data location (ASCE, 2005). Generally, the average time it takes to reach a peak gust is about 3 seconds, thus the 3-second gust speed. The ASCE 7 standard provides a map of the U.S. for selection of a Basic Wind Speed. The entire Midwest region lies in the area consistent with a Basic Wind Speed of 90 miles per hour (mph). The next item to discuss is the height and exposure chosen for the data stations.

3.1.5 Terrain Characteristics

A mixture of land and water terrains present on the earth's surface affect wind speeds. This effect is in correlation with the power law mentioned previously. Dr. Narendra Taly summarizes the effect of the power law as follows: “The wind velocity at the ground surface is near zero. The transition from the surface velocity to the gradient velocity is referred to as variation of wind velocity with height. The variation in wind speed with height is logarithmic up to about 300 ft above the ground, beyond which the variation in wind speed is insignificant. Ground roughness and man-made obstructions together retard the movement of air close to the ground surface; the rougher the terrain, the greater the retardation – reduction in wind speed. Below the gradient height, wind speed varies; the variation is strongly influenced by ground surface roughness, which is the cumulative drag effect of any obstacle to the free movement of wind." (Taly, 2003) The Midwest region contains large and small cities, open farmland, rolling hills and others. A velocity pressure exposure coefficient and a topographic factor must be selected for a specific site in order to determine the overall design wind pressure. The first coefficient, exposure coefficient, is based on an Exposure Category, while the latter factor, topographic factor, has separate requirements that must be examined.

The ASCE 7 standard describes three exposure categories based on Ground Surface Roughness. The Ground Surface Roughness categories describe the types of terrain that the building is surrounded by, such as forest or open land. Surface Roughness B is intended for urban and suburban locations, wooded areas, or other terrain with many closely spaced obstructions. Surface Roughness C is intended for terrain that is open and flat, with scattered obstructions of heights less than 30 feet, including grasslands and water surfaces that are in hurricane prone regions. Surface Roughness D is intended for terrain that is flat and contains no obstructions, or water surfaces outside of hurricane regions. (ASCE, 2005) Next, the Exposure Categories describe the distance requirements that a Surface Roughness must meet for the Exposure to hold true. The distance is generally one half to one mile in the upwind direction of the building or 20 times its height. Exposure C is the standard for when the requirements of B or D are not met. The focus of this report is midrise structures in suburban/urban areas in the Midwest of the U.S. Therefore, Exposure Category B is used for this report.

The topographic factor used in wind pressure design is influenced by the landscape. This factor accounts for wind speed-up when abrupt changes occur in the landscape such as over hills, ridges or escarpments. Five constraints must be met in determining the value of this coefficient; otherwise it will take a value of one. Figure 3-2 below is a flowchart illustrating the process of determining the topographic factor, K_{zt}.

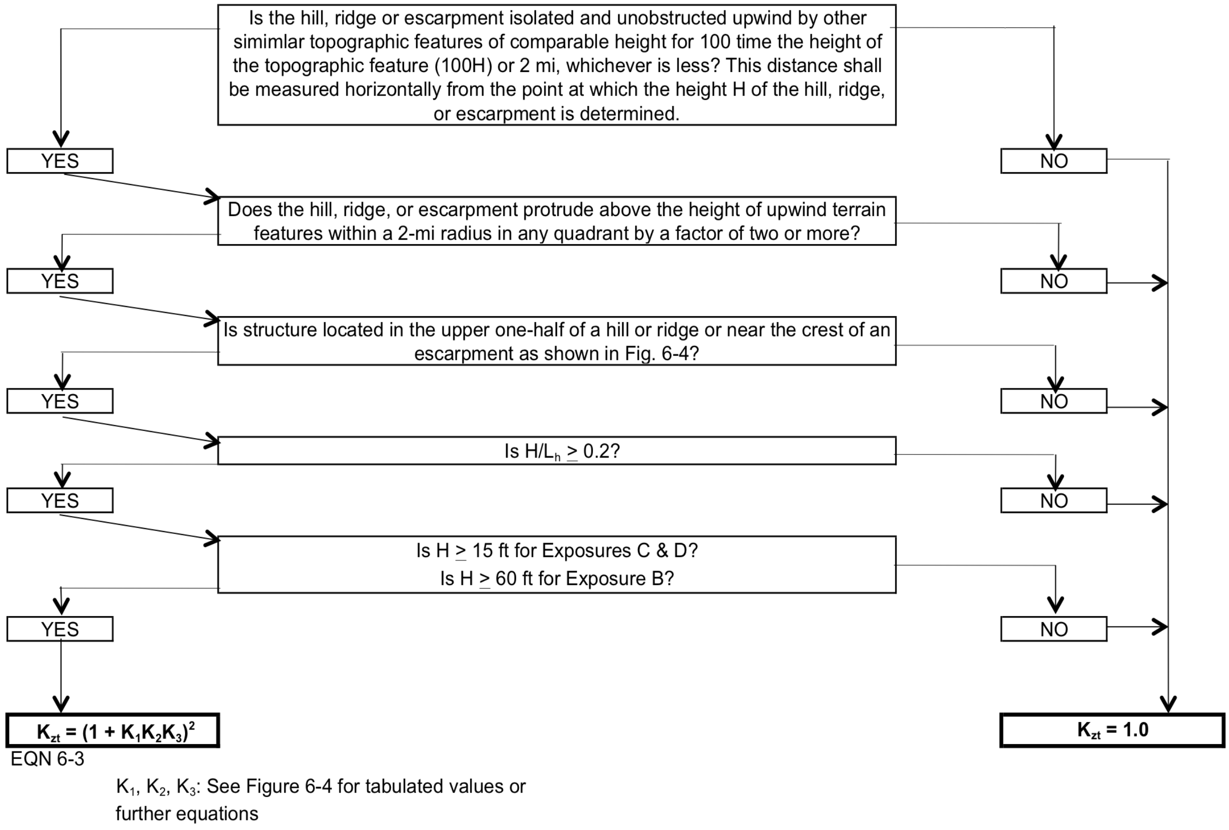


Figure 3-2: Flowchart for Determination of Topographic Factor, K_{zt}

As noted in the figure, values for K_1, K_2, and K_3 are tabulated with accompanying pictures for reference. The five criteria have changed slightly since previous versions of the ASCE 7 standard. All of the aforementioned factors are used to determine a Velocity Pressure for a given building or structure.

3.2 Method 2: Analytical Procedure

Wind is a load which induces a dynamic response in the structure. The three methods of determining the wind forces on a building are given in the ASCE 7. The first two methods, the simplified and analytical, apply the wind statically to the structure. The third method, wind tunnel, uses dynamic response of the structure. For rigid and some flexible structures, the wind-induced resonant vibrations are negligible and the fluctuating wind responses can be calculated using procedures applicable for static loads. The analytical procedure assumes application of static wind pressures to the structure. The gust effect factor applied within the design process accounts for the dynamic response of flexible buildings that is actually occurring. All factors used in the analytical procedure design process to calculate the design wind pressures are: velocity pressure, wind directionality factor, gust effect factor, internal and external pressure coefficients.

3.2.1 Velocity Pressure

The velocity pressure is the equivalent pressure after being converted from the basic wind speed. A coefficient, as well as multiple factors already discussed, is included in the equation for an accurate adjustment. The velocity pressure is not the final design pressure applied to the building; gust effect factors and pressure coefficients must still be accounted for. The equation for determining velocity pressure is given in the ASCE 7-05 as follows:

$$q_z = 0.00256K_zK_{zt}K_dV^2I \qquad \text{Equation 3.2.1-1}$$

The constant, 0.00256, is a conversion factor that takes into account the mass density of the air. It is based on a standard temperature of 59 degrees Fahrenheit and a sea level pressure of 29.92 inches of mercury (ASCE, 2005). Air density is dependent on altitude and temperature; therefore, the constant could be different for locations across the United States. It is noted in the commentary that other values for the constant may be used if there is sufficient weather data available to validate the use. The second term, K_z, is the velocity pressure coefficient. It is based on both height above the ground and the terrain exposure. Values have been tabulated, but may also be determined with the equation provided in the footnotes of Table 6-3 in the ASCE 7-05. The theory behind the formulation of the velocity pressure coefficient values is based on the power law relationship and boundary layer models, discussion of which is outside of the scope of this report. The topographic factor, K_{zt}; Basic Wind Speed, V; and Importance Factor, I; were all discussed previously. The final term, K_d, is the wind directionality factor, which has two purposes. The first is to account for the reduced possibility that maximum winds will come from any given direction and the second is for the reduced possibility of the maximum pressure coefficient occurring for any given wind direction. For all buildings, this factor has a set value of 0.85 given in Table 6-4. This factor is only to be used in conjunction with the Load Combinations. In previous standards, the wind directionality factor was included with the wind load factor in the load combinations. Separation of these two factors allows them to be modified independently of one another as further research and data becomes available (ASCE, 2005).

Since the focus of this report is to compare surface pressures on mid-rise buildings, the directionality factor does not need to be used.

3.2.2 Gust Effect Factor

A gust effect factor is used in one of the final steps of determining the wind pressures. As the name implies, the gust effect factor, G or G_f, accounts for the unpredictable wind gusts that occur in nature, and how the turbulence created interacts with the structure. According to the commentary on the ASCE 7, the gust effect factor "also accounts for along-wind loading effects due to dynamic amplification for flexible buildings. It does not account for across-wind loading effects, vortex shedding, and instability due to galloping or flutter, or dynamic torsional effects." (ASCE, 2005).

For low-rise structures it is paired with the external pressure coefficient, GC_{pf}, and tabulated. The gust effect factor can also be determined and applied separately from the external pressure coefficient for any building height. Buildings of higher heights, such as mid-rise buildings, have a different type of interaction with wind turbulence than low-rise buildings; therefore, two gust effect factors might be used in design. The first one, G, is for rigid structures. The standard provides a direct method for determining a rigid gust effect factor, with the alternative that a typical, conservative value of 0.85 may be use instead. The second factor is the flexible gust effect factor, G_f, used in conjunction with flexible buildings, accounting for the dynamic response of the building. This factor can either be determined using the direct method provided in the standard or by another rational procedure (ASCE, 2005), such as wind tunnel testing and computer modeling. Factors for both rigid and flexible buildings are utilized in the parametric study, as they are applicable. Five tables have been generated to show how the gust effect factor changes based on building dimensions, material, and slenderness. Calculated frequencies shown in Table 3-3 were used in making the following tables.

Building Ht.	Building Material				
(ft)	Steel MF	Concrete MF	Steel BF	All other (S)	All other (C)
60	0.835	0.835	0.835	0.835	0.835
70	0.835	0.835	0.835	0.835	0.835
80	0.835	0.835	0.835	0.835	0.835
90	0.863	0.835	0.835	0.835	0.835
100	0.867	0.852	0.835	0.835	0.835
120	0.875	0.857	0.862	0.835	0.835
140	0.883	0.863	0.867	0.834	0.834
160	0.891	0.868	0.872	0.833	0.833
180	0.899	0.874	0.877	0.833	0.833
200	0.907	0.880	0.881	0.851	0.845

Table 3-4: Gust Effect Factors for 100ft x 100ft Building

Building Ht.	Building Material				
(ft)	Steel MF	Concrete MF	Steel BF	All other (S)	All other (C)
60	0.811	0.811	0.811	0.811	0.811
70	0.813	0.813	0.813	0.813	0.813
80	0.814	0.814	0.814	0.814	0.814
90	0.831	0.815	0.815	0.815	0.815
100	0.834	0.826	0.816	0.816	0.816
120	0.840	0.830	0.832	0.817	0.817
140	0.846	0.834	0.836	0.818	0.818
160	0.851	0.838	0.840	0.818	0.818
180	0.857	0.842	0.843	0.818	0.818
200	0.863	0.846	0.847	0.829	0.826

Table 3-5: Gust Effect Factors for 100ft x 200ft Building – Transverse Direction

Building Ht.	Building Material				
(ft)	Steel MF	Concrete MF	Steel BF	All other (S)	All other (C)
60	0.835	0.835	0.835	0.835	0.835
70	0.835	0.835	0.835	0.835	0.835
80	0.835	0.835	0.835	0.835	0.835
90	0.863	0.835	0.835	0.835	0.835
100	0.866	0.852	0.835	0.835	0.835
120	0.874	0.857	0.862	0.835	0.835
140	0.882	0.862	0.866	0.834	0.834
160	0.889	0.867	0.871	0.833	0.833
180	0.897	0.873	0.875	0.833	0.833
200	0.905	0.878	0.880	0.851	0.845

