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An Assessment of ASCE 7-10 Standard Methods for Determining Wind Loads

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ABSTRACT

The purpose of this paper is to discuss issues associated with ASCE 7-10 Standard methods for determining wind loads on buildings and other structures, that warrant comment, correction or improvement. The assessment is intended to serve as a resource in the development of a new version of the American Society of Civil Engineers ASCE-7 Standard, and to stimulate a wider participation in that development by the structural engineering community. Issues discussed in the paper include: wind speeds in non-hurricane regions; alternative analytical methods for determining wind loads and wind effects on Main Wind Force Resisting Systems and Components/Cladding; aerodynamic pressure coefficients; pressures on rooftop equipment; component and cladding pressures on arched roofs; and the wind tunnel procedure. It is noted that the ASCE 49 Standard essentially covers wind tunnel testing, rather than the wind tunnel procedure, of which wind tunnel testing is only a part.

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KEYWORDS: Arched roofs; rooftop equipment; standards; wind engineering; wind loads; wind pressures; wind speeds; wind tunnels.

INTRODUCTION

The purpose of this paper is to discuss the following issues: Wind speed maps for non-hurricane regions; alternative analytical methods for determining wind loads on Main

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Wind Force Resisting System and Component/Cladding; aerodynamic pressure coefficients; pressures on rooftop equipment; component and cladding pressures on arched roofs; and the wind tunnel procedure. It is noted that the ASCE 49 Standard essentially covers wind tunnel testing, rather than the wind tunnel procedure, of which wind tunnel testing is only a part.

Improvements in the methods for determining wind loads on buildings and other structures can eliminate the underestimation of wind effects on some types of buildings or reduce unnecessary costs due to overestimates of wind effects. Reference is made to procedures incorporated in ASCE **7** (2010). The assessment of how the Standard addresses these issues is intended to serve as a resource in the development of a new version of the American Society of Civil Engineers ASCE-7 Standard, and to stimulate a wider participation in that development by the structural engineering community.

WIND SPEEDS FOR NON-HURRICANE REGIONS

According to Simiu et al. (2003), a methodologically erroneous application by Peterka and Shahid (1998) of the superstation approach led to the artificial smoothing out of geographical variations of the extreme non-hurricane wind climate, both in the western states and throughout the other states of the Union. For this reason, and to take advantage of the larger data sets currently available, NIST has undertaken the development of new wind speed maps that will be provided to the ASCE 7 Subcommittee on Wind Loads for dis-

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cussion and possible incorporation into the ASCE 7-16 Standard. The maps will be based on data measured at nearly 1200 Automated Surface Observing System (ASOS) stations with the majority of the stations having records approaching 30 to 40 years in length (by comparison, the wind speed map in ASCE 7-02 was developed from approximately 500 stations typically having 15 to 25 years of data). The data extraction is described in Lombardo et al. (2009), as is the analysis procedure, which accounts separately for thunderstorm and non-thunderstorm wind speeds. See also Simiu, Lombardo, and Yeo (2012) and Lombardo (2012) for details..

ANALYTICAL METHODS FOR DETERMINING WIND LOADS

In some instances the ASCE 7-10 Standard provides two, three, or four alternative analytical methods for determining wind loads. For example, four different methods can be used to determine Main Wind Force Resisting System loads on enclosed simple diaphragm low-rise buildings – the Directional Procedure, the Simplified Directional Procedure, the Envelope Procedure, and the Simplified Envelope Procedure (ASCE 7, 2010). As suggested by one of the reviewers, it would be desirable to eliminate the distinction between buildings higher and lower than 60 ft. Given the complex structure of the current version of the Standard, this would have numerous ramifications; pertinent recommendations would therefore exceed the scope of this technical note, but should be the object of debate as a new version of the ASCE 7 Standard is developed.

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Where more than one method is available the user needs to know to what extent the choice of method matters. In some instances some guidance is offered on this issue. Examples 1 and 2 below suggest that the guidance is not always dependable. For details see Simiu (2011, pp. 47-51, 59-62 for Example 1; 82-84 for Example 2; 105-106 for Example 3; 78-80 for Example 4).

