International Comparison of Wind Tunnel Estimates of Wind Effects on Low-Rise Buildings: Test-Related Uncertainties

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Abstract: The consistency of measurements in various wind tunnels is of concern to designers and code writers. This study attempts to quantify the variability of wind effects estimates based on tests conducted at six wind tunnel laboratories. Pressure tap measurements were made on wind tunnel models of four buildings. Comparisons were made between estimated 50th percenttiles of (1) peak positive moments in a frame section near the knee joint and (2) peak pressure coefficients of a roof tap nearest a building corner. Modeling of suburban terrain contributes significantly to the variability. Other factors are eave height, wind direction, and frame location within the building. Coefficients of variation were about 10–40%. A subsequent phase of this research entails a detailed analysis of the reasons for the variabilities. The results could help future improvement of wind load factors that account for all relevant uncertainties in the estimation of wind effects and efforts to improve and standardize wind tunnel simulations.

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Introduction

The use of recorded simultaneous wind tunnel pressure measurements to assist in the design of buildings has become more widespread in recent years. Due to the complexity of the turbulent wind structure and differences in wind tunnel simulation and measurement techniques, one would expect a certain level of variability in the aerodynamic results used for standard provisions development or structural design. However, such variability is seldom considered explicitly.

The National Institute of Standards and Technology (NIST) has initiated an effort wherein six reputable wind tunnel facilities provided pressure measurements on typical low-rise, gable-roof industrial buildings (Cui 2003; Endo et al. 2003; Flamand 2002; Ho et al. 2003; Kikitsu 2003; Letchford 2005). The intent was to (1) determine the degree of mutual consistency of the respective results and (2) obtain preliminary data on uncertainties associated with the use of any one wind tunnel.

Prototype Buildings, Wind Tunnel Models, and Pressure Data

The prototype buildings were low-rise, gable-roofed structures 30.5 m by 61 m in plan. Two eave heights were considered: 6.1 and 9.8 m. The roof slope was 1/2 in 12 (2.39°). Four prototype buildings were designed as follows: 6.1 m (20 ft) and 9.8 m (32 ft) eave heights, open terrain (O20 and O32) and suburban terrain (S20 and S32). Each design consists of nine equally sized built-up steel portal frames spaced evenly at 7.6 m. Fig. 1 shows the frame layout and elevation. Steel girts and purlins transmit wind loads to the frames.

Six wind tunnels, designated by A–F and located in North America, Europe, and Asia provided measurements on scaled models with no openings, in terrain with uniform roughness. The models were placed on a rotating device at the floor level. For each of up to 36 wind directions, measurements were recorded simultaneously at hundreds of taps over the entire exterior surface, although in two cases only part of the building was provided with taps. For example, Laboratory C used taps covering the entire structure (furthest tap row from the end face is 96% of the 61 m at full scale), whereas Laboratory B provided data adequately concentrated, but distributed over less than one-quarter the length of the building model. Laboratory F only provided

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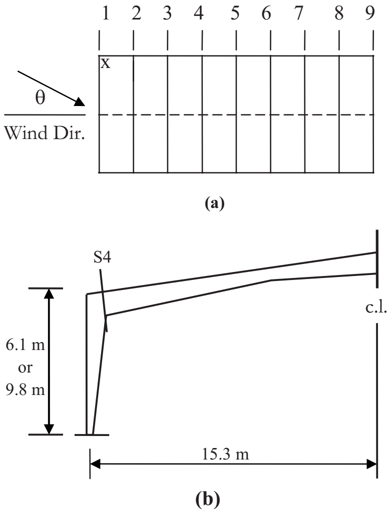

Fig. 1. (a) Plan view of typical frame layout (F1–F9), wind directions and location of pressure tap A (cross). Center line (c.1.) indicated by interrupted line "dashed-line"; (b) schematic of a typical frame at full scale.

measurements for Model O20. The records were sampled for about 1 min (about 1 h prototype time). Except for Laboratory A, all laboratories provided data at 23 and 25 taps per row for the 6.1 and 9.8 m eave height models, respectively: 14 taps spaced over both halves of the roof, and 1 tap on the ridge, as well as 4 or 5 taps spaced along each building wall depending on eave height.

