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Evaluation of ASCE 7-10 Wind Velocity Pressure Coefficients on the Components and Cladding of Low-Rise Buildings Using Recent Wind Tunnel Testing Data

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ABSTRACT

In the USA, wind loads for building design are specified in a publication of the American Society of Civil Engineers (ASCE 7). The current version, ASCE 7-10, relies on wind tunnel tests that date back 30 to 50 years. In recent decades, many more test results have become available, and advances in computer technology have allowed the simultaneous recording of many more pressure taps than was possible half a century ago. In an effort to update the wind velocity pressure coefficients on the components and cladding of low-rise buildings, we made use of the wind tunnel tests performed at Tokyo Polytechnic University. Pressure tap locations and time history data were used to calculate peak wind pressure coefficients for a comprehensive sweep of sample areas. The peak pressures were estimated using Rice's zero up-crossing method applied to a 60-minute (full scale) windstorm. This process was repeated over all of the wind directions available from the wind tunnel tests. By sampling relevant area combinations with their contributing taps, we obtained a curve relating the effective wind velocity pressure coefficient versus sample area. Preliminary results show that the current ASCE specifications for components and cladding of gable roofs on low-rise buildings are unconservative.

KEYWORDS: *Wind pressure coefficients, low-rise gable building, Voronoi diagram, tributary area, ASCE 7*

1. INTRODUCTION

Since hurricanes cause substantial damage to buildings, the accurate determination of wind pressures on a structure is key to the design of damage resistant components and cladding. Wind pressures specified for the enclosures of low-rise buildings in the current 2010 edition of the American Society of Civil Engineers 7 Standard (ASCE 7-10) are based on wind tunnel test data compiled 30 to 50 years ago. Significant upgrades in computing technology over the last half century have made it possible to perform wind tunnel tests that have higher levels of precision in recording pressure data. This precision is attributed to the wind tunnel facility's ability to collect time history data for many densely-distributed adjacent pressure taps at the same time. Utilizing a modern aerodynamic pressure database, this paper discusses a methodology for analyzing such data and provides results for one building along with a qualitative comparison to the current ASCE 7-10 standards. The goal of this research is to reexamine long-standing ASCE 7 standards on components and cladding using modern testing procedures.

Over the last twenty years, multiple wind tunnel databases have been created for low-rise buildings. Beginning in 2003, the University of Western Ontario (UWO), in cooperative agreement with the National Institute for Standards and Technology (NIST) and Texas Tech University (TTU), released an aerodynamic database for low-rise buildings titled: Wind Tunnel Experiments on Generic Low Buildings. The objective of their initiative was to "conduct research to mitigate detrimental effects of wind storms on low-rise buildings and structures and on human activities" (Ho et al., 2003). Beginning in 2007, the Tokyo Polytechnic University (TPU) released an aerodynamic database for low-rise buildings titled: the TPU Aerodynamic Database for Low-Rise Buildings (Tamura, 2012). These two aerodynamic databases feature an assortment of tested building sizes, for which the building width, length, height, roof slope, and type of terrain vary and were tested using the high frequency pressure integration wind tunnel test method. Both of the databases are publically accessible, making them well-regarded tools in the wind engineering community.

Previous research conducted at Florida International University (FIU) compared three geometrically similar buildings from the TPU aerodynamic database to the UWO aerodynamic database (Hagos et al., 2014). For each surface, Hagos et al. (2014) typically selected three to five neighboring taps which shared similar locations between the databases. For three wind directions (0, 45, and 90 degrees) they estimated the peak pressure coefficients, using the method developed by Sadek and Simiu (2002). They concluded that the peak results from the examined pressure taps show minor differences between the databases, and are therefore regarded as equally valid. It is important to note that there are differences between the databases in building sizes, tap resolution, etc., meaning that the databases are not redundant, simply that they are comparable in overlapping scenarios.