Table 3-6: Gust Effect Factors for 100ft x 200ft Building – Longitudinal Direction

Building Ht.	Building Material				
(ft)	Steel MF	Concrete MF	Steel BF	All other (S)	All other (C)
60	0.779	0.779	0.779	0.779	0.779
70	0.782	0.782	0.782	0.782	0.782
80	0.785	0.785	0.785	0.785	0.785
90	0.795	0.787	0.787	0.787	0.787
100	0.798	0.794	0.789	0.789	0.789
120	0.804	0.798	0.800	0.792	0.792
140	0.809	0.802	0.804	0.794	0.794
160	0.814	0.806	0.807	0.795	0.795
180	0.818	0.810	0.810	0.797	0.797
200	0.823	0.813	0.813	0.803	0.802

Table 3-7: Gust Effect Factors for 100ft x 400ft Building – Transverse Direction

Building Ht.	Building Material				
(ft)	Steel MF	Concrete MF	Steel BF	All other (S)	All other (C)
60	0.835	0.835	0.835	0.835	0.835
70	0.835	0.835	0.835	0.835	0.835
80	0.835	0.835	0.835	0.835	0.835
90	0.862	0.835	0.835	0.835	0.835
100	0.866	0.852	0.835	0.835	0.835
120	0.874	0.857	0.861	0.835	0.835
140	0.881	0.862	0.866	0.834	0.834
160	0.889	0.867	0.870	0.833	0.833
180	0.896	0.872	0.875	0.833	0.833
200	0.903	0.877	0.879	0.851	0.844

Table 3-8: Gust Effect Factors for 100ft x 400ft Building – Longitudinal Direction

Each table includes the typical height ranges for mid-rise buildings, 60 feet to 200 feet. The upper portion of each table has been shaded in orange to indicate a rigid structure. In this area of the table, the gust effect factor is denoted as G. A direct method involving equations 6-4 and 6-5 of the ASCE 7 standard were used to calculate these values. The minimum value for rigid buildings is 0.779, found in Table 3-7. This is roughly 8.4% lower than the conservative value of 0.85 allowed by the ASCE 7 standard, and can be attributed to the 400 ft horizontal length. When the wind is acting parallel to the long dimension of the building, the building diaphragm acts similar to a beam: the long side resists bending well. In other words, the structure is more rigid when the wind acts in the longitudinal direction of the building. As indicated in the tables, all rigid gust effect factor values are less than 0.85, which is more exact and less conservative. Another characteristic with the rigid gust effect factors is that they are identical for each floor plan size in the longitudinal direction of the building, shown in Tables 3-4, 3-6, and 3-8. This is due to the fact that the gust effect factor is a function of the building dimension perpendicular to the wind, namely 100ft, which is constant for each of the three buildings in the parametric study.

Building material is a large factor in determining a flexible gust effect factor. The ASCE 7-05 separates material type into four categories: Steel Moment Frame, Concrete Moment Frame, Steel Braced Frame, and All Other. For the purpose of the parametric study, the All Other' category was further split into Steel, denoted as “S”, and Concrete, denoted as “C”. The gust effect factor for flexible buildings is a function of steel or concrete as a building material. For each building in the parametric study, the tables indicate that Steel Moment Frames have the highest flexible gust effect factor. The primary reason for this result is that steel buildings have less ability to dampen the effects of wind on the structure. Concrete is a heavier material and more capable of reducing the negative effects on the structure from the wind.

3.2.3 Pressure Coefficients

Pressure coefficients are applied in conjunction with the gust effect factors and velocity pressure to obtain a final design wind pressure. Both internal and external pressure coefficients account for the effect of wind pressures on all surfaces of a building. As mentioned previously, mid-rise buildings make use of separated factors. Figure 6-6 in the ASCE 7-05 has tabulated the external pressure coefficients, C_p, for walls and roofs. The parametric study in this report discusses and compares pressures acting on the walls of the MWFRS. Values of C_p reflect the most recent data from boundary-layer tests on wind-tunnel and full-scale tests (ASCE, 2005).

Internal pressure coefficients, GC_{pi}, are associated with the enclosure category of a building. Values are tabulated in Figure 6-5 of the ASCE 7-05. Enclosed, partially enclosed, or open buildings have varying values. The parametric study compares only enclosed and partially enclosed buildings. A characteristic of internal pressure coefficients is the dual nature of their magnitude; meaning there are positive internal pressure coefficients and negative internal pressure coefficients. Both positive and negative affects on the internal walls must be calculated in the wind pressure design process. An overabundance of positive internal pressure will result in a ballooning affect on the building, whereas an excess of negative internal pressure will result in a suction affect.

3.2.4 Design Wind Pressure

The design wind pressure is obtained using the velocity pressure multiplied by the appropriate pressure coefficient. The ASCE 7-05 standard provides design equations for the MWFRS of buildings of all heights, low-rise buildings, flexible buildings, and parapets. All equations follow the same overall principle. The standard provides separate equations for the design of Components and Cladding. Below are the design equations for buildings of all heights and flexible buildings, respectively, which were utilized in the parametric study. The ASCE 7-05 defines the pressure for rigid buildings as:

$$p = qGC_p - q_i(GC_{pi}) \qquad \text{Equation 3.2.4-1}$$

The ASCE 7-05 defines the pressure for flexible buildings as:

$$p = qG_fC_p - q_i(GC_{pi}) \qquad \text{Equation 3.2.4-2}$$

The terms, q and q_i, are velocity pressure that vary with which wall is under consideration. Windward walls utilize a velocity pressure, q, which varies with height above the ground. Leeward walls utilize a constant velocity pressure, q, which is based on the mean roof height. The second velocity pressure term, q_i, can be defined as q_z or q_h for use in evaluating partially enclosed buildings with positive internal pressure. For the parametric study, q_h was used in place of q_i for two reasons. First, no openings are specified which is a stipulation for specifying q_z. Second, wind pressure design for negative internal pressure utilizes q_h; therefore it is more efficient to use the same definition of the term for both internal pressure conditions.

The above equations (3.2.4-1 and 3.2.4-2) generate the net pressure on each wall. The parametric study considers windward and leeward walls and determines the total net pressure acting on the MWFRS. Results for each building plan evaluated are presented and discussed in Section 4.2.

Each of the primary components and factors necessary for determining the design wind pressure have now been discussed as they exist in the standard, and how they relate to the parametric study subsequently presented. The final step in designing a structure for wind pressures is to apply the calculated design pressures to the building, using various load cases, in order to determine the governing case. For buildings greater than 60 feet in height, Figure 6-9 in the ASCE 7-05 illustrates the four design wind load cases. Cases 1 through 4 each allot a specific magnitude of the wind pressure to be applied to every wall of the structure, separately or simultaneously. See Figure 3-3 below.

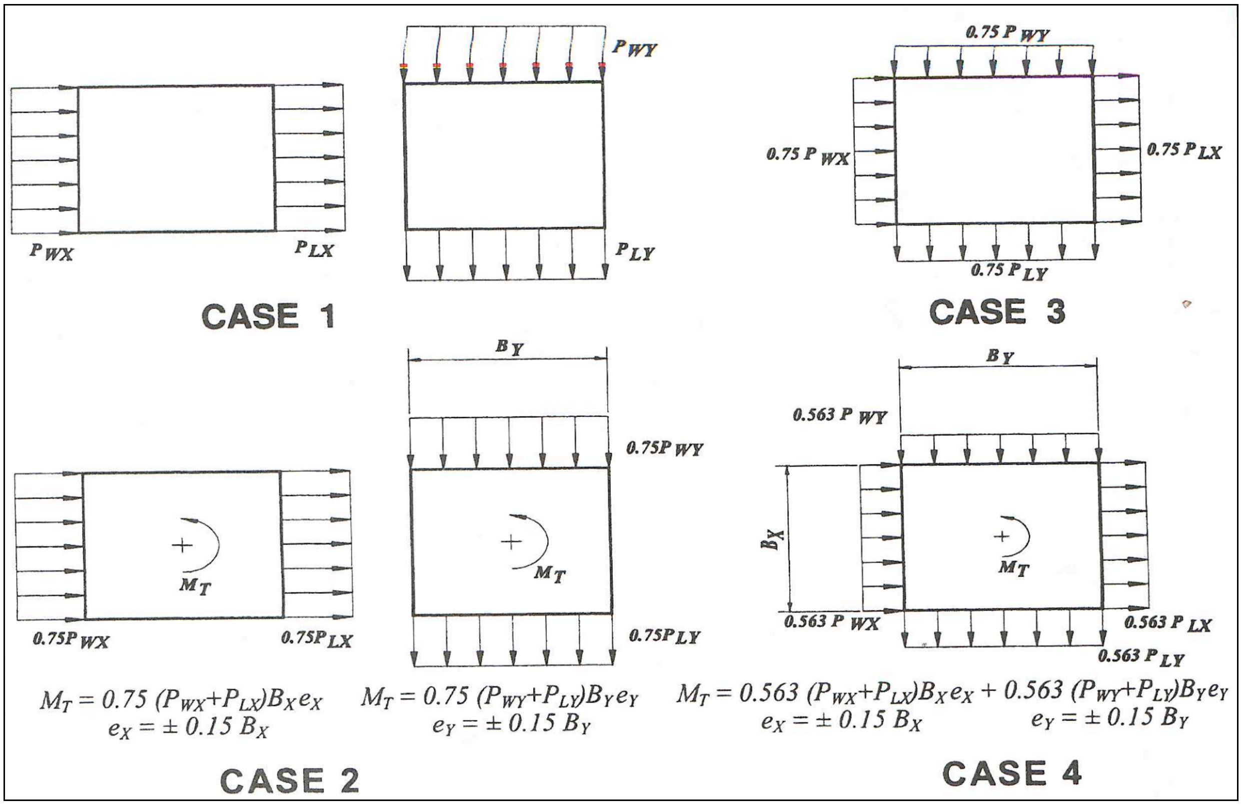


Figure 3-3: Design Wind Load Cases from ASCE 7-05, Figure 6-9

With permission from ASCE

Case 1 evaluates the structural frame with 100 percent of the design wind pressure. Case 2 evaluates a structure with 75 percent magnitude and an applied moment caused by eccentricity of the resultant wind pressure, namely torsion. Both cases 1 and 2 examine the windward and leeward wall separately. Case 3 evaluates a structure with 75 percent of the design wind pressure, acting on each building face simultaneously. Finally, case 4 evaluates a structure at 75 percent of the magnitude in case 3; that is, 56.3 percent. Similar to case 2, case 4 also includes an applied moment to account for torsion on the structure.

The structural frame of a building experiences torsional effects when inconsistent or non-uniform pressures are acting on the different wall surfaces simultaneously. According to the ASCE 7-05 commentary, research employing wind tunnels has shown that the non-uniform pressures are caused by the following:

- Typical wind flow around a building
- Interference effects of terrain features
- Interference effects from neighboring buildings
- Dynamic effect when a building is flexible

For the parametric study and case study presented within this report, only loading Case 1 is considered. Designing the actual structural frame for loads due to wind pressures is outside of the scope of this report. Load case 1 assumes 100 percent of the design wind pressure to be acting in each direction, longitudinal and transverse, separately.

