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MEETING THE IBC WIND LOADING STUDY REQUIREMENTS

1.0 Summary

The International Building Code recommends methods to be used to determine the wind-induced pressures on the face of a building. Estimates of wind pressures are calculated using equations provided in the code and compared to the results of computational fluid mechanics (CFD) modeling. Figures are included which illustrate the distribution of pressure across the faces of a model building. The values calculated by CFD are similar to, but provide more detail than those calculated by the more limited application equations.

2.0 International Building Code 2003

The International Building Code of 2003 (IBC, 2003) is the new governing code of building construction in many jurisdictions, including Washington. In IBC section 1609, the guidelines for determining a conservative estimate of wind pressures exerted on a structure are outlined in a simplified method. However, it is stated in section 1609.6.1 that the simplified method is not applicable to structures with a mean roof-height greater than 60 feet above the surface. This report describes a model calculation of wind pressures on an approximately square box building, longer from north-to-south than east-to-west, with a mean roof-line 135 feet above the surface. This model building was designed with an extension, or bridge, joining it to an existing building on the west, which reaches from the second floor to the roof. The model building is located in a dense urban commercial area on a hillside (a common situation in Seattle, Washington).

Because the model building is greater than 60 feet in height, and contains a "unique structure" feature, the simplified method presented in the IBC is not applicable. In section 1609.1.1 the IBC requires that the wind-loading calculation be performed under the guidance of Chapter 6 ("Wind loads") of **ASCE 7-02: Minimum Design Loads for Buildings and Other Structures**, if the simplified method can not be used.

The ASCE 7-02 document outlines three different methods for determining wind-loading pressures, depending on the specifics of the case. These methods are outlined in 6.4, 6.5, and 6.6:

6.4, Method 1: the "simplified procedure"
6.5, Method 2: the "analytical procedure"
6.6, Method 3: the "wind tunnel procedure"

Method 1 is a method for structures with simplified geometries, roof slopes less than 10°, and a mean roofline 30 feet or less above the surface. The structure must not be dynamic nor subject to topographic effects or contain expansion joints or separations. These and more details are outlined in ASCE 7-02 6.4.1: Method 1 Scope.

Method 2 is a method for structures with simplified geometries that are not dynamic. This method accounts for topographical effects, different roof shapes, closed or open structures, and various exposure classes dependent on the density of trees and buildings near the structure. This method can be used for simplified structure shapes that are above 60 feet in mean roof height. This method can not be used for structures that are located in areas of high urban density, where channeling may heavily influence wind interacting with the building. These exceptions are outlined in ASCE 7-02 6.5.1: Method 2 Scope and 6.5.2: Method 2 Limitations.

Method 3 is the method for structures that do not qualify to be examined under Methods 1 or 2, but it is not limited to this and can be applied to any structure. This method involves detailed atmospheric modeling of wind pressure to a scale model of the subject structure in a wind tunnel.

According to the ASCE guidance, Method 3 is the preferred method for estimating wind pressures on our model building for several reasons:

- The mean roof height is 135 feet, greater than the 30-foot limit for Method 1.
- The extension to the existing building qualifies it as a unique structure.
- Since it is located in a dense urban core, more than 50% of the buildings directly upwind of the model building during the strongest wind events are greater than 70 feet tall for ½ mile, classifying the region as Exposure A (exposure areas are defined in section 6.5.6.1 of ASCE 7-02, 1616 of UBC, and 1609.4 of IBC 2003). Section 6.5.6.1 directs that "possible channeling effects or increased velocity pressures due to the building or structure being located in the wake of adjacent buildings shall be taken into account."

Nevertheless, it is likely that wind-tunnel modeling will demonstrate that lower wind induced pressures occur during high speed winds than determined through the conservative equations of Methods 1 and 2 or from the IBC 2003 simplified method. Method 2 can be used for buildings of the height of our model building in other than dense urban areas. Therefore for comparison, a Method 2 equation will be used to determine the highest wind load pressure.