Wind tunnel tests are scaled down in both length and time when compared to their full-scale analogs. In particular, the fluctuations in wind pressure are only explicitly known for the scaled duration of the test. Analysis of wind tunnel data relies on algorithms for finding the peak pressures over a standard duration of time, which can be different from simply scaling up wind tunnel test duration. The procedure used herein is based on Rice's zero up-crossing method, developed by Sadek and Simiu (2002), which suggests that the peak pressures are generally non-Gaussian and can be represented by the Gamma distribution. Main (2011) programmed the Sadek and Simiu (2002) method into a MATLAB function.

In this paper, a detailed description of the TPU low-rise building aerodynamic database, which was used for our analysis, is first provided. This is followed by a description of the methodology used to analyze a set of low-rise buildings. Results are provided from our analysis of one representative gable building. The paper concludes with a discussion of the results and future research.

2. TOKYO POLYTECHNIC UNIV. LOW-RISE BUILDING WIND TUNNEL DATABASE

TPU's aerodynamic database contains multiple sub-databases ranging from low-rise buildings with and without eave to high-rise buildings. Each of the distinct sub-databases, which can be found online via the TPU aerodynamic database website (Tamura, 2012), are listed as follows: Wind Pressure Database for High-Rise Building, Wind Pressure Database of Two Adjacent Tall Buildings, Database of Isolated Low-Rise Building Without Eaves, Database of Isolated Low-Rise Building With Eaves, and Database of Non-Isolated Low-Rise Building. This article will solely focus on the database of isolated low-rise buildings without eave. The sub-database is categorized in the following order: roof type, height to breadth ratio, depth to breadth ratio, and roof pitch. Fig. 2.1 provides example dimensions of breadth B, depth D, eave height $H0$, roof pitch β, and wind angle θ of a typical building. TPU's database for low-rise buildings without eave contains a wide variety of tested building sizes and combinations in which the roof slope is varied. Each of the building combinations contains corresponding data files which were tested for the following wind angles θ: 0, 15, 30, 45, 60, 75, and 90 degrees. TPU's database is publically available for download as MATLAB files. The database files contain the buildings geometric information including: eave height, breadth, depth, and roof slope. Each of the associated pressure taps is provided an identification number, a surface number, and its x and y coordinates.

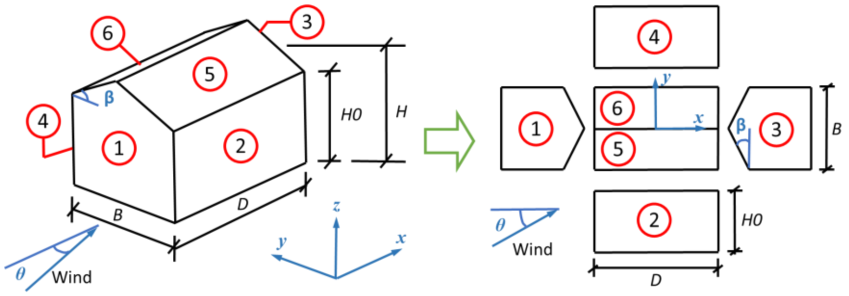


Figure 2.1 Test model and definitions of geometrical parameters and coordinates (Tamura, 2012)

TPU's Boundary Layer Wind Tunnel is 2.2 m wide by 1.8 m tall. The wind tunnel tests were performed at the following scales: a length scale of 1/100, a velocity scale of 1/3, and a time scale of 3/100. Tests were performed in accordance to terrain category III (suburban) as defined in the Architecture Institute of Japan (AIJ, 2004). According to TPU, the turbulence density at a height of 10 cm was roughly 0.25. Additionally, the test wind velocity at a height of 10 cm was roughly 7.4 m/s, which corresponded to 22 m/s at a height of 10 m in full scale. This wind speed corresponds to the mean hourly wind speed as utilized in ASCE 7-10 calculations. Wind pressure coefficient time-history data, sampled at 500 Hz, are provided in TPU's database files. The datasets correspond to 10 minutes of full scale data, or 8 seconds of model scale data.