SECTION 4.0: Parametric Study for Midrise Buildings

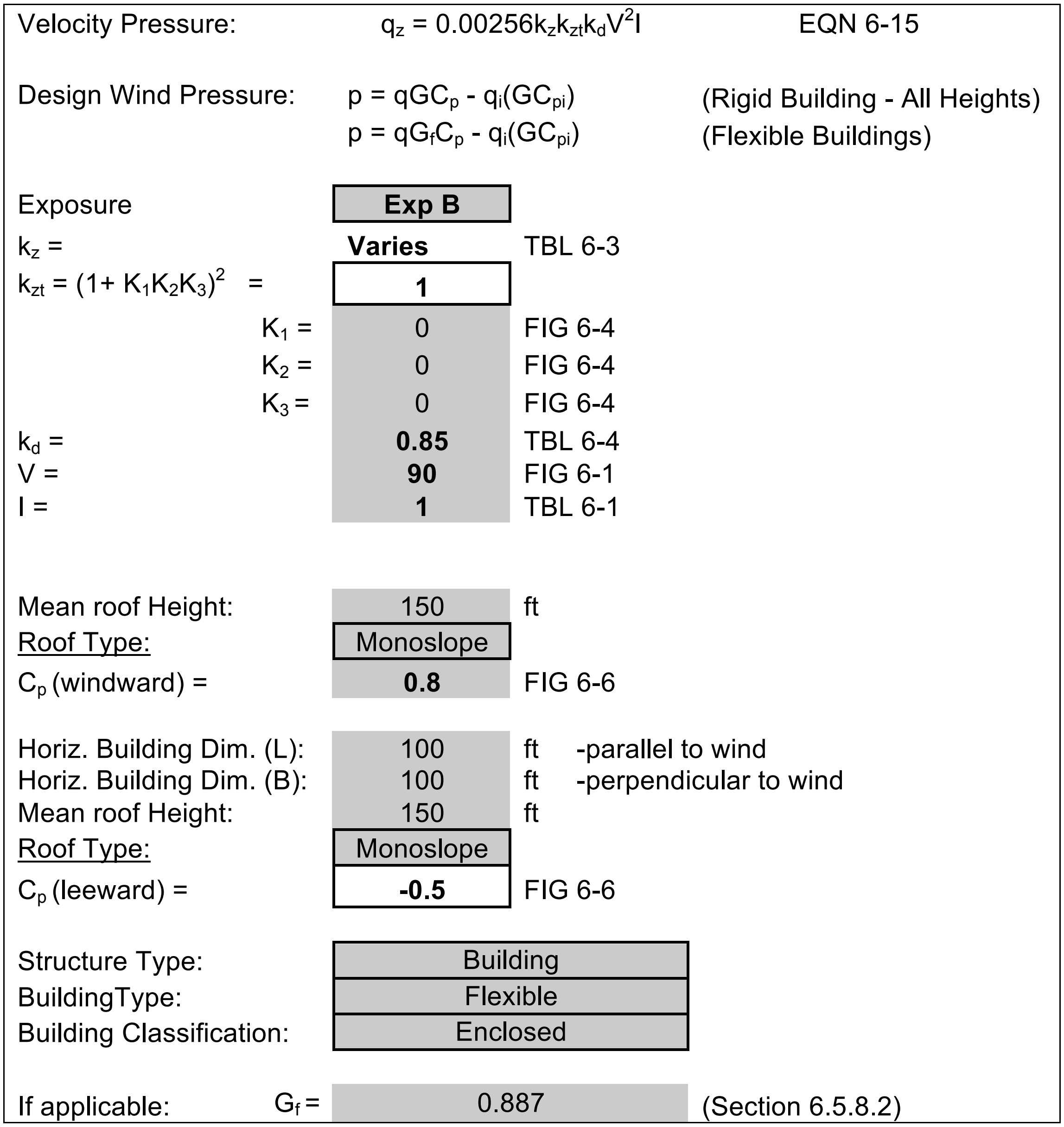
In order to better evaluate how the wind interacts with buildings, a simple parametric study has been selected and set up. Using Method 2, the Analytical Procedure, design wind pressures are determined for three different floor plans. The first is a 100ft by 100ft floor plan; the second, 100ft by 200ft; and the third, 100ft by 400ft. For each of the floor plans, results are tabulated for heights ranging from 60 feet to 200 feet; the typical range for mid-rise structures. Although material type is generally arbitrary, this study focuses on steel moment frames and concrete moment frames as they relate to the overall rigidity or flexibility of the structure. These two framing systems were selected due to their common use in mid-rise structures. The parametric study will evaluate both enclosed and partially enclosed buildings.

All of the variables and factors discussed in the previous sections (3.1 and 3.2) are further examined as deemed necessary by the results of the parametric study. The goal is to discover how similar or different the calculated design wind pressures are for the various floor plans chosen and the varying height of the building. In order to direct the parametric study towards the aforementioned goal, certain variables are kept constant throughout the design process. These are outlined below:

- Buildings are located in Exposure Category B
- There are no abrupt changes in the terrain (i.e. $K_{zt} = 1.0$)
- The Basic Wind Speed is the same throughout the Midwest region (V = 90 mph)
- Occupancy Category II – All other building types (I = 1.0)
- The Wind Directionality Factor is not included

4.1 Define Design Process

For the three building plans within the parametric study, various heights and gust effect factors were inserted into a spreadsheet to obtain net pressures. The spreadsheet was specifically designed and formatted for this parametric study and follows the ASCE 7-05 Analytical Method for wind pressure design. Figure 4-1 illustrates the data input area within the spreadsheet. The net pressures, which are tabulated in subsequent sections, are calculated using Equations Equation 3.2.4-1 and 3.2.4-2.



Velocity Pressure:	$q_z = 0.00256k_zk_{zt}k_dV^2I$	EQN 6-15	
Design Wind Pressure:	$p = qGC_p - q_i(GC_{pi})$	(Rigid Building - All Heights)	
	$p = qG_fC_p - q_i(GC_{pi})$	(Flexible Buildings)	
Exposure	**Exp B**		
$k_z =$	**Varies**	TBL 6-3	
$k_{zt} = (1+ K_1K_2K_3)^2 =$	**1**		
$K_1 =$	0	FIG 6-4	
$K_2 =$	0	FIG 6-4	
$K_3 =$	0	FIG 6-4	
$k_d =$	**0.85**	TBL 6-4	
V =	**90**	FIG 6-1	
I =	**1**	TBL 6-1	
Mean roof Height:	150	ft	
Roof Type:	Monoslope		
C_p (windward) =	**0.8**	FIG 6-6	
Horiz. Building Dim. (L):	100	ft	-parallel to wind
Horiz. Building Dim. (B):	100	ft	-perpendicular to wind
Mean roof Height:	150	ft	
Roof Type:	Monoslope		
C_p (leeward) =	**-0.5**	FIG 6-6	
Structure Type:	Building		
BuildingType:	Flexible		
Building Classification:	Enclosed		
If applicable: $G_f =$	0.887	(Section 6.5.8.2)	

Figure 4-1: Data Input for Wind Pressure Design Spreadsheet

Cells shaded in gray require that a value be entered or selected from a dropdown menu set-up within spreadsheet. In some cases, tables or figures within the ASCE 7-05 standard must be referenced manually so a particular value can be selected. Notice in the above data that the building type has been classified as Flexible. As discussed in Section 3.1.2, the period and natural frequency of a building must be determined prior to calculating the wind pressures it, because there are separate gust effect factors for rigid or flexible buildings. From Equation

3.1.2-3 and Table 3-3 in this report for buildings measuring 100 ft by 100 ft, it is found that the natural frequency, f, is equal to 0.649Hz for the 150ft high, steel moment frame building in this comparison. Since f < 1Hz, the building is classified as flexible and a flexible gust effect factor needs to be established.

Equation 3.2.4-1 is utilized when the structure is classified as rigid, and Equation 3.2.4-2 is utilized for flexible structures. This is primarily dependent on the frequency of the building and how that changes the Gust Effect Factor. The equations are used in determining both the windward and leeward wind pressures. The net pressure acting on the building is calculated from the resultant of the windward and leeward walls. The factors q and q_i in the above equations represent the velocity pressure. Each form of "q" has a slightly different definition, but Equation 3.2.1-1 stated previously in this report shows the basic form of the equation.

The subscript 'z' means any arbitrary height above the ground that is being evaluated. All factors in Equation 3.2.1-1 are set to a constant value as noted previously. The only term that changes with the height of the building is K_z. For windward walls, the term q in Equation 3.2.4-1 and Equation 3.2.4-2 is evaluated as q_z because the wind pressure increases with height above the ground. For leeward walls, the term q is evaluated as q_h, where h is the height of the buildings. The second velocity pressure term, q_i, in Equations 3.2.4-1 and 3.2.4-2 is conservatively evaluated as q_h for both windward and leeward wall in this parametric study. Section 3.2.4 (Design Wind Pressure) describes other ways that q_i could be evaluated.

The Gust Effect Factors, G and G_f, in Equations 3.2.4-1 and 3.2.4-2 are described in Section 3.2.2 and values are tabulated in Tables 3-4 through 3-8 for the floor plans and heights in the parametric study. A typical calculation outlining the process for determining the flexible gust effect factor is shown in Appendix section A.1.3. The pressure coefficients, C_p and GC_{pi}, in Equations 3.2.4-1 and 3.2.4-2 are described in Section 3.2.3. The first varies based on building dimensions, and wind direction being considered. For the windward walls, C_p is always 0.8; and for leeward walls it can be -0.5, -0.3, or -0.2. While determining roof pressures are not in the scope of this report, it should be noted that the buildings examined in the parametric study have flat, monoslope roofs; therefore, the roof wind pressures are vertical and would not factor into the resultant horizontal net pressures. The latter term, GC_{pi}, is dependent on the building enclosure classification. As noted previously, this parametric study will examine both enclosed and partially enclosed buildings.

4.2 Calculations and Results

Design wind pressure results are calculated for a building modeled from 60 feet in height up to 200 feet in height using the design spreadsheet mentioned previously. Summaries of all the results are tabulated in the following sections. The vertical axis of each table, labeled “Building Height” refers to the height of the building above ground. Height increments are based on the same increments listed in the Table 6-3 of the ASCE 7-05 for K_z, Velocity Pressure Exposure Coefficient. The heights listed on the horizontal axis refer to the specific building height being examined. Values within the tables are pressures measured in pounds per square foot (psf).

Each floor plan size in the parametric study includes tables for the building modeled as Rigid and Flexible because the classification changes as the height of the building increases. This will be noted in the figure heading. Calculations are carried out assuming the building to be enclosed and partially enclosed.

4.2.1 100x100 Floor Plan

The first building examined in the parametric study is a simple square building measuring 100 feet by 100 feet in plan. For this particular floor plan, the wind pressures will be equal for both the longitudinal and transverse directions; therefore each table applies to both directions.

Table 4-1 has values tabulated only up to 90 feet because the building is classified as flexible beyond this height. See Section 3.1.2 for information about the natural frequency of the building. For rigid structures, it is not necessary to incorporate the building material type unless calculating a more exact value for the Gust Effect Factor. This parametric study assumes the conservative Gust Effect Factor value of 0.85. Steel moment frames and concrete moment frames are both classified as rigid up to 80 feet, with concrete moment frames classified as rigid up to 90 feet high. Concrete has stiffer properties making it more rigid at higher heights than steel.

Building Ht (ft)	Net Pressure, P (psf) for Rigid Enclosed Building			
	60 ft	**70 ft**	**80 ft**	**90 ft**
15	15.53	15.88	16.23	16.50
	15.53	15.88	16.23	16.50
20	16.23	16.59	16.94	17.20
	16.23	16.59	16.94	17.20
25	16.80	17.15	17.50	17.77
	16.80	17.15	17.50	17.77
30	17.36	17.71	18.07	18.33
	17.36	17.71	18.07	18.33
40	18.21	18.56	18.91	19.18
	18.21	18.56	18.91	19.18
50	18.91	19.26	19.62	19.88
	18.91	19.26	19.62	19.88
60	19.48	19.83	20.18	20.45
	19.48	19.83	20.18	20.45
70	-	20.39	20.75	21.01
	-	20.39	20.75	21.01
80	-	-	21.31	21.57
	-	-	21.31	21.57
90	-	-	-	22.00
	-	-	-	22.00

Table 4-1: Net Design Wind Pressures, Rigid Enclosed Building, 100’x100’

In Table 4-1 shown above, two identical pressures are given per height increment. As an example, consider a building with height of 80 feet and a height increment 40 feet above the ground. The first value listed, 18.91 psf, is calculated assuming a positive internal pressure, while the second value, also 18.91 psf, is calculated assuming a negative internal pressure. Since the parametric study is evaluating net pressures on the building as a whole, these values should always be equal. Due to this conclusion, all other tables of results presented in this section, as well as sections 4.2.2 and 4.2.3 will only show one value for each height increment.

Table 4-2 tabulates net pressure values for the building modeled as flexible and enclosed, with steel moment frames. Tabulated values start at a height of 90 feet, which correlates to the natural frequency of the building, and continues to 200 feet in height. Table 3 tabulates net pressure values for the building modeled as flexible and enclosed, with concrete moment frames. Here, tabulated pressures start at a height of 100 feet.

