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The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part 2. Comparison of data with wind load provisions

L.M. St. Pierre, G.A. Kopp*, D. Surry, T.C.E. Ho

Alan G. Davenport Wind Engineering Group, Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, London, On, Canada N6A 5B9

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Abstract

Wind tunnel test data on generic low buildings have been obtained at the University of Western Ontario (UWO) to contribute to the NIST aerodynamic database. In Part 1 the basic data and archiving format are presented. In the present paper, data from two models of different roof slope (1:12 and 3:12) at four eave heights each (4.9 m (16 ft), 7.3 m (24 ft), 9.8 m (32 ft), and 12.2 m (40 ft)), in open and suburban terrain conditions, were examined in detail. The data were compared to the historical data obtained by Stathopoulos in the late 1970s from which current North American code provisions were developed. Structural response coefficients were calculated on an assumed structural system and these data were compared with the current wind load provisions for low buildings in the ASCE 7-02 (ASCE Standard, Minimum Design Loads for Building and other Structures, ASCE 7-02, ASCE, New York, USA, 2002), the AS/NZS 1170.2 (Australian/New Zealand Standard Structural Design Actions, Part 2: 2002—AS/NZS 1170.2:2002, Standards Australia International Ltd., Sydney, AS and Standards New Zealand, Wellington, NZ, 2002), the Eurocode (Eurocode 1: Basis of Design and Actions on Structures. Part 2–4: Wind Actions, ENV–1991–2–4–1, CFN, Brussels, 1995), and the NBCC (National Building Code for Canada 1995 (NBCC(1995)); Includes User's Guide—NBC 1995 Structural Commentaries (Part 4), NRCC, Ottawa, Canada, 1995. The peak response coefficients from the current data set were found to increase with eave height. The ASCE 7-02 and the NBCC (1995) underestimated the peak response coefficients

*Corresponding author. Tel.: +1-519-661-3338; fax: +1-519-661-3339.
E-mail address: gakopp@uwo.ca (G.A. Kopp).

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calculated for the current data set by ~15% for the lowest eave height; and were worse for larger eave heights. Generally, the Eurocode (ENV, 1995) wind load provisions match the peak response coefficients from the data set at all eave heights. The response coefficients calculated using the AS/NZS (2002) provisions were generally a good match for the interior region only, however they significantly underestimated the wind tunnel response coefficients for the end bays.

Keywords: Low buildings; Wind loads; Building codes; Aerodynamic database

1. Introduction

Low-rise buildings are defined in the American Society of Civil Engineers Standard for Minimum Design Loads for Buildings and Other Structures (ASCE 7-02 [1], Section 6.2, p. 23) as structures with a mean roof height less than the least horizontal dimension and less than 18.3 m (60 ft). These structures are common; they represent the majority of commercial, residential, and industrial buildings.

Current wind load provisions for low-rise buildings are based on "reductive plots and tables" [2] that do not allow designers access to the variation of wind effects with time and space [3]. For most current standards, these plots and tables were determined by obtaining equivalent pressure coefficients that envelope responses calculated from wind tunnel data for a range of assumed structural wind resisting systems. Structural analysis programs are now widely used in the design of structures; these methods can yield accurate structural effects, and can account for both static and dynamic loading. However, the wind loads currently available for low-rise buildings through code provisions do not take advantage of these refined analysis techniques.

Suggestions have been made [4] to create a database of sets of pressure coefficient time series for a variety of low buildings that could be used by a designer for the design of the main wind force resisting systems. The University of Western Ontario (UWO) contribution to such a database has been documented in the companion paper [5]. The wind loads provided by the aerodynamic database could take into account design parameters that are virtually impossible to include in traditional code formats, such as: building geometry, building orientation, and proximity of adjacent structures [3], as well as the variation of the wind load with time and space. The very first of these data sets was produced by Lin and Surry [6], and used by Whalen et al. [2] to evaluate the potential benefits of such data. The current paper focuses on the next of these data sets obtained at UWO. Structural responses calculated using the new data are compared with four wind load provisions: the ASCE 7-02 [1], the National Building Code of Canada (NBCC, 1995) [7], the Australian/New Zealand Standard (AS/NZS, 2002) [8] and the Eurocode 1: Basis of Design and Actions on Structures (ENV, 1995) [9]. Only structural loads are investigated here; the pressure coefficients presented in this work are not representative of local loads, which can be found in Ref. [5]. It is important to note that only wind loads were considered in the analysis herein; no other loads (e.g. dead load or snow load) were included in the response analysis. No internal pressures were included in the calculations; these will be analyzed separately.