The following calculations outline the method which TPU used for calculating the normalized wind pressure coefficients $C_p(i,t)$, from each individual taps measured wind pressure data p_i. The calculation for $p(i,t)$ of Eq. 2.1 represents the net tap pressure above ambient/reference pressure and is expressed by subtracting the individual tap measured wind pressure data p_i by the static atmospheric pressure p_0 at the reference height, which is defined by Tamura (2012) as the mean roof height H.

$$p(i,t) = p_i - p_0 \tag{2.1}$$

The value p_H of Eq. 2.2 represents the reference wind pressure of the approaching wind velocity at the mean roof height and is calculated using the mean hourly wind speed V_{3600} at reference height and the air density ρ.

$$p_H = 0.5\rho V_{3600}^2 \tag{2.2}$$

The normalized wind pressure coefficients are denoted by $C_p(i,t)$ at tap i and time t and are calculated by dividing the net tap pressure by the reference wind pressure as in Eq. 2.3. To make the wind pressure coefficients correspond to a full scale duration of 0.2 s, TPU uses a moving average over 0.006 s of the measured time series (Tamura, 2012).

$$C_p(i,t) = p(i,t)/p_H \tag{2.3}$$

3. METHODOLOGY FOR COMPUTING EXTERNAL PEAK ENVELOPE WIND VELOCITY PRESSURE COEFFICIENTS

The methodology we used to analyze the wind velocity pressure coefficients of low-rise buildings begins by selecting a wind tunnel database and a building. A typical database file contains the location of each pressure tap along with its respective pressure time history data for a given wind direction. Other related attributes are also provided, such as the terrain exposure, wind speed, model scale and building dimensions. In order to observe the building's geometry and tap distribution, the building is first flattened and plotted displaying the location of each of the pressure taps and outlining the boundaries of the building's surfaces. This plot provides the grounds for which the tap tributary areas can be determined and the pressure coefficients can be assigned.

To assign the pressure coefficient time history data to the surfaces of the building, each pressure tap's tributary area must first be defined. A Voronoi diagram (Matlab 2014b) is used to account for potential irregular tap distributions, by dividing the total area into tributary areas surrounding each tap. A Voronoi diagram begins with a Delaunay triangulation (Matlab 2014b), where a set of points is connected forming triangles that: (1) do not overlap, (2) cover the entire interior space formed by the points, and (3) do not have any points within the triangle's circumcircle. Next, a Voronoi diagram is created by drawing straight lines perpendicular to the triangle boundaries, equidistant from the boundaries' vertices. Regions are formed from these lines that encompass one point each, with every location in the region closer to that point than to any other point. Fig. 3.1 shows three elevation views for the wall of a gable roof building with roof slope of 45 degrees. Pressure tap locations are marked by red circles and tap tributary area boundaries marked by blue lines and blue circles. Fig. 3.1 (a) indicates the location of individual pressure taps with no tributary areas identified. Fig. 3.1 (b) shows an example in which simple 2 m × 2 m tributary areas were assigned to each pressure tap. Fig. 3.1 (c) shows an example with a Voronoi diagram applied to determine the pressure tap tributary areas. Voronoi diagrams provide a simple and automated means to determine the tributary areas for irregularly spaced taps.

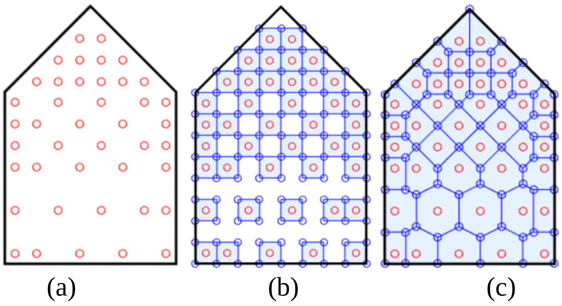


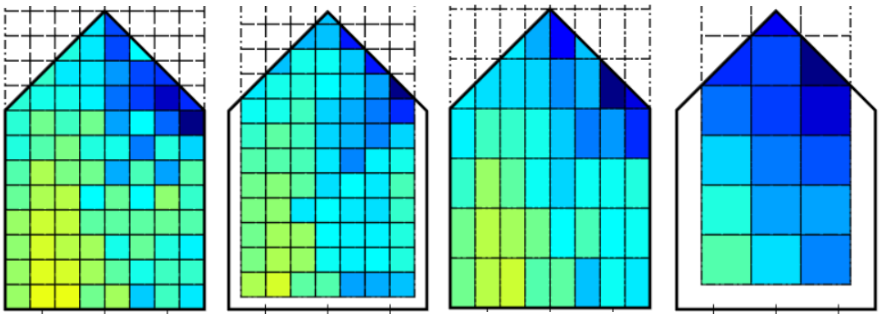
Figure 3.1 Examples of Pressure Tap Tributary Areas