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Steel MF Building						
	90 ft	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.75	17.10	17.71	18.33	18.86	19.41	19.86
20	17.47	17.82	18.43	19.06	19.60	20.15	20.61
25	18.04	18.39	19.01	19.65	20.19	20.75	21.21
30	18.61	18.97	19.60	20.23	20.79	21.34	21.82
40	19.47	19.83	20.47	21.11	21.67	22.24	22.72
50	20.19	20.55	21.19	21.84	22.41	22.99	23.47
60	20.76	21.12	21.77	22.43	23.00	23.58	24.07
70	21.33	21.70	22.35	23.02	23.59	24.18	24.68
80	21.90	22.27	22.93	23.60	24.18	24.77	25.28
90	22.33	22.71	23.37	24.04	24.63	25.22	25.73
100	-	23.14	23.80	24.48	25.07	25.67	26.18
120	-	-	24.53	25.21	25.81	26.42	26.93
140	-	-	-	25.95	26.55	27.16	27.68
160	-	-	-	-	27.14	27.76	28.29
180	-	-	-	-	-	28.35	28.89
200	-	-	-	-	-	-	29.34

Table 4-2: Net Design Wind Pressures, Flexible Enclosed SMF Building, 100’x100’

Tables 4-4, 4-5, and 4-6 below show design wind pressures for the building modeled as partially enclosed. Again, values are measure in pounds per square foot (psf). Similar to Table 4-1, the values in table 4-4 are only tabulated up to 90 feet due to the rigidity classification of the building.

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Concrete MF Building					
	100 ft	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.80	17.34	17.91	18.38	18.87	19.27
20	17.51	18.06	18.63	19.10	19.59	20.00
25	18.07	18.62	19.20	19.67	20.17	20.58
30	18.64	19.19	19.77	20.25	20.75	21.17
40	19.49	20.05	20.63	21.11	21.62	22.04
50	20.19	20.76	21.35	21.83	22.35	22.77
60	20.76	21.32	21.92	22.41	22.93	23.36
70	21.32	21.89	22.49	22.98	23.51	23.94
80	21.89	22.46	23.07	23.56	24.09	24.52
90	22.31	22.89	23.50	23.99	24.52	24.96
100	22.74	23.32	23.93	24.42	24.96	25.40
120	-	24.03	24.64	25.14	25.68	26.13
140	-	-	25.36	25.86	26.41	26.86
160	-	-	-	26.44	26.99	27.44
180	-	-	-	-	27.57	28.03
200	-	-	-	-	-	28.47

Table 4-3: Net Design Wind Pressures, Flexible Enclosed CMF Building, 100’x100’

Building Ht	Net Pressure, P (psf) for Rigid, Partially Enclosed Building			
(ft)	**60 ft**	**70 ft**	**80 ft**	**90 ft**
15	15.53	15.88	16.23	16.50
20	16.23	16.59	16.94	17.20
25	16.80	17.15	17.50	17.77
30	17.36	17.71	18.07	18.33
40	18.21	18.56	18.91	19.18
50	18.91	19.26	19.62	19.88
60	19.48	19.83	20.18	20.45
70	-	20.39	20.75	21.01
80	-	-	21.31	21.57
90	-	-	-	22.00

Table 4-4: Net Design Wind Pressures, Rigid Partially Enclosed Building, 100’x100’

Building Ht	Net Pressure, P (psf) for Flexible, Partially Enclosed, Steel MF Building						
(ft)	**90 ft**	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.75	17.10	17.71	18.33	18.86	19.41	19.86
20	17.47	17.82	18.43	19.06	19.60	20.15	20.61
25	18.04	18.39	19.01	19.65	20.19	20.75	21.21
30	18.61	18.97	19.60	20.23	20.79	21.34	21.82
40	19.47	19.83	20.47	21.11	21.67	22.24	22.72
50	20.19	20.55	21.19	21.84	22.41	22.99	23.47
60	20.76	21.12	21.77	22.43	23.00	23.58	24.07
70	21.33	21.70	22.35	23.02	23.59	24.18	24.68
80	21.90	22.27	22.93	23.60	24.18	24.77	25.28
90	22.33	22.71	23.37	24.04	24.63	25.22	25.73
100	-	23.14	23.80	24.48	25.07	25.67	26.18
120	-	-	24.53	25.21	25.81	26.42	26.93
140	-	-	-	25.95	26.55	27.16	27.68
160	-	-	-	-	27.14	27.76	28.29
180	-	-	-	-	-	28.35	28.89
200	-	-	-	-	-	-	29.34

Table 4-5: Net Design Wind Pressures, Flexible Partially Enclosed SMF Building, 100’x100’

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Partially Enclosed, Concrete MF Building					
	100 ft	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.80	17.34	17.91	18.38	18.87	19.27
20	17.51	18.06	18.63	19.10	19.59	20.00
25	18.07	18.62	19.20	19.67	20.17	20.58
30	18.64	19.19	19.77	20.25	20.75	21.17
40	19.49	20.05	20.63	21.11	21.62	22.04
50	20.19	20.76	21.35	21.83	22.35	22.77
60	20.76	21.32	21.92	22.41	22.93	23.36
70	21.32	21.89	22.49	22.98	23.51	23.94
80	21.89	22.46	23.07	23.56	24.09	24.52
90	22.31	22.89	23.50	23.99	24.52	24.96
100	22.74	23.32	23.93	24.42	24.96	25.40
120	-	24.03	24.64	25.14	25.68	26.13
140	-	-	25.36	25.86	26.41	26.86
160	-	-	-	26.44	26.99	27.44
180	-	-	-	-	27.57	28.03
200	-	-	-	-	-	28.47

Table 4-6: Net Design Wind Pressures, Flexible Partially Enclosed CMF Building, 100’x100’

After careful inspection, it can be observed that pressure values in Tables 4-1, 4-2, and 4-3 (Enclosed buildings) match those for similar building heights and height increments in Tables 4-4, 4-5, and 4-6 (Partially Enclosed buildings). For example, a 70 ft tall, rigid building, evaluated at 50 feet above the ground, produces a design wind pressure of 19.26 psf for both enclosed and partially enclosed classification, as shown in Tables 4-1 and 4-4. The reason for this phenomenon is due to the fact that the parametric study examines the entire building envelope (i.e. net pressure), instead of each wall or component separately. Due to this conclusion, all other tables of results presented in sections 4.2.2 and 4.2.3, will only show tables for the building modeled as Enclosed.

4.2.2 100x200 Floor Plan

The second building examined in this parametric study is a rectangular building measuring 100 feet by 200 feet in plan. One horizontal dimension of the building is doubled in order to evaluate how much, if any, the magnitudes of the net pressures change in each horizontal direction. Design wind pressure results are tabulated for the building modeled from 60 feet in height up to 200 feet in height. The building will have different pressure magnitudes for each horizontal direction, longitudinal and transverse. Results are shown for both directions, with the exception of Rigid Enclosed in the longitudinal direction because this case is identical to Figure 4-1; with the side perpendicular to the wind measuring 100 feet.

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Steel MF Building						
	90 ft	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.13	16.45	17.00	17.56	18.02	18.50	18.90
20	16.82	17.14	17.70	18.26	18.72	19.21	19.61
25	17.37	17.69	18.25	18.82	19.29	19.78	20.19
30	17.92	18.24	18.81	19.38	19.85	20.35	20.76
40	18.75	19.08	19.65	20.23	20.70	21.20	21.62
50	19.44	19.77	20.34	20.93	21.41	21.91	22.33
60	19.99	20.32	20.90	21.49	21.97	22.48	22.91
70	20.54	20.87	21.46	22.05	22.53	23.05	23.48
80	21.09	21.43	22.02	22.61	23.10	23.62	24.05
90	21.51	21.84	22.43	23.03	23.52	24.04	24.48
100	-	22.26	22.85	23.45	23.95	24.47	24.91
120	-	-	23.55	24.16	24.65	25.18	25.63
140	-	-	-	24.86	25.36	25.89	26.34
160	-	-	-	-	25.92	26.46	26.91
180	-	-	-	-	-	27.03	27.49
200	-	-	-	-	-	-	27.92

Table 4-7: Net Design Wind Pressures, Flexible Enclosed SMF Building, Transverse Direction, 100’x200’

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Concrete MF Building					
	100 ft	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	16.29	16.80	17.31	17.74	18.18	18.53
20	16.97	17.49	18.00	18.44	18.87	19.23
25	17.52	18.04	18.56	18.99	19.43	19.79
30	18.07	18.59	19.11	19.55	19.99	20.35
40	18.89	19.41	19.94	20.38	20.83	21.19
50	19.58	20.10	20.63	21.08	21.53	21.89
60	20.13	20.65	21.18	21.63	22.09	22.45
70	20.67	21.20	21.74	22.19	22.65	23.02
80	21.22	21.75	22.29	22.75	23.20	23.58
90	21.63	22.17	22.71	23.16	23.62	24.00
100	22.04	22.58	23.12	23.58	24.04	24.42
120	-	23.27	23.81	24.28	24.74	25.12
140	-	-	24.51	24.97	25.44	25.82
160	-	-	-	25.53	26.00	26.38
180	-	-	-	-	26.56	26.95
200	-	-	-	-	-	27.37

Table 4-8: Net Design Wind Pressures, Flexible Enclosed CMF Building, Transverse Direction, 100’x200’

Building Ht	Net Pressure, P (psf) for Rigid Enclosed Building			
(ft)	**60 ft**	**70 ft**	**80 ft**	**90 ft**
15	12.53	12.74	12.95	13.11
20	13.24	13.45	13.66	13.82
25	13.80	14.01	14.22	14.38
30	14.36	14.58	14.79	14.95
40	15.21	15.42	15.63	15.79
50	15.92	16.13	16.34	16.50
60	16.48	16.69	16.90	17.06
70	-	17.26	17.47	17.63
80	-	-	18.03	18.19
90	-	-	-	18.61

Table 4-9: Net Design Wind Pressures, Rigid Enclosed Building, Longitudinal Direction, 100’x200’

Building Ht	Net Pressure, P (psf) for Flexible, Enclosed, Steel MF Building						
(ft)	**90 ft**	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	13.31	13.52	13.92	14.32	14.66	15.01	15.31
20	14.03	14.24	14.64	15.05	15.39	15.75	16.06
25	14.60	14.81	15.22	15.64	15.98	16.35	16.66
30	15.18	15.39	15.80	16.22	16.57	16.94	17.26
40	16.03	16.25	16.67	17.10	17.46	17.84	18.17
50	16.75	16.97	17.40	17.83	18.19	18.58	18.92
60	17.32	17.54	17.98	18.42	18.78	19.18	19.52
70	17.90	18.12	18.56	19.00	19.37	19.77	20.12
80	18.47	18.69	19.14	19.59	19.96	20.37	20.72
90	18.90	19.12	19.57	20.03	20.41	20.81	21.17
100	-	19.56	20.01	20.47	20.85	21.26	21.62
120	-	-	20.73	21.20	21.59	22.00	22.37
140	-	-	-	21.93	22.32	22.75	23.12
160	-	-	-	-	22.91	23.34	23.72
180	-	-	-	-	-	23.94	24.32
200	-	-	-	-	-	-	24.77

Table 4-10: Net Design Wind Pressures, Flexible Enclosed SMF Building, Longitudinal Direction, 100’x200’

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Concrete MF Building					
	100 ft	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	13.30	13.65	14.00	14.29	14.61	14.86
20	14.01	14.36	14.71	15.01	15.33	15.58
25	14.58	14.93	15.28	15.59	15.91	16.17
30	15.14	15.50	15.85	16.16	16.49	16.75
40	15.99	16.35	16.71	17.03	17.36	17.62
50	16.70	17.06	17.43	17.74	18.08	18.35
60	17.26	17.63	18.00	18.32	18.66	18.93
70	17.83	18.20	18.57	18.89	19.24	19.52
80	18.39	18.77	19.14	19.47	19.82	20.10
90	18.82	19.19	19.57	19.90	20.26	20.54
100	19.24	19.62	20.00	20.33	20.69	20.97
120	-	20.33	20.72	21.05	21.42	21.70
140	-	-	21.43	21.77	22.14	22.43
160	-	-	-	22.35	22.72	23.01
180	-	-	-	-	23.30	23.60
200	-	-	-	-	-	24.03

Table 4-11: Net Design Wind Pressures, Flexible Enclosed CMF Building, Longitudinal Direction, 100'x200'

4.2.3 100x400 Floor Plan

The final building examined in this parametric study is a rectangular building measuring 100 feet by 400 feet in plan. Again, one horizontal dimension of the building is doubled in order to evaluate how much, if any, the magnitudes of the net pressures change compared to the previous two building plan sizes. Design wind pressure results are tabulated for the building modeled from 60 feet in height up to 200 feet in height. The building will have different pressure magnitudes for each horizontal direction, longitudinal and transverse. Results are shown for both directions, with the exception of Rigid Enclosed in the transverse direction because this case is identical to Figure 4-1; with the transverse wall of the MWFRS measuring 100 feet.