Example 1. *Main Wind Force Resisting Systems (MWFRS): Directional procedure for buildings of all heights, ASCE 7 (2010), Sect. 27.4.1 vs. Envelope procedure for low-rise buildings, ASCE 7 (2010), Sect. 28.4.1.*

Consider a rectangular office building with dimensions in plan of 45 ft × 40 ft (13.7 m × 12.2 m), eave height 15 ft (4.6 m), gable roof with slope $\theta = 26.6°$ and mean roof height $h = 15$ ft + ½(½ × 40 ft) tan 26.6° = 20 ft (6.05 m). (Since $h < 60$ ft (18.3 m) and h /least horizontal dimension = 20/40 < 1, the building is defined in current practice as a low-rise building.) Assume that the building is in flat terrain, has suburban exposure in all directions, and is fully enclosed. For wind parallel to long building dimension the envelope procedure yields pressures higher in absolute value by 50% to 60% than the directional procedure. See also Example 2, Case I below.

It is stated in ASCE 7 (2010), Sect. 28.2 that the envelope procedure "…*generally yields the lowest wind pressure of all of the analytical methods specified in this standard."* Example 1, which was chosen at random, shows that this is not necessarily the case. In fact, not only can wind pressures be larger for the envelope procedure than for

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the directional procedure, but the discrepancies between wind effects produced by those pressures can be even larger. For winds parallel to the ridge the moment at a bent of the windward end frame is -8.96 kips-ft if determined by the directional procedure and, owing in part to the asymmetry of the loads, it is -17.58 kips-ft if determined by the envelope procedure; thus, the moment is far larger (rather than being smaller) if determined by the envelope rather than by the directional procedure.

Example 2. *MWFRS: Directional procedure (regular approach for buildings of all heights, ASCE 7 (2010), Sect. 27.4.1) vs. Envelope procedure (regular approach for low-rise buildings, ASCE 7 (2010), Sect. 28.4.1) vs. Directional procedure (simplified approach for buildings of all heights, ASCE 7 (2010), Sect. 27.6.*

For the building of Example 1, assumed to be a simple diaphragm building, for flow direction parallel to the ridge, Zone 3 of the gable roof (ASCE 7, 2010, Table 27.6-2, Directional Procedure, simplified approach) may be considered to correspond to Zone 2E, Load Case B (7, 2010, Fig. 28.4-1, Low-Rise Buildings, regular approach). If the basic wind speed is V = 115 mph (51.4 m/s), the pressures on the roof for these zones are:

Directional proc., regular approach, bldgs. of all heights: p = -16.8 psf (803 Pa)

Directional proc., simplified approach, bldgs. of all heights: p = -19.0 psf (908 Pa)

Envelope procedure, regular approach, low-rise buildings: p = -25.1 psf (1200 Pa)

In this case the pressure is *larger* if obtained by the envelope procedure.

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Example 3. *Components and Cladding: Regular approach for h ≤ 60 ft (18.3 m) (ASCE 2010, Sect. 30.4) vs. Simplified approach for h ≤ 60 ft (18.3 m) (ASCE 7, 2010, Sect. 30.5) vs. Simplified approach for h ≤ 160 ft (48.8 m) (ASCE 7, 2010 Sect. 30.7).* For an enclosed office building with height h = 60 ft (18.3 m), we assume: area of the cladding 4 ft^2 (0.37 m^2) flat roof; suburban exposure; flat terrain; basic wind speed 115 mph (51.4 m/s). For wall Zones 4 and 5 (ASCE 7, 2010), the calculated pressures, in psf, are listed in Table 1. The largest and smallest Zone 4 and Zone 5 pressures are shown in bold. The differences between those pressures are as high as about 20% and 40%, respectively.

PRESSURE COEFFICIENTS FOR LOW-RISE STRUCTURES: ENVELOPE METHOD VERSUS WIND-TUNNEL MEASUREMENTS

We consider in this section only pressures on low-rise buildings, on which several studies are available. A procedure for low-rise buildings entails the use of tailored coefficients applicable to portal frames of industrial buildings and referred to as "pseudo-pressure" coefficients. These coefficients are based on wind tunnel data measured at the University of Western Ontario (UWO) mostly in the 1970s (Davenport, Stathopoulos, and Surry, 1978), and were developed with a view to enveloping the frame's peak load effects: bending moments, resultant vertical uplift, and horizontal shear for about 15 distinct building geometries. St. Pierre et al. (2005) compared these quantities as obtained from