The tributary areas span the entire building surface as in Fig 3.1 (c) and each have a unique pressure coefficient time history $C_p(i,t)$ as given in the database. However, to develop ASCE 7 provisions, pressure coefficient time histories are needed for arbitrary sample areas to account for spatial and temporal incoherence. When a sample area overlaps with the tributary area of only one pressure tap, the sample area's pressure coefficient time history will remain the same as that of the individual tap. However, when a sample area includes more than one tributary area, then a weighted average calculation of the time histories of all tributary areas which overlap with the sample area must be performed to determine the sample area's pressure coefficient time history.

This calculation is summarized by Eq. 3.1, where the hourly wind pressure coefficients GC_{p3600} are determined by an area-weighted average calculation in which the tributary areas a_i of all taps i which fall into the sample area of interest are multiplied by their respective wind pressure coefficients $C_p(i,t)$ and then the sum is divided by the sample area of interest A. The peak factor G accounts for variability of the pressure coefficient due to the randomness of the aerodynamic response and is introduced implicitly when the averaging process and the peak selection process are applied (Simiu, 2011).

$$GC_{p3600} = \frac{\sum a_i \, C_p(i,t)}{A} \tag{3.1}$$

To calculate the wind pressure coefficients varying as a function of sample area size and location, the building surfaces were overlaid with sample area grids. Both the size of the sample area and the offset of the grid are incremented for a complete sweep of all areas of interest. It is worth noting that any sample areas which cross outside of the boundary of the surface, even partially, were discarded. The size of the minimum sample area and the size of the offsets are based on the nominal tributary areas of the individual taps, as there is no justification to resolve a smaller sample area than the tributary area itself. Fig. 3.2 shows example sample area grids. Fig. 3.2 (a) shows a 2 m × 2 m sample area with no offset. Fig. 3.2 (b) shows the same 2 m × 2 m sample area with 1 m offset in each direction. Fig. 3.2 (c) shows a 2 m × 4 m sample area with no offset. And Fig. 3.2 (d) shows a 4 m × 4 m sample area with 2 m offset in each direction. Fig. 3.2's color scale is related to Fig. 4.2, but is unimportant here.



(a) (b) (c) (d)

Figure 3.2 Example Sample Area Sizes and Increments.

The following additional example shows this method of using and offsetting sample areas over one wall of a gable roof building. In this example, a sample size of 2 m × 2 m is incremented by 1 m in each direction to achieve sample sizes up to, say, 3 m × 3 m. Additionally, these sample sizes can be offset in each direction by a specified increment, say, 1 m. The possible sample area/offset combinations are shown in Table 3.1.

Table 3.1 - Applicable Sample Sizes Example

x (m)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
y (m)	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3
x offset (m)	0	0	1	1	0	0	0	1	1	1	0	0	1	1	2	2	0	0	0	1	1	1	2	2	2
y offset (m)	0	1	0	1	0	1	2	0	1	2	0	1	0	1	0	1	0	1	2	0	1	2	0	1	2

Peak pressure coefficient values are obtained for each sample area using the Rice method (Sadek and Simiu, 2002), which consists first in estimating the mean upcrossing rate of a given threshold from the spectral density function of a random process. From this estimate, the cumulative distribution function of the largest peaks for a given time interval is calculated. The calculation of distributions of non-Gaussian peaks is based on a standard translation process, which requires fitting an optimal marginal distribution, in this case the three-parameter Gamma distribution, to the time series of interest. This method was implemented in the MATLAB function