3.0 Wind loading pressure estimates using IBC 2003 simplified method

Wind load guidelines are covered in section 1609 of the IBC 2003. Though the simplified method is only applicable to structures with a mean roofline less than 60 feet above the surface, an estimate for a taller structure can be made using the simplified formula, modified for a higher structure. This and others are performed in this document to develop a number of conservative estimates to compare to the results of CFD modeling.

The formula for the main wind-force-resisting system is outlined in 1609.6.2.1 and is:

$$P = \lambda \, I_w \, p_{v40} \qquad (1)$$

where λ is the adjustment factor for building height and exposure, I_w is the importance factor, and p_{v40} is the simplified design wind pressure.

Figure 1609 of the IBC shows the high 3-second gust speed for the Seattle area to be 85 mph. This wind speed then generates the value of the variable p_{v40}, as described below. This plot does not list Seattle as being within a “special wind region.” Seattle did fall under this category under the Uniform Building Code (UBC), and a climatological study by Envirometrics found that 81 mph is the likely highest observed wind gust to impact the region of interest. Therefore, 85 mph is a good conservative estimate of a strongest regional gust. Further discussion of the study is in the UBC section of this memo.

The IBC defines two regions on the windward wall with different p_{v40} values, labeled region A and region C. Region A is the area near the corners of the building and Region C is the center of the windward wall. The roof is assumed to have a 0º slope. Horizontal pressure, in Table 1609.6.2.1(1) is 11.5 pounds per square foot (psf) for region A and 7.6 psf for region C.

The value of λ for exposure B increases nearly linearly with height. This value is provided for buildings up to 60 feet in height in Table 1609.6.2.1(4). This value was extrapolated to 135 feet and is calculated as 1.67 (unitless).

The importance factor, I_w, is 1.15 (unitless), the same for all these scenarios, as we are assuming a critical use of the structure. The importance factor is in Table 1604.5 in IBC 2003.

Calculating Equation (1) gives a value of **14.6 psf** for the region C areas and **22.1 psf** for the region A areas.

4.0 Wind loading pressure estimates using modified Method 2

In Method 2, wind loads are calculated using the formula in ASCE 7-02 6.5.12.2.1:

$$p = q\, G\, Cp - q_i\, G\, C_{pi} \tag{2}$$

where q is the static velocity pressure at a height z, G is the gust factor, C_p is the external pressure coefficient, and C_{pi} is the internal pressure coefficient.

First of all, q must be determined for both the cladding and main-force system for all heights up to 135 feet. The equation for q at a height z is given in 6.5.10 as:

$$q = 0.00256\, K_z\, K_{zt}\, K_d\, V^2\, I \tag{3}$$

where K_z is the velocity pressure exposure coefficient, K_{zt} is the topographic factor to account for wind speedup over hills, K_d is the wind directionality factor, V is the gust wind speed, and I is the importance factor.

K_z, the velocity pressure coefficient, is defined for both the cladding and main system as Case 1 and Case 2 respectively. Exposure B was used for heights from 0 feet up to 140 feet, at intervals of 5 to 20 feet, increasing with greater height. This factor basically accounts for the increasing wind with height in the standard gust environment of the lower atmosphere.

K_{zt} is the topographic factor available to account for increases of ground speed for structures on hills. The five qualifications that require use of this coefficient are listed in ASCE 7-02 6.5.7.1. Although hills in Seattle qualify under several of these factors, most will not under item #1 on the list. This guideline requires that the topographic feature be isolated from similar topographic features by at least 2 miles in any direction. Many hills in Seattle are easily within 2 miles of another, similar hill.

The 85-mph gust speed is determined to be a sufficiently conservative value regardless of the site's location on a hill. The climatological study, included in the UBC section of this document (section 5.0) demonstrated that highest likely wind gusts at sites along Seattle hills will be around 80 mph. Also, the model building is defined as located in a highly dense urban area, which will further suppress wind speed. The highest recorded wind gust speeds at Boeing Field (which is at the bottom of a sharp river valley and would therefore be the reference level to determine K_{zt}) is 66 mph. Thus, 85 mph is nearly 30% greater than the reference level speed, more than adequate to account for any hill influenced increase in speed. Therefore, 85 mph is a conservative gust wind speed estimate and K_{zt} will be ignored (set to equal1).