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pressure coefficient plots in ASCE 7 (2003) (identical to the corresponding pressure plots in the later versions of the Standard) to their counterparts calculated from pressures measured also at UWO but by using state-of-the-art experimental techniques (Ho et al. 2005). They reported that the responses predicted by ASCE 7 (2003) were in many cases lower in absolute value by about 30% than the responses obtained using their recent pressure measurements. These discrepancies are attributed to the fact that the earlier experiments were conducted in flows with lower turbulence intensities, for wind directions in increments of mostly 45°, as opposed to 5° in the later tests, with a number of pressure taps lower by almost one order of magnitude, and with fixed distances between frames, thus disregarding the dependence of the loads on distance between frames. In addition, even if the coefficients resulted in estimates of the bending moments at the frame knees and ridge to within, say, 10% of the actual values (which is not always the case), their suitability for calculating bending moments at other locations is questionable. The results obtained by St. Pierre et al. (2005) were confirmed by Coffman et al. (2010), who analyzed seven portal frame buildings with open terrain exposure for which pressure measurements by Ho et al. (2005) are recorded in the NIST aerodynamics database (http://www.nist.gov/wind). Coffman et al. (2010) found that, "depending on the building dimensions, the peak bending moments at the knee based on Database-Assisted design (DAD) techniques are generally larger by 10 to 30% than their counterparts based on the ASCE 7 (2006). (In one case with a relatively steep roof slope of 26.6° the discrepancies

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exceed 70%.) For the buildings considered, the discrepancies increase with increasing roof slope and with increasing eave height." From results reported by Fritz et al. (2008) it may be surmised that the discrepancies would be larger for buildings in suburban terrain.

ASCE's Technical Council on Wind Engineering has identified the need for an "…extensive program of wind tunnel testing to establish design pressure coefficients for a wide range of different shapes…", citing the concern that existing pressure coefficients are based on tests done over 30 years ago, using wind tunnel technology far less advanced than available today (Irwin, 2011). A testing program has recently been performed by Tokyo Polytechnic University (TPU), which has issued a large public aerodynamic database that could be used as a coherent, traceable source of data for the development of improved provisions on wind pressure coefficients (Tamura, 2011; www.wind.arch.t-kougei.ac.jp/system/eng/contents/code/w). An evaluation of the TPU data is performed through comparisons with existing data obtained in wind tunnel (e.g., UWO and Colorado State University), full-scale, and large-scale facility measurements. We suggest that a review of the sources of the Standard's aerodynamic data be performed, and that data based on inadequate testing be eliminated to the extent possible.

WIND LOADS ON ROOFTOP EQUIPMENT

Two procedures for estimating forces on rooftop equipment are currently available for widespread use in the United States (U.S.). The choice of procedure depends on building

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height. If the height of a building is over 60 ft (18.3 m) the procedure included in ASCE (2010) as Eq. 29.5-1 is applicable. For buildings with height less than or equal to 60 ft (18.3 m) the procedure included in ASCE 7 (2010) as Eq. 29.5-2 is applicable. The two procedures are mutually inconsistent insofar as, for values close to 60 ft (18.3 m), they yield markedly different results.

Example 4. *Rooftop equipment, Directional procedure: approach for $h > 60$ ft (18.3 m) (ASCE Sect. 29.5) vs. approach for $h \leq 60$ ft (18. 3 m) (ASCE Sect. 29.5.1).*

Two rectangular office buildings, located in Iowa in flat terrain with exposure B in all directions, have dimensions in plan 45 ft × 45 ft (13.7 m × 13.7 m) and a flat roof, but eave height 62.5 ft (19. 1 m) and 60 ft (18.3 m), respectively. The rooftop equipment is a cube structure with 2.4 ft (0.73 m) sides. The procedure applicable to the building with h = 62.5 ft (19.1 m) estimates a design lateral wind force of 180 lb (802 N), while the approach for the building with h = 60 ft (18.3 m) results in a design lateral wind force of 400 lb (1780 N) and the design vertical uplift wind force of 220 lb (980 N). Note that the vertical uplift force on rooftop equipment is not considered in the procedure for buildings with height greater than 60 ft (18.3 m). To correct this inconsistency, an option would be to apply conservatively the provision restricted to buildings with $h \leq 60$ ft (18.3 m) of ASCE Sect. 29.5.1 to buildings of all heights. The proposed unified approach would also specify an uplift force on rooftop structures, regardless of building height. Note that code change recommendations for the Florida Building Code (FBC, 2010) to correct the in-

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consistency pertaining to wind loading on rooftop equipment were unanimously approved by the Florida Building Commission on December 8, 2010..

WIND LOADS FOR COMPONENTS AND CLADDING OF ARCHED ROOFS

A procedure for estimating wind loads for components and cladding of arched roofs is available in Fig. 27.4-3, ASCE 7 (2010). The procedure specifies that the pressure coefficients for components and cladding should be equal to the pressure coefficients for the Main Wind Force Resisting Systems multiplied by the factor 0.87 (Fig. 27.4-3, Note 4). This is likely to be an inadvertent error: divided, rather than multiplied by that factor would make more sense. Indeed, because the spatial coherence of the pressures is greater between pressures acting over small areas than between pressures acting over large areas, pressure coefficients for Components/Cladding should be larger than the pressure coefficients for Main Wind Force Resisting Systems.