Pressure measurements were converted to pressure coefficients referenced to the mean velocity pressure at eave height.

Table 1 provides information on testing, model scale, measurement frequency, and numbers of taps used on each model. Laboratory D provided tests that allowed the analysis of two separate records. Column 11 in Table 1 lists the number of equidistant rows along the length of the model. The variable D_t is the ratio between (1) the distance from the building's end face along the direction of the ridge (0° wind direction) to the furthest tap row and (2) the building length.

Analyses and Results

The program Wind Load Design Environment for Low-Rise Structures was used for the analysis (Simiu et al. 2003). The program applies measured pressure coefficient time histories to a computer model of the building. The main wind-force resisting system was modeled through a detailed input of all sectional properties of the frames. Because the output consists of 50th percentiles of the peak distributions (Sadek and Simiu 2002), the comparisons are not affected by the randomness of the peaks. All analyses assume a design wind speed of 44.7 m/s (100 mi/hr) 3 s gust at 10 m above open terrain. Surface roughness lengths are z_0=0.03 and 0.3 m for open and suburban terrain, respectively, but profiles reported by some laboratories were not fully consistent with the logarithmic profiles inherent in those values. Wind directions being considered were 0 (normal to the building's short side), 40, and 90°. For each combination of terrain roughness, eave height, frame number, and wind direction, two measures of the variability are presented: (1) the ratio of the largest to the smallest of the six values and (2) the coefficient of variation (COV) based on those six values.

Peak Positive Moments at Section S4

Owing to space limitations we present results for Frames F1, F2, and F5 only [Fig. 1(a)]. We examine the cross section at a knee joint section at 0.30 m along the windward rafter from the intersection of column and rafter axes [S4 in Fig. 1(b)]. The results are shown in Table 2. Both variability measures behave similarly. The results for the estimated 90th percentile were similar to those for the 50th percentile. Laboratory A had the minimum moment in 9, 8, 9, and 4 of the possible 9 cases (3 frames and 3 wind directions) for Models O20, S20, O32 and S32, respectively, possibly because it had the largest model size (1:150).

The variability among wind tunnels is clearly greater for modeling in suburban than in open terrain. The max/min ratio for moments at section S4 is greatest for frame F5 and smallest for Frame F1. The variability increases as the wind direction changes from 90 toward 0°, and is larger for the 6.1 m eave height than the 9.8 m eave height.

Peak Negative Pressure Coefficient

A single roof pressure tap nearest the building corner, modeled at the same location by all laboratories with the exception of Laboratory B, is used. The tap is located at 1.02 m along the length and 0.63 m across the width of the prototype. Table 3 shows the results for the four models for winds blowing from 0 and 90°. The variability measured by the COV was roughly 10–30%.

Table 1. Summary of Wind Tunnel Setup at Each of the Six Facilities

Wind tunnel	Model				Wind directions (deg)	Model scale	Measured frequency (Hz)	Number of taps[a]	Tap rows	D_t
	O20	S20	O32	S32						
A	X	X	X	X	0–185[b]	1:150	400	336/364	14	0.55
B	X	X	X	X	0–180[b]	1:200	400	115/125	5	0.21
C	X	X	X	X	0–180[b]	1:200	400	437/475	19	0.96
D1	X	X	X	X	0–180[c]	1:200	300	207/225	9	0.54
D2	X	X	X	X	0–180[c]	1:200	300	207/225	9	0.54
E	X	X	X	X	0–180[b]	1:200	1000	437/475	19	0.96
F	X				10–360[c]	1:200	350	322	14	0.55

[a] Number of taps for model with eave height 6.1 m/number of taps for model with eave height 9.8 m; taps on end walls were not considered.

[b] Measurements made at 5° increments.

[c] Measurements made at 10° increments.