K_d is a directionality factor that changes depending on the structure type. It is designated in Table 6-6 to be 0.85 for both the main wind-force resisting system and components and cladding.

Calculation using Equation (3) leads to a maximum velocity pressure of 19.7 psf for both the cladding and main system. When applied to the load equation (2), using a C_p of 0.9 for windward walls (from Table 6-8: external pressure coefficient C_p for enclosed buildings and a roof slope of 0°) and 0.18 for GC_{pi} (from table 6-7: internal pressure coefficients for buildings, enclosed) we obtain a value of **18.1 psf** for both the cladding and main system.

5.0 Wind-loading according to the UBC

The Uniform Building Code (UBC) is a traditional, accepted conservative method for estimating loading that we can use to the ICB 2003 Methods 1 and 2 results and to the CFD modeling results. Chapter 16, Div. III outlines the standard method for estimating maximum pressures exerted on buildings from winds using empirical formulas. The main formula for the calculation is 20-1:

$$P = C_e\, C_q\, q_s\, I_w \qquad (4)$$

C_e: The combined height, exposure, and gust factor coefficient, which depends on the height above the ground of the element being analyzed.
C_q: Pressure coefficient, which depends on the type of building element being analyzed.
q_s: Wind stagnation pressure at 10 meters, which depends on the maximum gust wind speed for the region.
I_w: Wind importance factor, which depends on the function of the structure.

The value of C_e varies depending on the height that is being analyzed, and is higher at higher heights above the ground due to the increase in wind speed, even during wind gusts, with greater elevation above the ground. Again, the model building is located in a dense urban environment, surrounded by tall structures, which leads to the assumption that the exposure is very low. Though not included in the gust factor table, Exposure A would probably be the most likely category for exposure if the building were not located on a hill. The damping effect on high winds of the high-density urban environment is less severe because of the exposed position on the hill. Therefore, Exposure B is a conservative and more likely set of coefficients to apply to this study. At roof level of the model building (about 120 feet above the surface), with Exposure B, C_e is 1.2 (from Table 16-G: combined height, exposure, and gust factor coefficient).

The pressure coefficient, C_q, helps to determine loads on individual elements of the building. From Table 16-H, the wall elements on IEB have a factor of 1.2. For load on the entire windward wall, this factor is 0.8.

The value of q_s is determined by the maximum gust wind speed for the region. Figure 16-1 included in the UBC chapter illustrates the distribution of historical high wind speeds over the United States. The Seattle region is located near to the isopleth of 70 and 80 mph wind and 80 mph is the more conservative choice for the wind-loading estimate. However, the UBC recommends consultation by a meteorologist in regions marked as a "special wind region." The Puget Sound is marked in this manner, so a closer look into maximum wind gust speed for the area is warranted.

Envirometrics, Inc. performed a climatological study to determine the worst case gust winds for the Seattle area. The strongest wind gusts recorded in the Pacific Northwest occurred during the infamous event known as the "Columbus Day Storm," which was a strong extratropical cyclone reinforced with tropical energy from a dying Pacific Hurricane. This event produced hurricane force winds throughout the Pacific Northwest and was considered to be a 100-year event. A good compilation of data on Puget Sound wind-storms is available at http://oregonstate.edu/~readw/index.html, prepared by a climatologist from Oregon Climate Services. A comparison of peak gusts at Seattle metro stations are available on this site in the document "Seattle's Strongest Windstorms 1950-2002."