INSUFFICIENT SPECIFICITY OF PROVISIONS ON THE WIND TUNNEL PROCEDURE

Largely because the U.S. provisions with respect to the wind tunnel method lack sufficient specificity, discrepancies can occur among estimates of wind effects by various laboratories. This has been confirmed, for example, by differences of up to about 80 %

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among pressures measured on low-rise building models in six wind tunnels in the U.S., Canada, France, and Japan can be even greater (Fritz et al. 2008).

The simulation of the natural wind at specific locations and the evaluation of wind induced loads and/or structural responses are performed by methods that may differ from wind tunnel to wind tunnel. Principal reasons for differences among response estimates by various wind engineering consultants are discussed in (NIST 2005).and include, notably, wind climatological modeling, load combination estimates based on subjective judgments that can vary substantially from laboratory to laboratory (whereas in time-domain methods the combinations are determined objectively, see e.g., Yeo and Simiu 2011), and inadequate methods of estimating wind directionality effects, in spite of the availability of the simulated storm passages method, which is particularly effective in the prediction of wind action during passages of hurricanes or typhoons (Isyumov et al. 2003), and of time-domain approaches (Yeo and Simiu, 2011). One possible approach for limiting differences due to wind directionality is to require that laboratories evaluate the reliability of their wind climate descriptions and make allowance for the uncertainties in those descriptions. For example, the effects of uncertainties in wind directionality can be reduced by rotating the extreme wind rosette by, say, 15 degrees clockwise as well as counter-clockwise when determining the wind effects. Another useful approach is to put in place a lower bound on the ratio of predictions obtained with and without the use of wind directionality. The limitation on wind loads obtained by using the Wind Tunnel

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Procedure specified in Sect. 31.4.3 of ASCE 7-10 is helpful in eliminating possibly unconservative results.

On the need for standard provisions on the *wind tunnel procedure*, as opposed to standard provisions on *wind tunnel testing*, see Simiu (2009). Wind tunnel testing (ASCE 49, 2012) is only one phase in the process of determining wind effects by the wind tunnel procedure. Once the physical (aerodynamic) testing is completed it is necessary to produce on its basis estimates of wind effects to be considered in design, as noted earlier in this section. The 40 % differences between estimates of wind effects on the World Trade Center towers were due in large part to the lack of standard provisions on the wind tunnel procedure, which is not covered by ASCE 49 (2012) – see also NIST (2005).

CONCLUSIONS

For non-hurricane regions, inadequately differentiated wind speed maps can result in the underestimation of basic wind speeds in some regions of the country and in their overestimation in other regions. New wind speed maps and databases are being developed by NIST's National Windstorm Impact Reduction Program and Statistical Engineering Division. These maps and databases will be provided to the ASCE 7 Subcommittee on Wind Loads for discussion and possible incorporation into the ASCE 7-16 Standard.

According to recent studies, pressure coefficients for low-rise buildings used in the U.S. within the framework of the so-called "envelope procedure" are in many cases lower

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by as much as 30% than values obtained by state-of-the-art wind tunnel testing methods. The underestimation of pressure coefficients for low-rise buildings can lead in some situations to designs that do not meet intended minimum requirements for wind loads.

Results of calculations shown in the paper demonstrate that alternative analytical methods for the determination of design wind loads can produce significantly different results. In particular, the "envelope method" can yield internal forces that, owing in part to asymmetries in the wind load distribution, can be twice as large as those yielded by the "directional method." It is pointed out in the paper that current provisions for roof-top equipment and for components/cladding for arched roofs are inadequate and, where feasible, suggestions are presented for an improvement of those provisions.

With respect to existing provisions on the wind tunnel procedure, it is noted that they are not sufficiently specific, and that this can explain large discrepancies that have been found to exist between estimates of wind effects on buildings performed by different wind tunnels. It was noted that the ASCE 49 Standard essentially covers wind tunnel testing, rather than the wind tunnel procedure, of which wind tunnel testing is only a part.

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Table 1. Pressure Comparisons (1 psf = 47.88 Pa)

	Regular procedure, $h \leq 60$ft (18.3 m)	Simplif. procedure, $h \leq 60$ft (18.3 m)	Simplif. procedure, $h \leq 160$ft (48.8 m)
Zone 4	-28.7 psf	**-31.5 psf**	**-26.5 psf**
Zone 5	**-35.3 psf**	-38.9 psf	**-48.7 psf**

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