Maxminest by Main (2011). For the pressure coefficient time history data of a particular sample area, the method will output both maximum and minimum peak pressure coefficients. The method uses a duration ratio parameter D_R (Eq. 3.2) to account for the fact that the expected peak pressures in a 60-minute storm are different from the peaks derived from a ten-minute (full scale) wind tunnel test record. The calculation of the peak pressure coefficients is repeated for each sample area over all wind directions. Finally, the envelope of the peaks is extracted for each sample area considering all wind directions.

$$D_R = (\text{duration of storm of interest})/(\text{full-scale duration of measured record}) \tag{3.2}$$

To compare the calculated minimum and maximum peak wind pressure coefficients to the ASCE 7-10 values, we must renormalize the hourly wind speed to a peak three-second gust. The three-second gust speed V_3 can be taken as 1.52 times the hourly wind speed (Durst, 1960). This factor is demonstrated by performing the following calculations, where the wind pressure coefficient for the three-second gust is represented by GC_{p3} and the 3600 s storm wind pressure coefficient is represented by GC_{p3600}. ASCE 7-10 external peak pressure coefficients are simply identified as GC_p, corresponding to GC_{p3} in Eq. 3.3.

$$GC_p = GC_{p3} = GC_{p3600}(V_{3600}/V_3)^2 = GC_{p3600}(1/1.52)^2 \tag{3.3}$$

Results using this method for the TPU database are compared to ASCE 7-10 wind pressure coefficient charts using the ASCE 7 zoning specifications. Applying these zones allows us to sort the wind pressure coefficients and compare with the ASCE 7-10 charts. As the TPU database is limited by the smallest tap tributary areas of 2 m × 2 m, we must consider partial tributary areas to be able to populate zone 3 (corner regions) which has dimensions of 1.6 m × 1.6 m for the building considered. To accommodate the narrow zones and coarse tap spacing, a decision was made to accept partial sample areas if at least 50% of the sample area falls within the zone. Partial areas were considered for zones 2, 3, and 5 (see Fig. 4.4) and rejected for zones 1 and 4.

4. RESULTS

The gable building selected for analysis has the following dimensions: depth D = 24 m (78.74 ft), breadth B = 16 m (52.5 ft), eave height $H0$ = 12 m (39.37 ft), and a roof slope of β = 5 degrees (Fig 2.1). The building plan is shown in Fig. 4.1 with the dimensions above, along with the pressure taps represented by red circles and the tributary area boundaries represented by blue lines and blue circles.

The next step involves deciding relevant sample areas. TPU's pressure taps are spaced at 2 m on center, therefore, we have selected the smallest possible sample area as 2 m × 2 m. The sample areas are varied from 2 m × 2 m up to 7 m × 7 m, within which the sample areas were incremented by values of 0.5 m. Likewise, the offset increments in each dimension were set equal to the sample area increments. Using this distribution, the total number of sample area combinations is 9,801 (e.g., 9,801 sample area grids, each grid with a unique sample area/offset combination). Combining the worst case peak pressure coefficients from all tested wind directions, allows us to plot the building envelope peaks for each sample area/offset combination. The plots of the minimum and maximum peak wind pressure coefficients for a sample size of 2 m × 2 m with no offset are shown in Figs. 4.2 and 4.3, respectively.