Highest wind speed gusts in the Seattle area varied depending on altitude, and local topography. The highest recorded gust in the metropolitan area was in Renton with a gust recorded at 100 mph. However, this value varied greatly compared to the highest speeds of 66 mph recorded nearer to the downtown core at Boeing field and the Seattle naval station. Though Boeing field is the nearest meteorological station to downtown Seattle, it is at a lower elevation with quite different topography. The Renton recording is also not very representative of downtown Seattle due to its distance from the Puget Sound. The most representative reading is assumed to be the Everett Paine Field reading of 81 mph. Like downtown Seattle, Paine field is located on Puget Sound, but on a bluff at a similar altitude to the hills in and surrounding downtown Seattle. Though it is quite distant from Seattle, the similarity in position and elevation are more important factors. In addition, 81 mph is near to the average of the 100 mph and 66 mph gust recordings.

Therefore, the 80-mph estimate of high gust speed according to the UBC Figure 16-1 is a reasonable estimate for our model building. We have assigned 16.4 psf to q_s.

I_w is a factor assigned to provide a more conservative estimate of loading for structures with critical functions such as law enforcement, emergency or disaster relief purposes. To be conservative we have classified our model building as a critical structure, which qualifies I_w for a value of 1.15 from Table 16-K.

Calculating Equation (4) gives us a value of **27.16 psf** at the 120 foot level of the model building. Pressure loading will be lower, according to the formula, at lower heights.

6.0 ASCE 7-02 method 3 and CFD modeling

Method 3, in Section 6.6 of ASCE 7-02, the wind tunnel procedure, is required under ASCE 7-02 6.5.2 for structures with unique geometries and recommended in lieu of Methods 1 and 2 for any structure. Wind tunnel modeling is useful for determining distribution of pressures along the building surface as well as a comparison of the conservative Method 1 and 2 solution to a more realistic solution high pressure.

A Computational Fluid Dynamic (CFD) model had been previously developed for air pollution dispersion modeling involving several buildings in downtown Seattle. This model was readily available for wind-loading simulations as a computerized wind tunnel. The guidance does not directly state that CFD is an accepted alternative to physical wind tunnel modeling although it is widely understood to be useful in these calculations. However, the CFD modeling allows the visualization of the distribution of pressure across the building surface, useful data that Method 2 can not calculate.

The test conditions for Method 3 are listed in ASCE 7-02 6.6.2 and are discussed here:

1. The natural atmospheric boundary layer has been modeled taking into account the variation of wind speed with height.

To accurately model an incoming wind gust, we had to ensure an accurate wind profile of the gust. A careful look into current meteorological literature revealed that modeling the urban wind profile below building height is quite difficult due to the randomness of the turbulence below the urban canopy. The best method we could configure depended on using two wind profile equations and the recommended “zero-plane displacement height.”

The displacement height is the effective increase in height of the base of a wind profile due to the increased height and density of friction elements in an area when compared to an Exposure C area. The displacement height is a common term in urban meteorology and is expected to lie between the surface and the average height of the roughness elements (Arya, 151). For regions with tall dense friction elements, the displacement height could reach 70 to 80% of the average height of the elements. Unfortunately, there are few published site studies to base a standard equation for the displacement.

The most applicable study in this case is most likely the recent work of the COST 715, a European group focused on deriving better mathematical simulation of the urban atmosphere. Additionally, a recent paper reviewed the urban wind profile (Fisher, 2001) and described several methods of defining the displacement height based on urban properties. This paper also refers to a document produced by the COST 715 group which outlines a good method for determining the displacement height based on site studies: “Estimation of the wind speed at an ‘urban reference height’ from an observation at some other height.” (Rotach) Several equations are available to estimate the displacement height from the density of the buildings in the region. Based on downtown Seattle area density, the zero-plane displacement height is estimated to be about 0.7 times the average building height in a dense urban core. Our estimate for this height was 15.4 meters, from the average height of a selection of buildings in our previous CFD modeling study.

The above method does not apply to the wind profile below the displacement height. A second wind profile is necessary for the area below the “reference height” (10 meters above the zero-plane displacement height). Most of the literature agrees with the fact that the profile below the displacement height (within the urban canopy) is difficult to assess because the wind is very turbulent with high horizontal variance depending on the orientation of the friction elements. Therefore, two wind profiles are developed which join together at the reference height 10 meters above the zero plane displacement height.