2. Experimental methodologies

The details pertaining to the experiments analyzed herein can be found in Part 1 [5], some of which are briefly reviewed here for completeness. The data analyzed here were obtained from two 1:100 scale, gable-roofed models with equivalent full-scale plan dimensions of 24.4 m (80 ft) by 38.1 m (125 ft), with the ridge parallel to the longer side. Two roof slopes were investigated (1:12 (4.76°) and 3:12 (14.04°)) at four eave heights each (4.9 m (16 ft), 7.3 m (24 ft), 9.8 m (32 ft), and 12.2 m (40 ft)). Fig. 1(a) shows an exploded view of the 1:12 roof slope model tap layout for all of the eave heights. The model was tested in two boundary layer flows, one matching an open country exposure with a roughness length $z_0 = 0.03$ m, and the other a suburban terrain with $z_0 = 0.3$ m.

Seven structural responses were calculated on an assumed main wind force resisting system for each model configuration using the time series obtained from wind tunnel testing. These responses were selected to envelope the major structural actions important to designing a building with frames of uniform spacing. All loads were calculated assuming a frame spacing of 7.6 m (25 ft). Two area-averaged loads were calculated: vertical uplift and horizontal thrust. These are global load actions, and do not depend on any assumed structural system. Vertical uplift is simply the vertical component of the wind load acting on the roof bay area. Horizontal thrust is the net horizontal shear acting on opposite vertical planes of the structure (i.e., windward face and leeward face), including the vertical projection of the roof. Five bending moments covering two major types of structural systems were calculated on each of the six frames: the moments at the ridge and at both knees of a

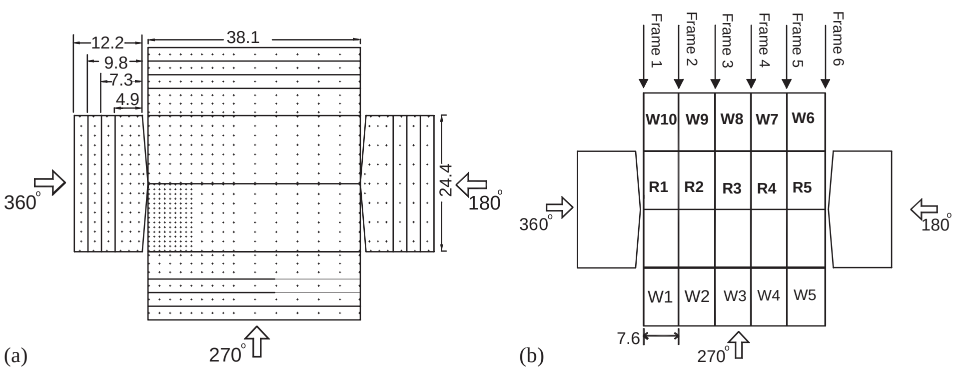

Fig. 1. Exploded view of 1:12 roof slope model with definition wind angles investigated showing (a) tap layout and (b) frame and bay definition. All dimensions are in full-scale metres.

frame pinned at the base, and the moments at the knees of a frame pinned at the base and at the ridge. Fig. 1(b) defines the bay and frame locations used to calculate these responses on an exploded view of the 1:12 roof slope model. These frame and bay definitions are the same for all eave heights and roof slopes investigated in this study. The above structural responses were also calculated using the wind load provisions from each of the building codes for comparison.

3. Comparison with the data set of Stathopoulos [10]

Stathopoulos [10] (see also Ref. [11]) conducted extensive research at UWO in the late 1970s on wind-induced loads acting on low-rise buildings. One model used in the current experimental investigation is similar to that used in those early experiments; therefore, it is useful to compare the aerodynamic data from both experiments. There are, however, a number of differences between the experiments including the boundary layer simulation, tap density, length of the time series and the data analysis parameters such as filtering frequency.

The geometric scale of the boundary layer created in Stathopoulos' experiment was on the order of 1:500. The corresponding model length scale was relaxed for the experiment, and models with length scales of 1:500, 1:250, and 1:100 were investigated in the same flow. For example, the model-scale integral scale is effectively halved if a 1:250 model is used in a 1:500 scale flow simulation. Stathopoulos and Surry [12] concluded that the length scale relaxation to 1:250 was the largest possible without significant distortion of the results. The resulting database from the Stathopoulos experiments was, thus, largely based on the test data obtained from 1:250 scale model tests of three roof slopes (1:12, 4:12, and 12:12) and three eave heights (4.9, 7.3, and 9.8 m) in an open country exposure. This data formed the basis of low building wind load codification in North America [13,14].