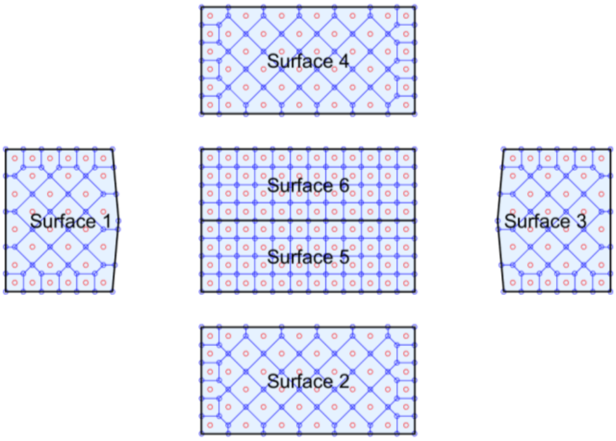


Figure 4.1 Plot of Pressure Tap Locations and Tributary Areas

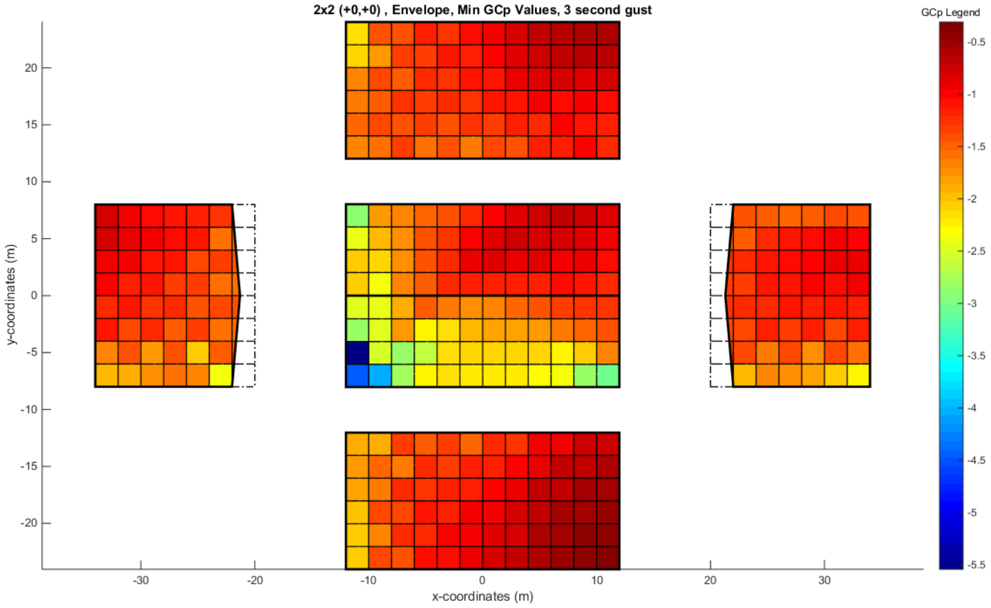


Figure 4.2 Envelope of Minimum Peak Wind Pressure Coefficients for 2 m × 2 m Sample Size (No Offset)

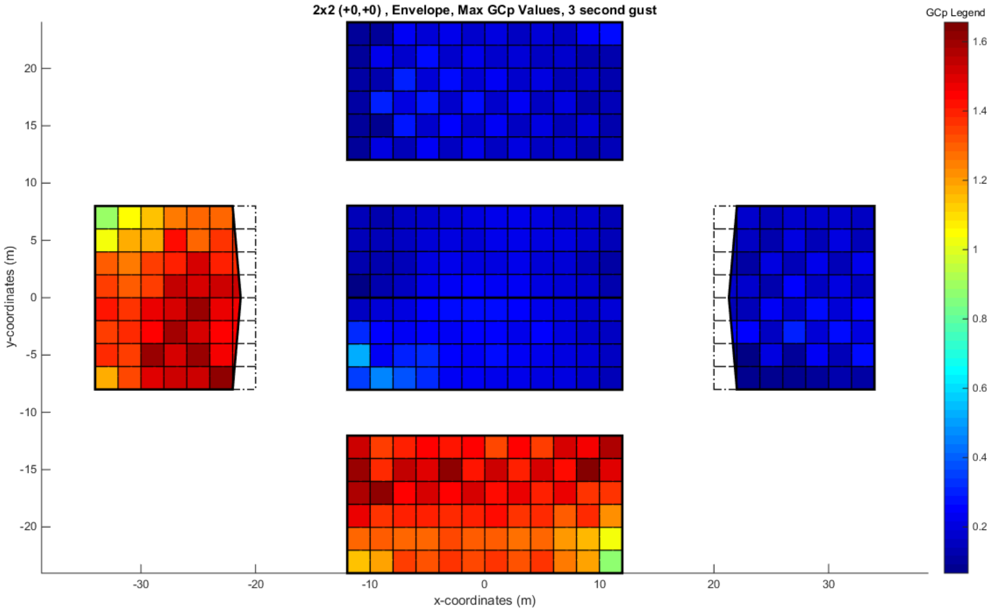


Figure 4.3 Envelope of Maximum Peak Wind Pressure Coefficients for 2 m × 2 m Sample Size (No Offset)