Building Ht	Net Pressure, P (psf) for Flexible, Enclosed, Steel MF Building						
(ft)	**90 ft**	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	15.43	15.74	16.27	16.79	17.23	17.66	18.02
20	16.09	16.40	16.94	17.46	17.91	18.34	18.70
25	16.62	16.93	17.47	18.00	18.45	18.88	19.25
30	17.14	17.46	18.01	18.54	18.99	19.42	19.80
40	17.94	18.25	18.81	19.34	19.80	20.24	20.62
50	18.60	18.91	19.47	20.01	20.47	20.91	21.30
60	19.12	19.44	20.01	20.55	21.01	21.46	21.84
70	19.65	19.97	20.54	21.09	21.55	22.00	22.39
80	20.18	20.50	21.07	21.62	22.09	22.54	22.94
90	20.57	20.90	21.47	22.03	22.50	22.95	23.35
100	-	21.30	21.87	22.43	22.90	23.36	23.76
120	-	-	22.54	23.10	23.58	24.04	24.44
140	-	-	-	23.77	24.26	24.71	25.12
160	-	-	-	-	24.80	25.26	25.67
180	-	-	-	-	-	25.80	26.21
200	-	-	-	-	-	-	26.62

Table 4-12: Net Design Wind Pressures, Flexible Enclosed SMF Building, Transverse Direction, 100’x400’

Building Ht	Net Pressure, P (psf) for Flexible, Enclosed, Concrete MF Building					
(ft)	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	15.66	16.15	16.65	17.06	17.48	17.80
20	16.32	16.81	17.31	17.73	18.16	18.48
25	16.84	17.34	17.84	18.27	18.69	19.02
30	17.37	17.87	18.38	18.80	19.23	19.56
40	18.16	18.67	19.17	19.60	20.04	20.36
50	18.82	19.33	19.84	20.27	20.71	21.04
60	19.35	19.86	20.37	20.81	21.25	21.58
70	19.87	20.39	20.90	21.34	21.78	22.12
80	20.40	20.92	21.44	21.88	22.32	22.66
90	20.79	21.31	21.84	22.28	22.73	23.06
100	21.19	21.71	22.23	22.68	23.13	23.47
120	-	22.37	22.90	23.35	23.80	24.14
140	-	-	23.57	24.02	24.47	24.82
160	-	-	-	24.55	25.01	25.35
180	-	-	-	-	25.55	25.89
200	-	-	-	-	-	26.30

Table 4-13: Net Design Wind Pressures, Flexible Enclosed CMF Building, Transverse Direction, 100’x400’

Building Ht	Net Pressure, P (psf) for Rigid Enclosed Building			
(ft)	**60 ft**	**70 ft**	**80 ft**	**90 ft**
15	11.03	11.17	11.32	11.42
20	11.74	11.88	12.02	12.13
25	12.30	12.44	12.58	12.69
30	12.87	13.01	13.15	13.25
40	13.71	13.85	13.99	14.10
50	14.42	14.56	14.70	14.81
60	14.98	15.12	15.26	15.37
70	-	15.69	15.83	15.93
80	-	-	16.39	16.50
90	-	-	-	16.92

Table 4-14: Net Design Wind Pressures, Rigid Enclosed Building, Longitudinal Direction, 100’x400’

Building Ht	Net Pressure, P (psf) for Flexible, Enclosed, Steel MF Building						
(ft)	**90 ft**	**100 ft**	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	11.58	11.74	12.03	12.31	12.57	12.82	13.03
20	12.30	12.46	12.76	13.04	13.31	13.56	13.78
25	12.87	13.04	13.34	13.63	13.90	14.16	14.38
30	13.44	13.61	13.92	14.21	14.49	14.75	14.98
40	14.30	14.47	14.79	15.09	15.37	15.64	15.88
50	15.01	15.19	15.51	15.82	16.11	16.39	16.63
60	15.59	15.77	16.09	16.41	16.70	16.98	17.23
70	16.16	16.34	16.67	16.99	17.29	17.58	17.83
80	16.73	16.92	17.25	17.57	17.88	18.17	18.43
90	17.16	17.35	17.69	18.01	18.32	18.62	18.87
100	-	17.78	18.12	18.45	18.77	19.06	19.32
120	-	-	18.85	19.18	19.50	19.81	20.07
140	-	-	-	19.91	20.24	20.55	20.82
160	-	-	-	-	20.83	21.14	21.42
180	-	-	-	-	-	21.74	22.02
200	-	-	-	-	-	-	22.47

Table 4-15: Net Design Wind Pressures, Flexible Enclosed SMF Building, Longitudinal Direction, 100’x400’

Building Ht (ft)	Net Pressure, P (psf) for Flexible, Enclosed, Concrete MF Building					
	100 ft	**120 ft**	**140 ft**	**160 ft**	**180 ft**	**200 ft**
15	11.55	11.80	12.05	12.26	12.48	12.66
20	12.26	12.51	12.76	12.98	13.20	13.38
25	12.83	13.08	13.33	13.56	13.78	13.97
30	13.39	13.65	13.91	14.13	14.36	14.55
40	14.24	14.50	14.76	14.99	15.22	15.42
50	14.95	15.21	15.48	15.71	15.95	16.15
60	15.51	15.78	16.05	16.29	16.53	16.73
70	16.08	16.35	16.62	16.86	17.11	17.31
80	16.64	16.92	17.20	17.44	17.68	17.89
90	17.07	17.34	17.62	17.87	18.12	18.33
100	17.49	17.77	18.05	18.30	18.55	18.77
120	-	18.48	18.77	19.02	19.28	19.49
140	-	-	19.48	19.74	20.00	20.22
160	-	-	-	20.32	20.58	20.80
180	-	-	-	-	21.16	21.39
200	-	-	-	-	-	21.82

Table 4-16: Net Design Wind Pressures, Flexible Enclosed CMF Building, Longitudinal Direction, 100’x400’

4.3 Discussion of Results

Design wind pressure results for three floor plans of varying sizes are tabulated in the previous sections; 4.2.1, 4.2.2, and 4.2.3. First, the wind pressures for a building measuring 100 ft x 100 ft in plan were determined. Next, the base floor plan was doubled in size in one horizontal dimension, creating a 100 ft x 200 ft building, and again the design wind pressures were determined. Lastly, in increased horizontal dimension of the second floor plan was doubled again giving a building measuring 100 ft x 400 ft. The building for each floor plan size was modeled as a steel moment frame and concrete moment frame, as enclosed and partially enclosed, and from 60 ft to 200 ft tall. The results and conclusions presented here are based on an examination of the following areas:

- What is the difference in using Steel Moment Frames vs. Concrete Moment Frames?
- What happens when the building height increases?
- What happens when the transverse horizontal dimension is increased?
- What happens when the longitudinal horizontal dimension is increased?

Note that two conclusions regarding all results have been previously discussed in Section 4.2.1: (1) the significance of modeling the building as enclosed or partially enclosed and (2) the reason two equal pressures are calculated for each height increment. Due to these conclusions, modified tables were presented in Sections 4.2.2 and 4.2.3.

Both steel moment frames (SMF) and concrete moment frames (CMF) are common structural options for midrise buildings. The results show that design wind pressures for both framing types are equal when the building is classified as rigid, but differ once the building is classified as flexible. Design wind pressures for a CMF are always less than those for a SMF, for a flexible classification. CMF are stiffer than SMF (SMF are more flexible); therefore, the SMF may interact with the wind more and resonance may occur. The primary reason for the difference is due to the flexible gust effect factor, G_f, which is the only difference between the rigid versus flexible wind pressure design equation (Equations 3.2.4-1 and 3.2.4-2). Tables 3-4 through 3-8 consistently show higher G_f values for a SMF building, accounting for the possible resonance and dynamic response of the structure. Within the direct calculation of G_f (illustrated in Appendix Section A.1.3), a damping ratio, β (measured as a percent), takes into account the ability of a material to absorb lateral forces. Concrete has a greater damping ratio, which means it is a less flexible material.

The second area of discussion is in regards to increasing each dimension of the building, separately. First, the change in vertical dimension is examined and discussed. From the tabulated wind pressure results, it is seen for all floor plan sizes that as the building height increases, the net design wind pressures also increase. Fewer obstacles and interferences for the wind occur as the height above ground increases, therefore allowing the wind to obtain higher velocities. Also, the wind pressures increase for each height increment as the overall building height is increased. The reason for this is because the wind design methods in the ASCE 7 are assuming average pressures over the surface of a building. An analysis of the exact pressures on various surface locations would not show the parabolic shape that is assumed in design. As the building gets taller, more surface area is available for the wind to interact with (less wind goes around the building), thus causing greater average pressures.

Next, the change in horizontal dimension is assessed. One horizontal dimension of the building was increased and evaluated in the transverse and longitudinal directions. From the tabulated wind pressure results for a building evaluated in the transverse direction, it is shown that as the horizontal dimension of the building increases, the net design wind pressures remain constant for a rigid building. However, for a flexible building, the wind pressures decrease. Refer to a SMF building 160ft tall, at the 160 ft high increment, being evaluated in the transverse direction and under flexible design conditions:

- 100ft x 100ft floor plan: p = 27.14 psf
- 100ft x 200ft floor plan: p = 25.92 psf
- 100ft x 400ft floor plan: p = 24.80 psf

A closer look at Equation 3.2.4-1 shows why the pressures do not change for a rigid building. First, the rigid gust effect factor is constant at 0.85. Second, the pressure coefficient, C_p, is based on a length to width ratio (L/B) which stays in the same category (0-1) as the transverse dimension is increased; therefore, C_p is constant at -0.5 for all three floor plans. Both factors that would effect the magnitude of the wind pressure are constant, therefore the wind pressures do not change as the transverse dimension of a rigid building is increased. Similarly, the pressure coefficient C_p is constant for flexible buildings as well, but the gust effect factor is not. Figure 4-2 illustrates how wind interacts with a building in the transverse direction. As the building gets wider and wider, wind still only has to travel around the same short side dimension (100 feet). As the illustration shows, some turbulence is caused on the windward side, which counteracts the wind flow and is the reason for decrease in net pressure magnitude.

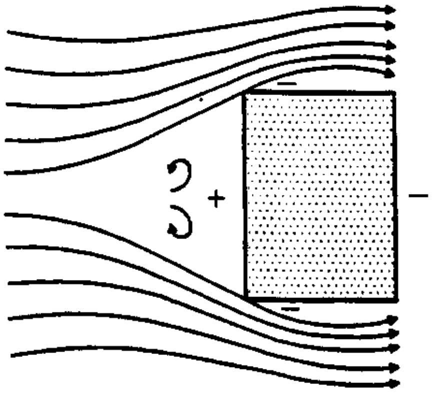


Figure 4-2: Wind flow around a building, transverse

Courtesy of Taly, 2003

For a building evaluated in the longitudinal direction, it is shown from the tabulated wind pressure results that as the horizontal dimension of the building increases, the net design wind pressures decrease. This is valid for both rigid and flexible buildings. For example, refer to a SMF building 160ft tall, at the 160 ft high increment, being evaluated in the longitudinal direction:

- 100ft x 100ft floor plan: p = 27.14 psf
- 100ft x 200ft floor plan: p = 22.91 psf
- 100ft x 400ft floor plan: p = 20.83 psf

For this direction, wind has further to travel to get to the leeward face of the building as the length increases and is slowed down by the friction and turbulence against the building side. Another observation is that the pressures decrease at a much greater rate than for a building evaluated in the transverse direction. Figure 4-3 illustrates how wind interacts with a building as the longitudinal direction is increased. The turbulence caused along the side walls counteracts the positive wind flow and is the reason for decrease in net pressure magnitude.