The lower profile has a higher power law coefficient due to the rapid decrease of wind speed with height nearer to the ground. The other profile extends to the top of the domain from the measuring height of the zero-plane displacement.

2. The longitudinal scales of atmospheric turbulence are realistic.

The scaling of the model is not as much of a concern in CFD modeling as in wind tunnel modeling, because the CFD model dimensions have the same relationship as reality. The model building in the CFD model is mathematically 135 feet tall, rather than a scale model of the building. Therefore, the critical factor in modeling the correct scales of turbulence flux is which mathematical model is chosen for the modeling. Currently, the LES (large eddy simulation) model is the best CFD turbulence model available for modeling the boundary layer of the atmosphere. However, this model requires excessive run times. The industry standard model is the K-ε model, which is efficient and commonly used in many, similar applications. We applied a modified K-ε model known as the Chen-Kim model, which has proven better at handling larger scale flows in the range of urban environments.

3. The modeled building, surrounding structures, and topography are geometrically similar to their full-scale counterparts. Tests shall be permitted for the modeled building in a single exposure site.

Current scales of the buildings are identical to the actual environment with a simplified geometry scheme to conform to the limits of the CFD model. The hillside topography is simplified to induce an incoming upwind flow from a southerly or westerly direction, but it is not an exact simulation of the relief in downtown Seattle. The actual geometry is too complex to put into this CFD model, but what is there is accurate enough to account for the main interactions of the geometry with the flow near the model building. CFD runs were also made with buildings removed in order to simulate a full hillside exposure conservative calculation. As mentioned earlier, Exposure B, was chosen due to the surrounding area being Exposure A, and the structure being located on an exposed hill.

4. The projected area of the modeled building is less than 8% of the test section cross-sectional area unless correction is made for blockage.

The test cross-section is the plane perpendicular to the windward building face out to the limits of the computational domain. It extends from the model domain walls parallel to the wind field (the geographic limits of computation) and from the surface to the top of the domain. The windward building face area must be less than 8% of the total area of the test cross-section plane. This ensures that the effects of turbulence at the modeled building face are independent of the interaction of the wind at the domain walls.

During south winds, the cross section of the model building is about 3.6% and during west winds, 5.2% of the total domain cross-section. In addition, the boundaries of the walls of the domains are modeled as open pressure surfaces, allowing air to enter or leave the domain depending on pressure forcing, effectively giving the domain no boundary limit. This can not be done in wind tunnel modeling, where the walls of the tunnel must be real and solid to ensure the steady flow of the wind. This factor reinforces the realism of the CFD model.

5. Longitudinal pressure gradient in the wind tunnel test section is accounted for.

This is not a factor in CFD modeling. The base pressure is initialized as uniform throughout the domain at the standard 1 atmosphere, 1013 mb. In reality a storm producing gusts to 85 mph would likely cause air pressure in the area to dip to as low as 960-975 mb. This would have little effect on the wind forcing though. Wind is forced in an inlet in the CFD domain at a constant speed well away from the modeled building faces. No longitudinal pressure gradient would therefore be a factor in this CFD setup.

6. Reynolds number effects on pressures and forces are minimized;

The Reynolds number is the ratio of the force of the turbulent flow to that of the inertial flow. When scaling wind tunnel modeling, it is important to keep this number similar to accurately simulate the real structures. This is often a difficult task. In the CFD model, the mathematical dimensions are again the same as in reality, so the Reynolds numbers will be similar if the choice of K-ε closure equations is reasonable.

7. Response characteristics of the wind tunnel instrumentation are consistent with the required measurements.

The CFD model allows for full access to pressure and wind fields directly solved by the CFD equations in all parts of the domain. CFD is not a physical model, but a mathematical engine designed to estimate elements of the flow, so no instrumentation is necessary for probing to determine the pressure fields.