The local turbulence intensities from Stathopoulos' open country simulation (1:250 scale), the current experimental setup for the open exposure, and ESDU item 83045 [15] for $z_0 = 0.03$ m are shown in Fig. 2. Fig. 2 also shows the mean velocity profiles for the open exposure, as well as the ESDU item 82026 [16] profiles, referenced to the full-scale eave height of 9.8 m. Since the experimental results are normalized by the mean dynamic pressure at eave height, it is clear that the differences in the mean profiles are inconsequential. However, while the current simulation matches the ESDU turbulence intensities for $z_0 = 0.03$ m, Stathopoulos' turbulence intensities for the 1:250 scale are significantly lower than the current target values, and match more closely ESDU intensities for $z_0 = 0.005$ m, shown also in Fig. 2. This reflects a change in thinking over the past 25 years as to what constitutes a "design" open country profile: in the 1970s, a naturally grown boundary layer with a power law exponent of 0.14 was generally accepted as an open country exposure. Based on quasi-steady theory, one would expect the current experiments to yield higher structural loads due to the higher turbulence intensities.

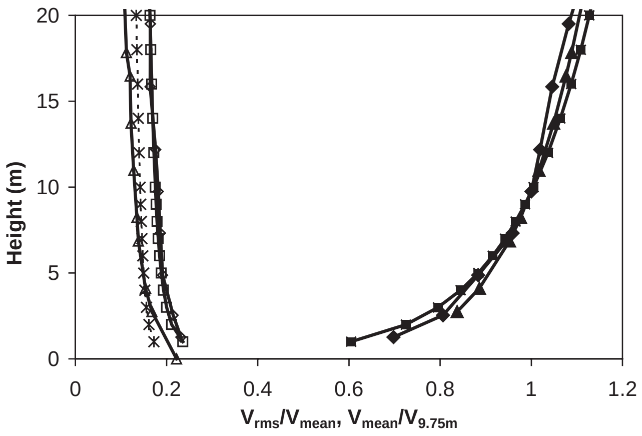

Fig. 2. Velocity profiles, referenced to 9.8 m (32 ft) eave height, and turbulence intensities for: ■, ESDU velocity profile [16] for $z_0 = 0.03$ m; □, ESDU turbulence intensity [19] for $z_0 = 0.03$ m; ▲, Stathopoulos velocity profile [10]; △, Stathopoulos turbulence intensity (1:250 scale) [10]; ♦, current experiment velocity profile; ◇, current experiment turbulence intensity; ×, ESDU turbulence intensity [19] for $z_0 = 0.005$ m.

Stathopoulos' data were obtained using the state-of-the-art measurement techniques and equipment of the time. Pressure coefficients were obtained over 360° at 45° intervals. The sampling time was 30 s for the 1:250 data, which corresponds to a full-scale time of about 25 min. The data were low-pass filtered at 95 Hz, corresponding to a full-scale frequency of 2 Hz for the 1:250 scale. Pneumatic averaging was used for four or five taps to obtain panel loads. Through pneumatic averaging, each tap was attributed the same area weighting. Statistics of up to sixteen structural responses for each wind angle were obtained.

For comparison purposes, an attempt was made to match the testing parameters in the experiments that could affect the peak response values (e.g., sampling time period and filtering frequency) through matching the full-scale reduced frequencies between the two data sets by

$$\left(\frac{fD}{V}\right)_{\mathrm{MS}} = \left(\frac{fD}{V}\right)_{\mathrm{FS}}, \tag{1}$$

where D is the length scale, f is the frequency, V is the eave height mean velocity, FS denotes full-scale and MS denotes model scale. The full-scale time period of 25 min in the Stathopoulos experiment corresponds to a model time period of 65 s for the current experiment. The model scale eave height wind speed for the current experiment was about 8.7 m/s, corresponding to a full-scale velocity of 38 m/s. The velocity used in the Stathopoulos experiment was not specified, although the ratio of model scale velocity to full-scale velocity was given as 1:5. The earlier filter frequency of 95 Hz corresponds to 44 Hz for the current data. This frequency (44 Hz) is very low since the tubing response is flat up to about 200 Hz in the current experiments.

Since Stathopoulos' data were filtered at a frequency of 95 Hz, the current data set was filtered at both 44 and 95 Hz for comparison.