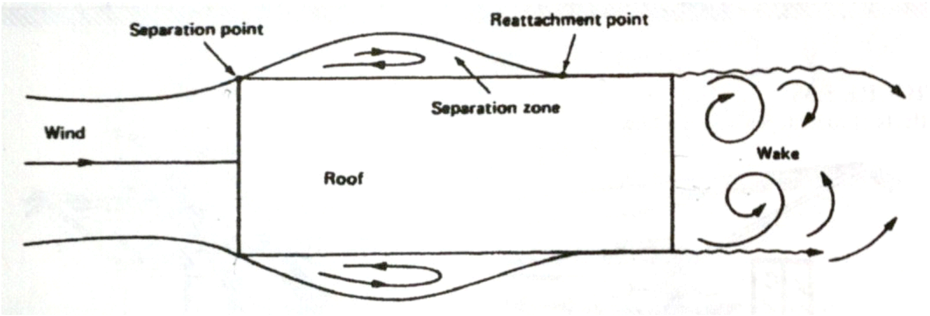


Figure 4-3: Wind flow around a building, longitudinal

Courtesy of Taly, 2003

SECTION 5.0: Comparison Study

The objective of the comparison is to evaluate how the analytical wind provisions have progressed. In order to evaluate the progression of the wind load design provisions, a comparison has been prepared between previous and current design provisions in codes and standards. As mentioned in Section 3, wind provisions have been in existence for over 80 years. Some of the earliest major changes to the codes and standards occurred in the early 1980's. The evaluation herein will compare the wind design provisions of the ANSI A58.1-1982 standard, the UBC 1982 code, and the current ASCE 7-05 standard. The objective of this comparison is to examine the variation in design wind pressure magnitudes among the three sets of wind design provisions. With the results of this comparison and opinions from other structural engineers, a conclusion will be formed as to whether or the not the provisions for wind design have become overly complicated.

As with the parametric study completed in the previous section, certain variables in the design process have been kept constant to streamline and direct the design process. The building in question is classified as mid-rise with a height of 150 feet, roughly 12 stories, and has a floor plan with dimensions of 100ft by 100ft. It is an enclosed structure. The building is located in Kansas City, Missouri giving an Exposure Category of B. The building will be used primarily for office space and the occupancy category will be determined from that.

5.1 Design Wind Pressure Results

The ANSI A58.1 published in 1982 was the Standard for minimum loads to buildings just previous to the ASCE 7. This particular year has been selected due to the significant changes that took place in the standard since the 1972 publication. After researching the factors that are associated with the wind pressure interaction on buildings, it was decided that the 1982 publication was a more accurate approximation in determining and comparing design wind pressures. The Uniform Building Code published in 1982 was the model building code used in many Midwestern states west of the Mississippi River. This code has been selected for comparison because it had not adopted the wind methods of the ANSI standard at this time. The 2005 publication of the ASCE 7 will be used as a means of determining the accuracy of the design wind pressures for each of the other design methods compared. It is assumed that, although the provisions might be more complicated, the output values are more accurate due to more recent research in wind design.

Design calculations for each of the methods are presented in Appendix A.1.1, A.1.2 and A.1.3, and follow the wind design procedures as outlined in the standard or code. It is important for this case study that the design provisions are followed as they appear in the standard or code, so that a more accurate conclusion may be made as to the relative simplicities of the various design processes. Table 5-1 shows the design wind pressures as calculated from the ANSI A58.1-1982 standard compared to those from the ASCE 7-05. The accompanying figure, Figure 5-1 shows a graphical illustration of the tabulated values.

Height above Ground (ft)	Net Pressure, Pnet (psf)		Difference (%)
	ANSI A58.1-1982	ASCE 7-05	
0-15	15.98	18.60	14.07
20	16.77	19.33	13.24
25	17.41	19.92	12.62
30	18.04	20.51	12.03
40	19.15	21.39	10.47
50	20.10	22.13	9.15
60	20.90	22.72	8.01
70	21.69	23.30	6.93
80	22.32	23.89	6.57
90	23.12	24.33	5.01
100	23.75	24.78	4.14
120	24.86	25.51	2.55
140	25.81	26.25	1.66
150	26.29	26.54	0.95

Table 5-1: Comparison of Design Wind Pressures - ANSI A58.1-1982 and ASCE 7-05

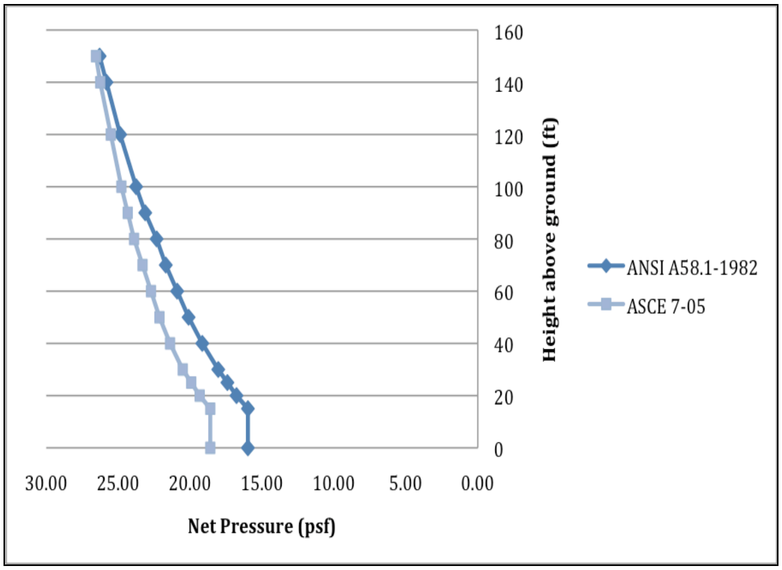


Figure 5-1: Comparison of Design Wind Pressures (1) (psf)

Table 5-2 shows the design wind pressures as calculated from the UBC 1982 code compared to those from the ASCE 7-05. Again, the accompanying figure, Figure 5-2 shows a graphical illustration of the tabulated values. Finally, Figure 5-3 represents an overlay of both pressure comparisons that were completed.

Height above Ground (ft)	Net Pressure, Pnet (psf)		Difference (%)
	UBC 1982	ASCE 7-05	
0-15	20.57	18.60	-10.62
20	21.93	19.33	-13.45
25	21.93	19.92	-10.09
30	21.93	20.51	-6.93
40	24.65	21.39	-15.24
50	24.65	22.13	-11.40
60	26.01	22.72	-14.51
70	26.01	23.30	-11.61
80	26.01	23.89	-8.86
90	26.01	24.33	-6.89
100	28.73	24.78	-15.96
120	28.73	25.51	-12.62
140	28.73	26.25	-9.46
150	28.73	26.54	-8.25

Table 5-2: Comparison of Design Wind Pressures - UBC 1982 and ASCE 7-05

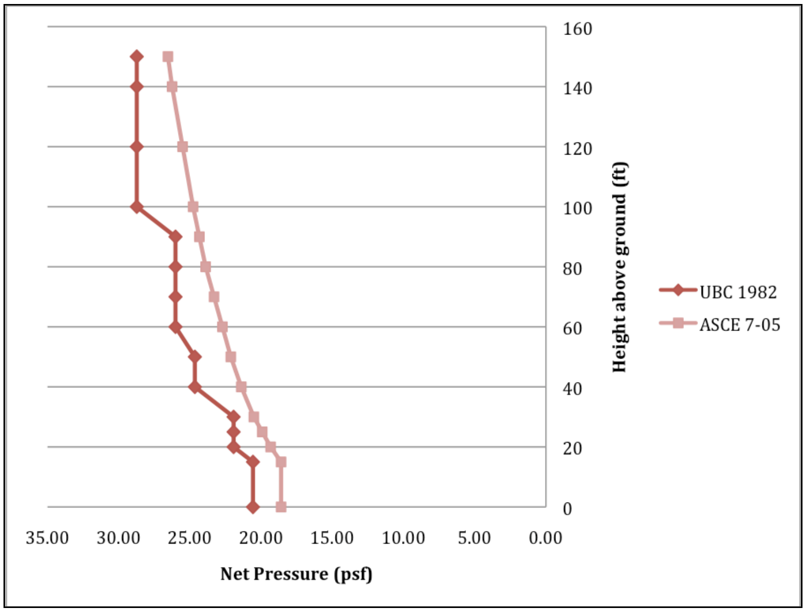


Figure 5-2: Comparison of Design Wind Pressures (2) (psf)

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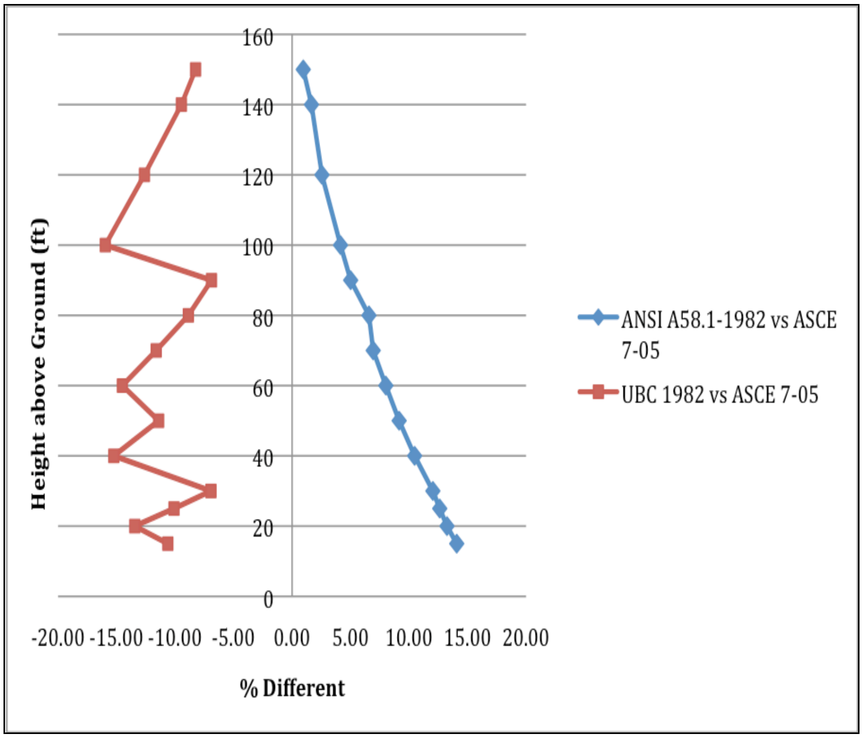

Figure 5-3: Net Pressure Comparison (%)

5.2 Discussion of Results and Conclusions

The ANSI A58.1-1982 and the ASCE 7-05 are very comparable, with design pressures reaching common values as the height above ground increases for a particular building, as can be seen from Table 5-1 and Figure 5-1. Other observations made from the results include:

- The largest difference in design pressure values is 14.07%, which occurs at a height increment of 0-15ft above ground.
- Design wind pressure values are consistently higher for the ASCE 7-05.

The ASCE 7 standard developed from the ANSI A58.1 standard, so it is expected that the two methods would provide similar design wind pressure values.

The design wind pressures for the UBC 1982 and the ASCE 7-05 both increase with height above ground, but not at the same rate. This is largely due to the fact that the height increments presented in each set of provisions is different. Those from the ASCE 7 were utilized for the comparison study. Other observations made from the results include:

- The largest difference in pressure value is 15.96%, which occurs at a height increment of 100 ft high.
- The design wind pressures become more dissimilar as the height of the building increases.
- Design wind pressure values obtained using the ASCE 7-05 provisions are consistently lower than when using the UBC 1982 provisions.

The design provisions for the ASCE 7-05 and the UBC 1982 are moderately different in procedure as can be seen from the calculations provided in Appendix section A.1.2. One of the primary reasons that the design wind pressures become more different as the building height increases is due to the gust effect factor determination. The ASCE 7-05 has a more user-friendly method, albeit still challenging, for calculating the flexible gust effect factor than the UBC 1982, which is a significant part of determining the design wind pressure for tall, flexibly classified buildings.

SECTION 6: Conclusions and Recommendations

Upon a detailed review of the progression of the wind provisions in both codes and standards throughout the last century, it can be concluded that they have changed immensely. Most revisions presented a positive result, making the design provisions more exact or easier to follow. An example of this is the formation of ICC and a single model building code. On the other hand, some revisions made the provisions more complicated. The Standard has repeatedly added new conditions and stipulations to the design process, which make determine wind pressure very tedious in some cases.