Following the calculation of peak wind pressure coefficients, we separated the building into zones to compare the results to the ASCE 7-10 wind pressure coefficient charts. The determination of zones varies by building roof type and roof pitch; our selected building corresponds to Figure 30.4-2A of ASCE 7-10 (External Pressure Coefficients GC_p for Enclosed and Partially Enclosed Buildings with Gable Roof of Slope 7° or less). Notations from ASCE 7-10 specify the dimension *a* of Fig. 4.4 to be, "10% of least horizontal dimension or 0.4h, whichever is smaller, but not less than either 4% of least horizontal dimension or 3 ft (0.9 m)". Applying the definition to our selected building, a = 1.61 m. Fig. 4.4 shows the zone layout for only surfaces 1, 5 and 6 of the tested gable roof building. However, all surfaces 1, 2, 3, 4, 5 and 6 were utilized to develop the results presented in Fig. 4.5. Note that the dimension *a* is measured on the projection of the roof onto a horizontal plane.

The peak wind pressure coefficients were assigned to their respective zones and the plots of the results are provided in Fig. 4.5. In these plots, the red data points represent the negative (suction) peak wind pressure coefficients, while the blue data points represent the positive (into the building) peak wind pressure coefficients. Additionally, the current ASCE 7-10 specifications for positive and negative external wind pressure coefficients were superposed to the plots using solid black lines.

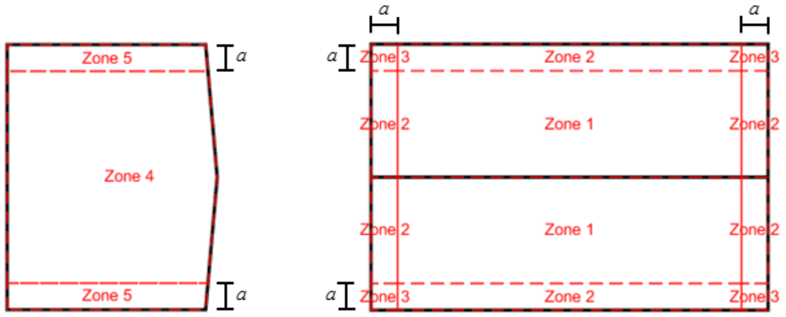
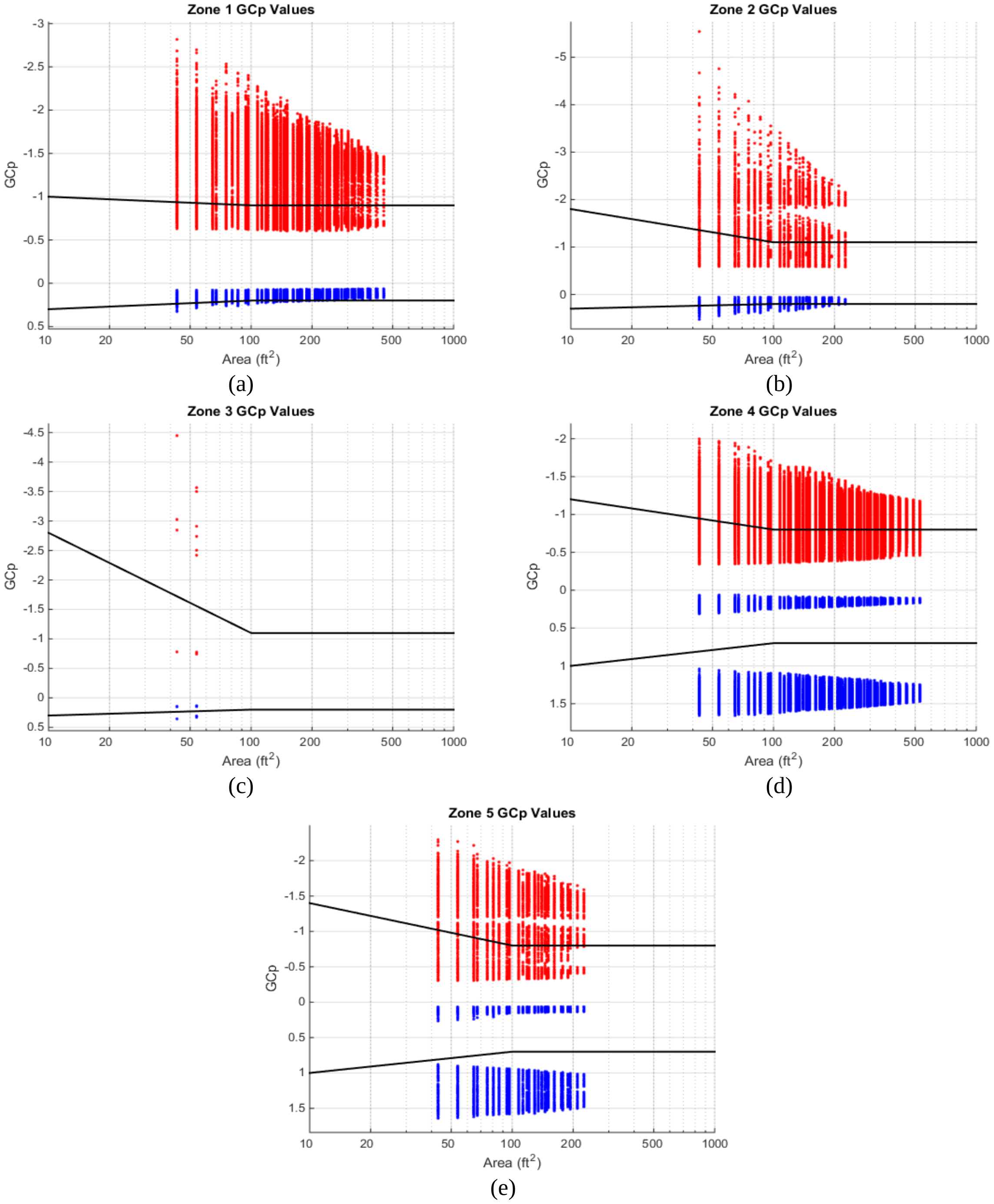