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Table 2. Estimated 50th Percentile of Peak Positive Moment (kN m) for Section IV of Frames 1, 2, and 5, Models O20 (Roman Type) and S20 (*Italic Type*)

Wind tunnel facility	Terrain: open				Eave height: 6.1 m				
		F1			F2			F5	
	90°	40°	0°	90°	40°	0°	90°	40°	0°
A	113	243	266	223	264	269	230	149	69
	67	*127*	*131*	*101*	*126*	*125*	*101*	*78*	*65*
B[a]	136	337	319	272	358	382	*	*	*
	93	*174*	*215*	*186*	*200*	*218*			
C	137	278	307	270	304	352	286	192	85
	80	*155*	*170*	*149*	*165*	*184*	*156*	*102*	*51*
D1	135	313	370	259	322	361	271	239	155
	103	*173*	*200*	*189*	*191*	*170*	*226*	*204*	*105*
D2	132	303	379	257	317	368	269	230	156
	108	*200*	*197*	*195*	*192*	*168*	*226*	*204*	*105*
E	181	357	326	362	434	375	293	263	210
	87	*164*	*155*	*171*	*200*	*181*	*134*	*130*	*93*
F	150[b]	354[b]	470[b]	263[b]	400[b]	584[b]	271[b]	266[b]	247[b]
Max/min	1.60	1.47	1.77	1.62	1.64	2.17	1.27	1.79	3.58
	1.61	*1.57*	*1.64*	*1.93*	*1.59*	*1.74*	*2.30*	*2.62*	*1.62*
COV (%)	15	13	19	16	17	25	8	20	45
	17	*15*	*18*	*21*	*16*	*17*	*34*	*39*	*29*

[a] Facility B did not provide sufficient data for reliable results on frame 5.

[b] Facility F did not provide data for the S20 model.

Summary and Conclusions

Ratios of maximum to minimum peak moments at the frame knee obtained from measurements at the six laboratories exceeded in most cases 1.6 for open terrain, and were on average higher—reaching as much as about 2.6—for suburban terrain. Ratios of maximum to minimum 50th percentile negative pressures at a corner tap varied between 1.2 and 3.0 for open terrain and 1.5 and 2.1 for suburban terrain.

Estimates of wind load factors require the estimation of *total* uncertainties, that is, of a composite of uncertainties associated with: the inherent variability of extreme wind speeds, errors due to the limited sample sizes, the estimated terrain roughness, the variability of peak wind effects, the lack of prior knowledge of the orientation of structures designed in accordance with code provisions, the effect of the violation of the Reynolds number in the laboratory, the choice of wind tunnel, and so forth. For this reason, the relative weight of individual uncertainties is less significant than would be the case if those uncertainties were considered in isolation. Typically, wind load factors that take into account the joint effects of all those variabilities and uncertainties need not be increased substantially on account of any single uncertainty. Whether this is the case for load factors affected by the uncertainties studied in this note remains to be ascertained. However, even if increases in load factors were not large, it still is the case that the differences between results obtained in the various laboratories can affect the design values significantly.

Possible contributions to the differences noted herein are (1) simulations of the atmospheric boundary layer, (2) characteristics of the instrumentation frequency response, (3) reference pressure measurements, and (4) ratios between model dimensions and integral turbulence scales. These factors are being considered in ongoing investigations. The results suggest the need for criteria

Table 3. Magnitude of the Estimated 50th Percentile of Peak Negative Pressure Coefficient at Tap A

Wind tunnel facility	Model							
	O20		S20		O32		S32	
	90°	0°	90°	0°	90°	0°	90°	0°
A	3.96	4.62	4.08	4.72	3.97	4.29	4.37	8.41
B	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
C	3.93	5.25	5.32	7.92	3.87	5.01	5.83	8.03
D1	4.19	6.29	6.82	7.06	4.56	5.93	6.91	8.22
D2	4.26	6.33	7.37	6.65	4.40	6.10	8.14	8.61
E	4.36	4.75	4.67	5.83	3.82	5.31	3.97	5.60
F	1.47	5.87	[b]	[b]	[b]	[b]	[b]	[b]
Max/min	3.0	1.4	1.8	1.7	1.2	1.4	2.1	1.5
COV (%)	30	14	25	19	8	14	30	16

[a] Closest tap row is too far (2.54 m) from end face for comparison purposes.

[b] Data provided only for the O20 model.

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on low-rise building testing and certifying laboratories that conduct such testing.

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