Section 3 outlined each part of the wind design process and the factors that accompany it. Most of these are straight-forward, but there are two items which should be reviewed for future revisions: the approximate natural frequency and the flexible gust effect factor. The latter is dependent upon the first. Three methods for approximating the natural frequency of a building were discussed and it was concluded to utilize the method that gave middle-ranged values. The only method actually available in the ASCE 7 standard is located within the Seismic Provisions, which is really the determination of the fundamental period of a building. While other natural frequency methods are described in the commentary for use, these are not approved methods. It would be helpful for engineers if there were a method for determining the approximate natural frequency presented within the wind design provisions. An appropriate natural frequency is then used to calculate the flexible gust effect factor. The process of equations used for calculating the flexible gust effect factor is very complicated and leaves room for error when assumptions need to be made. It is suggested that this calculation process be simplified if possible, or that flexible gust effect factors for typical building types be tabulated for easy application.

The parametric study presented in Section 4 illustrates the multitude of design wind pressures that are obtained for similarly shaped buildings and how challenging parts of the design process can be. In his two-part article published in the *Structure* magazine, S.K. Ghosh states, “Changes in the ANSI A58.1/ASCE 7 have not been consistently in the direction of lower or higher design wind pressures. If there is a consistent trend to the changes, it is that the complexity of wind design has been steadily increasing.” (Ghosh, 2007) Upon completion of the parametric study, the following are suggestions of how the wind design provisions could be changed or updated:

- Combine parts of the process in order to have less steps to go through
    - Use less variables
    - Combine surface roughness and exposure categories
- Provide flowcharts for the design process of each method

The comparison study presented in Section 5 illustrated that the wind design provisions have become more conservative for the lower portions of buildings when comparing to the previous standard, but less conservative when comparing the ASCE 7 to a previous model building code. The design process within the 1982 UBC was the simplest to complete, while that of the ASCE 7-05 was the most complex and time-consuming.

The scope of this report was the wind load provisions in regards to the Main Wind Force Resisting System. Further research related to the Components and Cladding design methods should also be examined in order to cover all aspects of the wind load provisions.

SECTION 7: Further Research: Future of the Wind Load Provisions

Numerous articles, papers, and reports have been written in the past fifteen years discussing changes, modifications, and additions that should be made to the ASCE 7-05 wind load provisions in order to create a more simple procedure. Towards the end of the research and writing process for this report, new information about the future ASCE 7-10 revisions was made public. Some of the intended revisions are similar to the conclusions and suggestions previously stated in Section 6. The following is a list of a few items to look for in the ASCE 7-10 as presented at the ASCE/SEI Conference in Austin, TX, April/May 2009:

- Complete reorganization of the wind provisions
    - 6 separate chapters will be used for breakdown of each design method
    - Flowcharts will be provided

- Wind speed maps based on a return period (RP)
    - These will reflect the importance factor for the building

- Simplified procedure for buildings with h < 160ft
    - Used for simple diaphragm buildings
    - There are frequency and torsional limitations

While having 6 chapters for wind load provisions instead of just one seems more complicated, it should help to lead engineers in the right direction based on which design method they are using. As is true for anything new, it may seem more difficult at first but engineers will eventually adapt to the new layout of the wind design provisions.

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Appendix -A : Comparison Study - Design Calculations

A.1: Comparison of Wind Design Provisions – Calculations

In the following three sections, B.1.1, B.1.2 and B.1.3, the calculations for the wind design provisions of the ANSI A58.1-1982, UBC 1982, and ASCE 7-05 are shown, respectively.

A.1.1: ANSI A58.1-1982

The first design step in the ANSI A58.1 is to determine the Velocity Pressure, q_z for the building. Equation 2-1 from Section 2.1.1 was utilized in this step. Other assumptions and their reference to the standard can be seen below in the calculations:

STEP 1: Determine Velocity Pressure (Section 6.4.2 (1))

$q_z = 0.00256K_z(IV)^2$ (Equation 3)

$V =$ 80 mph (Figure 1)
$I =$ 1.0 (Table 5)
(Occupancy Category II) (Table 1)

K_z: Varies with height, see below (Table 6)
(for Exposure B)

All references listed on the right hand side of the calculations are directly referencing the ANSI A58.1 Standard. Table A**§**.1 below shows the values of the velocity pressure measured in pounds per square foot (psf), with respect to the height of the building.

Height (ft)	K_z	q_z (psf)
0-15	0.37	6.06
20	0.42	6.88
25	0.46	7.54
30	0.5	8.19
40	0.57	9.34
50	0.63	10.32
60	0.68	11.14
70	0.73	11.96
80	0.77	12.62
90	0.82	13.43
100	0.86	14.09
120	0.93	15.24
140	0.99	16.22
150	1.02	16.71

Table A§.1: Velocity Pressures for ANSI A58.1-1082

The topographic factor, K_z, was included in Table A**§**.1 as a reference. These values came directly from the ANSI A58.1 standard. Also, the height increments shown are the same as those given in the standard. The table ends at 150 feet, which is the building height chosen for this case study. Next, the Gust Response Factor and the frequency of the building are determined.

STEP 2: Determine Gust Response Factor (Section 6.4.2 (2))

Is building Flexible or Rigid? (Section 6.6)

- Is frequency, $f < 1$ Hz?

$T = C_T h_n^{3/4}$ (Equation 9c)

$C_T =$ 0.035 (Section 9.4)

$h_n =$ 150 ft

$T = (0.035)(150)^{3/4} = 1.5$ ---> $f = 1/T = 1/1.5 = 0.667$ Hz

0.667 Hz < 1.0 Hz Therefore: building is flexible, use Gbar

$\text{Gbar} = 0.65 + [(P/\beta) + (3.32T_1)^2 S/(1+0.002c)]^{1/2}$ (Equation A7)

$P =$ fbarJY = (9.87)(.035)(0.00375) = 0.0013 (Equation A9)

fbar = 10.5fh/sV = (10.5*0.667*150)/(1.33*80)
= 9.87 (Equation A10)
f = 0.667
h = 150 ft
s = 1.33 (Table A9)
V = 80 mph

J: function of γ ---> J = 0.035 (Figure A6)
$\gamma = 3.28/h = 3.28/150 = 0.022$ (Table A9)

Y: function of γ, c/h, and fbar ---> Y = 0.00375 (Figure A7)
c/h = 100ft wide/150 ft high = 0.667
**Interpolate between graphs
for c/h = 0.40, Y = 0.005
for c/h = 1.0, Y = 0.0025

$\beta =$ 0.02 (Example in Commentary)

$$T_1 = \frac{2.35(D_o)^{1/2}}{(z/30)^{1/\alpha}} = \frac{2.35(0.010)^{1/2}}{(150/30)^{1/4.5}} = 0.164$$

$D_o = 0.010$ (Table A6)
$\alpha = 4.5$ (Table A6)

S = structure size factor = 1.0 (Exposure B) (Figure 8)

c = Building width = 100ft

$$\text{Gbar} = 0.65 + \left| \frac{0.0013}{0.02} + \frac{(3.32*0.164)^2(1.0)}{1 + 0.002(100ft)} \right|^{0.5} = \mathbf{1.21}$$

*Note: if the building were rigid, $G_h = 1.25$ (Table 8)

The third step in the design process is to determine the pressure or force coefficients for a building. Generally this is a simple step, only requiring the designer to look up values in a table or figure.

STEP 3: Determine Pressure or Force Coefficient (Section 6.4.2 (3))

Need to find Pressure Coefficients, C_p for this building (Section 6.7)

Windward: $C_p = 0.8$ (Figure 2)
(to be used with q_z)
Leeward: $C_p = -0.5$ (Figure 2)
(L/B = 100/100 = 1.0)

With the gust response factor and the pressure coefficients known, the design wind pressure can be calculated. For flexible buildings, Equation 2-2 from Section 2.1.1 of this report was used to calculate the design wind pressure on the windward and leeward walls, substituting Gbar in for G_h. Tables A**§**.2 and A**§**.3 show the tabulated pressure values.

Height (ft)	q_z (psf)	Gbar	C_p	**p (psf)**
0-15	6.06	1.21	0.8	**5.87**
20	6.88	1.21	0.8	**6.66**
25	7.54	1.21	0.8	**7.30**
30	8.19	1.21	0.8	**7.93**
40	9.34	1.21	0.8	**9.04**
50	10.32	1.21	0.8	**9.99**
60	11.14	1.21	0.8	**10.78**
70	11.96	1.21	0.8	**11.58**
80	12.62	1.21	0.8	**12.21**
90	13.43	1.21	0.8	**13.00**
100	14.09	1.21	0.8	**13.64**
120	15.24	1.21	0.8	**14.75**
140	16.22	1.21	0.8	**15.70**
150	16.71	1.21	0.8	**16.18**

Table A§.2: Design Wind Pressures for Windward Wall

Height (ft)	q_h (psf)	Gbar	C_p	**p (psf)**
0-15	16.71	1.21	-0.5	**-10.11**
20	16.71	1.21	-0.5	**-10.11**
25	16.71	1.21	-0.5	**-10.11**
30	16.71	1.21	-0.5	**-10.11**
40	16.71	1.21	-0.5	**-10.11**
50	16.71	1.21	-0.5	**-10.11**
60	16.71	1.21	-0.5	**-10.11**
70	16.71	1.21	-0.5	**-10.11**
80	16.71	1.21	-0.5	**-10.11**
90	16.71	1.21	-0.5	**-10.11**
100	16.71	1.21	-0.5	**-10.11**
120	16.71	1.21	-0.5	**-10.11**
140	16.71	1.21	-0.5	**-10.11**
150	16.71	1.21	-0.5	**-10.11**

Table A§.3: Design Wind Pressures for Leeward Wall

In order to determine the resultant base shear to the building, the individual resultant wind pressure forces at each height increment must be calculated and summed together. Figure 5-1 illustrates visually how the pressures are acting on the building. Table 5-4 below outlines the design pressure at each height and the resulting base shear associated with it. The bottom right hand corner of the table give the final, total base shear for the building in this case study.

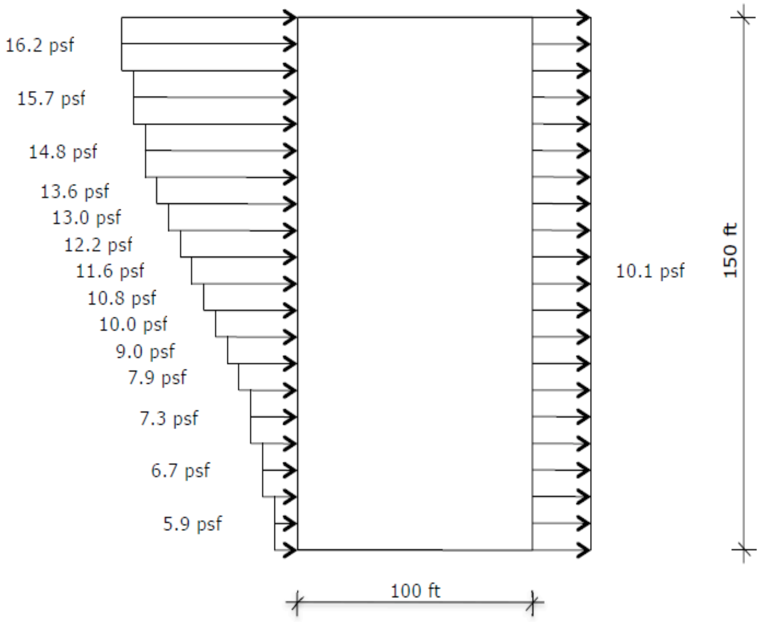

Figure A§.1 Elevation view of Windward and Leeward Pressures

Height (ft)	Greatest Horiz. Dim. (ft)	p_{net} (psf)	V (kips)
0-15	100	15.98	23.97
20	100	16.77	8.39
25	100	17.41	8.70
30	100	18.04	9.02
40	100	19.15	19.15
50	100	20.10	20.10
60	100	20.90	20.90
70	100	21.69	21.69
80	100	22.32	22.32
90	100	23.12	23.12
100	100	23.75	23.75
120	100	24.86	49.72
140	100	25.81	51.62
150	100	26.29	26.29
		Total V =	**302** **kips**

Table A§.4: Resultant Base Shear for Building

A.1.2: UBC 1982

STEP 1: Check Height to Width Ratio (Section 2311 (a))

$$\frac{150 \text{ feet}}{100 \text{ feet}} = 1.5$$

$1.5 < 5$ Therefore, building is not sensitive to dynamic effects

STEP 2: Select Basic Wind Speed (Section 2311 (b))

$V = 80$ mph (Figure No. 4)

STEP 3: Determine Exposure (Section 2311 (c))

Exposure B: Terrain with buildings that are ≥ 20 feet in height, covering at least 20% of the area extending one mile of more from the site

STEP 4: Determine Design Wind Pressure (Section 2311 (d))

$p = C_e C_q q_s I$ (Equation 11-1)

C_e: Combined height, exposure and gust factor coefficient (Table No. 23-G)

Height	C_e
0-20	0.7
20-40	0.8
40-60	1
60-100	1.1
100-150	1.3

C_q: Pressure coefficient

*Use Method 1 ---> Normal Force Method (Section 2311 (e)1)

*Windward wall (W)

$C_q = 0.8$ (inward) (Table No. 23-H)

*Leeward wall (L)

$C_q = 0.5$ (outward) (Table No. 23-H)

q_s: Wind stagnation pressure at a standard height of 30 feet

$q_s = 17$ psf (Table No. 23-F)

I: Importance factor

I = 1.0 (not an essential facility) (Section 2311 (h))

Table A§.5 below shows the tabulated wind pressures, measured in pounds per square foot (psf). Subsequently, Figure A§.2 illustrates visually how those pressures are acting on the building. Then, Table A§.6: below outlines the design pressure at each height and the resulting base shear associated with it. The bottom right hand corner of the table gives the final, total base shear for the building in this case study.