Figure 4.4 Applied Zone Layout (Figure 30.4-2A, ASCE 7-10)



(a)

(b)

(c)

(d)

(e)

Figure 4.5 Wind Pressure Coefficients by Respective Zone

5. DISCUSSION

Analysis of the wind pressure coefficients for a single building in the TPU database compared to the ASCE 7-10 specifications show that the specifications are unconservative for all corner, edge, and interior zones of the roof, especially for negative pressures (suction).

In analyzing the TPU data, we enforced a rule in which partial tap tributary areas were considered in a zone if at least 50% of the tap tributary area fell in that zone. It is worth noting that the TPU database has a wide variety of building types, however, it does not have densely spaced taps at areas of large pressure gradients, such as the windward corner of a gable roof. To analyze these particular pressure gradient regions, other databases such as the UWO database may be more useful. The UWO database provides a high resolution of pressure taps in corner roof regions, possibly providing a clearer picture of the extreme pressures in smaller zones, such as ASCE 7-10's zone 3. Furthermore, smaller tap tributary areas would justify smaller sample areas to better populate Fig. 4.5 for all zones.

6. CONCLUSIONS

This study focuses on a procedure to analyze the aerodynamic database for low-rise structures tested in TPU's wind tunnel with the goal of assessing the adequacy of ASCE 7 wind provisions for components and cladding. The details of the wind tunnel database were summarized. Through the subsequent sections, our methodology for analyzing a wind tunnel database were outlined step by step and explained in a method which can be easily reproduced to obtain our results. The Voronoi function was incorporated to automatically assign tributary areas to both irregularly and regularly spaced pressure taps. The proposed method was applied to one of TPU's buildings. Analysis shows that the wind velocity pressure coefficients prescribed by the ASCE 7-10 to all zones are much lower than the coefficients obtained from the database.

Based on these limited results, we conclude that current ASCE 7-10 specifications for components and cladding need to be updated. In further research, we intend to expand the results to a variety of tested buildings from TPU's and UWO's wind tunnel databases.

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