There is no discussion in ASCE 7-02 regarding the use of mathematical wind tunnels for determining wind loading. No ASCE finding has been made about CFD as a complete alternative to wind tunnel modeling, but it is making gains in its industrial use as advances in computer technology allows it to be more accurate and economical to use. Method 2 is applicable to the model building, but Method 3 using CFD provide additional, useful information.

7.0 Modeling Approach

The modeling was conducted using a speed up to 85 mph (38 m/s) to simulate the strongest sustained gust. Due to the zero plane displacement, this is the gust at a height 25 meters (82 feet) above the ground, which is reasonable in a dense urban environment where the strongest winds will be de-coupled from the turbulent mix of wind in the lower canopy. However, the displacement is still low enough that the strongest winds impact the upper half of the model building.

Two CFD modeling cases were completed to compare the UBC formulated pressures to a more realistic picture of pressures on building elements. CFD modeling is also advantageous because it accounts for the geometry of a hillside and the unique geometry of the extension. The distribution of pressure over the walls can also be examined, which is something that the conservative equations can not provide.

Highest pressures will occur when the strong incoming winds are perpendicular to the building faces. The meteorological study demonstrated that strong winds of the magnitudes observed will occur only out of the southwest. However, winds approaching the modeled building from the southwest are damped by the presence of several tall buildings upwind, as could be expected in a dense urban core. In our particular assembly of buildings there were fewer tall structures to the southsoutheast. Therefore, winds from the southsoutheast were also modeled to gauge maximum possible impacts.

Four different runs were completed to gauge the pressure field along the building walls during the highest gust speed. The main run used the southsoutheast geometry. A second run was identical to the first but with one of the obstructing buildings mathematically deleted to establish worst-case impacts without an immediate upwind obstacle. Though this might not be the most realistic case, it is conservative in determining maximum pressures.

A third run involved modeling incoming strong winds from project west. However, several buildings are upwind during these winds, so results were expected to be trivial in comparison to the southerly direction. A fourth run using the gust of 85 mph from the east was modeled to find a conservative estimate of maximum pressures along the longer east face of the building. Although it is unrealistic to expect such high winds from the east in Seattle, the guidance in ASCE 7-02 6.5.4 requires that all horizontal directions must be accounted for. The project east wind provides the most exposure and pressures are generally the highest along the widest side of a tall structure, so it was chosen as the worst case scenario. Obstructing buildings to the east were also mathematically deleted to reduce obstruction to the flow.

8.0 Modeling Results

For the base case, the upwind buildings do a good job of blocking the incoming wind and deflecting most of the inertia over the urban canopy. However, a stream of wind channeled between the buildings cause some regions of high pressures along the southwest corner of the building and central section of the extension. The pressures recorded in the model are multiplied by 1.15 to account for the importance factor assumed for the building, to be consistent with the manual calculations. The maximum values were 13 psf on the building and 13.3 on the extension. Figure 1, in the figures at the end of this report, is a visualization of the distribution of the pressures.

A more conservative estimate of pressure distribution is shown in Figure 2, which is the southsoutheast model run with upwind buildings removed. This could be the most realistic distribution of pressure depending on the unique structure of an incoming gust in the area and its interaction with the buildings. In this case, the highest pressure is near the center of the model building at **15 psf** with a value of 14.8 psf on the extension.

The west wind run showed little impact on the building, as expected. However, some high values of pressure still occur on the penthouse wall, with values up to 10.5 psf.

The east wind gives the highest pressures, as expected. The pressure distribution is illustrated in Figure 3, and a high pressure of **19.1** psf occurs near the top center of the east face.

Overall, the magnitude of the pressures modeled in the CFD case are similar to the conservative estimates for cladding in both the IBC 2003 modified equation and the ASCE 7-02 Method 2 equation. The UBC code is ultra-conservative compared to the others. Table 1 compares the results.

Table I: Results of the CFD modeling and conservative equations

	East face, CFD	South face, CFD	South face, CFD – max	Method 2, ASCE	IBC 2003, modified	UBC
PSF	19.1	13	15	18.1	14.6 (center) 22.1 (corners)	27.16

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