Height (ft)	W (psf)	L (psf)
0-20	9.52	11.05
20-40	10.88	11.05
40-60	13.6	11.05
60-100	14.96	11.05
100-150	17.68	11.05

Table A§.5: Design Wind Pressures for Windward and Leeward wall

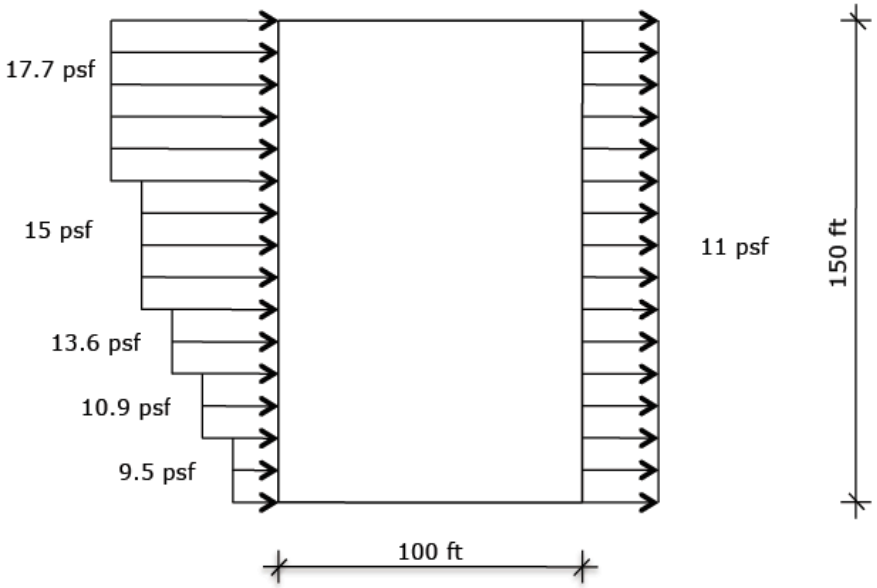

Figure A§.2: Elevation view of Windward and Leeward Pressures

Height (ft)	Greatest Horiz. Dim. (ft)	p_{net} (psf)	V (kips)
0-20	100	20.57	41.14
20-40	100	21.93	43.86
40-60	100	24.65	49.30
60-100	100	26.01	104.04
100-150	100	28.73	143.65
		Total V =	**382** **kips**

Table B§.6: Resultant Base Shear for Building

A.1.3: ASCE 7-05

As noted in Section 4 of this report, a spreadsheet was created in order to determine the design wind pressures for various building types and situations. This same spreadsheet is employed in the evaluation of the building being examined in this case study. The figures below are excerpts from the design spreadsheet, which show the variable input locations, definitions, references, and pressure results. The design process for the ASCE 7-05 provisions was previously described in Sections 3.1.1 and 4.1.

The first step is to establish the known variables for the particular building under evaluation and the equations that are needed to complete the design calculations. Figure 4-1 from Section 4.1 of this report illustrates the data input area within the spreadsheet.

The following calculations show the process for determining a flexible gust effect factor, which has been set up in an excel spreadsheet.

f	0.649	Hz	height, h (ft)	150	Material:	Steel
V	90	mph	Bldg width, B (normal to wind)	100		
Exp.	B		Bldg length, L (ll to wind)	100		

		REF.
$G_f = 0.925 \dfrac{1 + 1.7\, I_{z^*}\, \mathrm{sqrt}(g_Q^2 Q^2 + g_R^2 R^2)}{1 + 1.7\, g_v I_{z^*}}$	$= 0.887$	EQN 6-8

asterik (*) indicate a bar over the top	$g_Q =$		3.4		Section 6.5.8.2
	$g_v =$		3.4		Section 6.5.8.2
	$g_R =$	$\mathrm{sqrt}(2\ln(3600n_1)) + \dfrac{0.577}{\mathrm{sqrt}(2\ln(3600n_1))} =$	4.085		EQN 6-9
		n_1 = Bldg Natural Freqency = $f = 1/T_a$ =	0.649		KNOWN
	$R =$	Resonant Response Factor $= \mathrm{sqrt}((1/\beta)R_nR_hR_B(0.53 + 0.47R_L)) =$	0.344		EQN 6-10
	$R_n =$	$\dfrac{7.47N_1}{(1 + 10.3N_1)^{5/3}} =$	0.060		EQN 6-10
	$N_1 =$	$\dfrac{n_1 L_{z^*}}{V_{z^*}} =$	3.801		EQN 6-12
	$n_1 =$		0.649		KNOWN
	$L_z =$	$l\,(z^*/33)^{\varepsilon^*} =$		447.088	EQN 6-7
		$l =$		320.0	TBL 6-2
		$z^* = 0.6h,\ z_{min} =$		90.0	Section 6.5.8.1
		$\varepsilon^* =$		0.333	TBL 6-2
	$V_{z^*} =$	$b^*(z^*/33)^{\alpha^*}\, V(88/60) =$		76.334	EQN 6-14
		$b^* =$		0.450	TBL 6-2
		$z^* =$		90.0	Section 6.5.8.1
		$\boldsymbol{\alpha}^* =$		0.250	TBL 6-2
		$V =$		90.000	KNOWN

$R_h =$	$\frac{1}{\eta} - \frac{1}{2\eta^2}(1-e^{-2\eta}) =$	0.156	EQN 6-13a
$\eta =$	$\frac{4.6\ n_1\ h}{V_{z*}} =$	5.866	Section 6.5.8.2
$n_1 =$		0.649	KNOWN
$h =$		150.0	KNOWN
$V_{z*} =$		76.334	Previous (Eq 6-14)
$R_B =$	$\frac{1}{\eta} - \frac{1}{2\eta^2}(1-e^{-2\eta}) =$	0.223	EQN 6-13a
$\eta =$	$\frac{4.6\ n_1\ B}{V_{z*}} =$	3.911	Section 6.5.8.2
$n_1 =$		0.649	KNOWN
$B =$		100.0	KNOWN
$V_{z*} =$		76.334	Previous (Eq 6-14)
$R_L =$	$\frac{1}{\eta} - \frac{1}{2\eta^2}(1-e^{-2\eta}) =$	0.073	EQN 6-13a
$\eta =$	$\frac{15.4\ n_1\ L}{V_{z*}} =$	13.093	Section 6.5.8.2
$n_1 =$		0.649	KNOWN
$L =$		100.0	KNOWN
$V_{z*} =$		76.334	Previous (Eq 6-14)
$\beta =$	Damping ratio; measure as a % of critical (Generally 1% for steel; 1.5% for concrete) =	0.01	Section 6.5.8.2 C6.5.8
$I_{z*} =$	$c\,(33/z*)^{(1/6)} =$	$\boxed{0.254}$	EQN 6-5
$Q =$	$\text{sqrt}\left| \frac{1}{1 + 0.63((B+h)/L_{z*})^{0.63}} \right| =$	$\boxed{0.834}$	EQN 6-6
$B =$		100	KNOWN
$h =$		150	KNOWN
$L_z =$	$l\,(z*/33)^{\varepsilon*} =$	447.088	EQN 6-7

The shaded gray cells at the top indicate input cells. All references shown are referencing the ASCE 7-05 standard. Definitions of each variable presented in this calculation can be found in the ASCE 7-05 standard.

Next, Equations 3-2 and 3-4 of this report are used to tabulate the design wind pressures for the building established in this case study. Table A§.7 below shows a summary of all values calculated and obtained by the design spreadsheet. The final wind pressures tabulated for this building were determined by omitting the k_d factor within the velocity pressure equation because load combination equations are not being evaluated.

Height (ft)	K_z	K_z (at Ht. h)	q_z (psf) w/o k_d	q_h (psf) w/o k_d	External			Internal	Design Wind Pressures (psf)		Net Pressure p (psf)
					G_f	C_p (W)	C_p (L)	GC_{pi}	Windward	Leeward	
15	0.57	1.11	11.82	23.02	0.887	0.8	-0.5	0.18	4.24	-14.35	18.60
	0.57	1.11	11.82	23.02	0.887	0.8	-0.5	-0.18	12.53	-6.06	18.60
20	0.62	1.11	12.86	23.02	0.887	0.8	-0.5	0.18	4.98	-14.35	19.33
	0.62	1.11	12.86	23.02	0.887	0.8	-0.5	-0.18	13.27	-6.06	19.33
25	0.66	1.11	13.69	23.02	0.887	0.8	-0.5	0.18	5.57	-14.35	19.92
	0.66	1.11	13.69	23.02	0.887	0.8	-0.5	-0.18	13.85	-6.06	19.92
30	0.7	1.11	14.52	23.02	0.887	0.8	-0.5	0.18	6.16	-14.35	20.51
	0.7	1.11	14.52	23.02	0.887	0.8	-0.5	-0.18	14.44	-6.06	20.51
40	0.76	1.11	15.76	23.02	0.887	0.8	-0.5	0.18	7.04	-14.35	21.39
	0.76	1.11	15.76	23.02	0.887	0.8	-0.5	-0.18	15.33	-6.06	21.39
50	0.81	1.11	16.80	23.02	0.887	0.8	-0.5	0.18	7.78	-14.35	22.13
	0.81	1.11	16.80	23.02	0.887	0.8	-0.5	-0.18	16.06	-6.06	22.13
60	0.85	1.11	17.63	23.02	0.887	0.8	-0.5	0.18	8.36	-14.35	22.72
	0.85	1.11	17.63	23.02	0.887	0.8	-0.5	-0.18	16.65	-6.06	22.72
70	0.89	1.11	18.46	23.02	0.887	0.8	-0.5	0.18	8.95	-14.35	23.30
	0.89	1.11	18.46	23.02	0.887	0.8	-0.5	-0.18	17.24	-6.06	23.30
80	0.93	1.11	19.28	23.02	0.887	0.8	-0.5	0.18	9.54	-14.35	23.89
	0.93	1.11	19.28	23.02	0.887	0.8	-0.5	-0.18	17.83	-6.06	23.89
90	0.96	1.11	19.91	23.02	0.887	0.8	-0.5	0.18	9.98	-14.35	24.33
	0.96	1.11	19.91	23.02	0.887	0.8	-0.5	-0.18	18.27	-6.06	24.33
100	0.99	1.11	20.53	23.02	0.887	0.8	-0.5	0.18	10.42	-14.35	24.78
	0.99	1.11	20.53	23.02	0.887	0.8	-0.5	-0.18	18.71	-6.06	24.78
120	1.04	1.11	21.57	23.02	0.887	0.8	-0.5	0.18	11.16	-14.35	25.51
	1.04	1.11	21.57	23.02	0.887	0.8	-0.5	-0.18	19.45	-6.06	25.51
140	1.09	1.11	22.60	23.02	0.887	0.8	-0.5	0.18	11.90	-14.35	26.25
	1.09	1.11	22.60	23.02	0.887	0.8	-0.5	-0.18	20.18	-6.06	26.25
150	1.11	1.11	23.02	23.02	0.887	0.8	-0.5	0.18	12.19	-14.35	26.54
	1.11	1.11	23.02	23.02	0.887	0.8	-0.5	-0.18	20.48	-6.06	26.54

Table A§.7: Summary of Wind Pressure Design