Another difference is that the tap density of the current model is significantly higher than on Stathopoulos' model. Thus, the current data were analyzed using a tap density similar to the earlier experiments. The pneumatic averaging technique used by Stathopoulos was also mimicked with area averaging. No tap locations on the two models are identical; thus, an approximation was made in the selection of the taps used in the analysis to reflect the tap locations on Stathopoulos' model. The aerodynamic data available from these past experiments are in the form of structural response coefficients.

Two responses are compared with Stathopoulos' 1:250 scale 1:12 roof slope model for all three eave heights data: vertical uplift and horizontal thrust. These responses were calculated on an "end bay" region of 7.6 m (25 ft) in length along the entire width of the model (28.3 m), corresponding to bays R1, W1, and W10 in Fig. 1(b). Fig. 3 shows the peak (maximum) and mean horizontal thrust coefficients, referenced to mean roof height, h, obtained from the current data set analyzed with the matched parameters. All peak values were estimated from the time series using the Lieblein BLUE formulation [17]. This involves dividing the recorded time series into ten equal segments and fitting the Type I extreme value distribution to these points. Several observations can be made. First, the mean coefficients match very well. Second, the peak values are considerably larger in the current experiments,

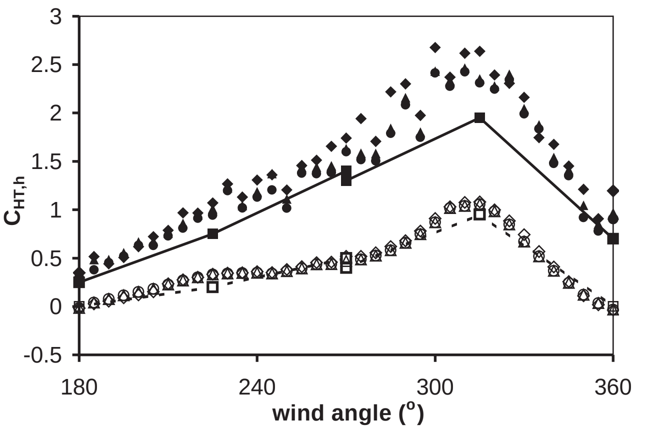

Fig. 3. Peak and mean horizontal thrust coefficients, referenced to the 9.8 m (32 ft) eave height, for different analysis parameters. Maximum values from Stathopoulos [10] included for comparison: ●, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, maximum; ▲, current experiment, Stathopoulos tap density, $f = 95$ Hz, $T = 65$ s, maximum; ♦, current experiment, all taps included, $f = 200$ Hz, $T = 100$ s, maximum; ■, Stathopoulos maximum, 1:250 scale; ○, Current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, mean; △, current experiment, Stathopoulos tap density, $f = 95$ Hz, $T = 65$ s, mean; ◇, current experiment, all taps included, $f = 200$ Hz, $T = 100$ s, mean; □, Stathopoulos mean, 1:250 scale; for clarity, Stathopoulos data points are joined by solid (maximum) and dotted (mean) lines.

as expected. The lower tap resolution, length of time series and filter frequency act to lower the peak results, but the major factor is the effect of the higher turbulence levels in the current experiments. This is explored further below. Third, there is some scatter in the peak values from the smooth curve one would draw through the current data. Interestingly, this scatter is sometimes larger than the effects of the other parameters (sampling time, filter frequency, and tap resolution).

Vertical uplift is shown in Fig. 4. Similar trends noted for the horizontal thrust are also seen for the vertical uplift: the mean response coefficients between the two experiments match reasonably well, whereas the peak values do not. Again, the new data, in a flow with higher turbulence intensities, show larger peaks than the historical data. The differences are due more to the higher turbulence intensities in the boundary layer than the other analysis parameters.

In order to compare the effects of the differences in the upstream terrain (turbulence intensity), "equivalent mean" coefficients ($C_{L,h,\mathrm{mean}}$) were obtained. These are referenced to mean roof height (h) wind speed and are obtained from the peak pressure coefficients using quasi-steady theory; i.e., the longitudinal peak pressure follows the square of the longitudinal peak velocity (neglecting lateral components for simplicity) so that

$$\mathrm{C}_{L,h,\mathrm{mean}} = \frac{\hat{L}}{\frac{1}{2}\rho\hat{V}_h^2} = \frac{\hat{L}}{\frac{1}{2}\rho\bar{V}_h^2\left(1+g\left(\bar{\bar{V}}/\bar{V}\right)\right)^2} = \frac{\hat{C}_\mathrm{L}}{\left(1+g\left(\bar{\bar{V}}/\bar{V}\right)\right)^2}, \tag{2}$$

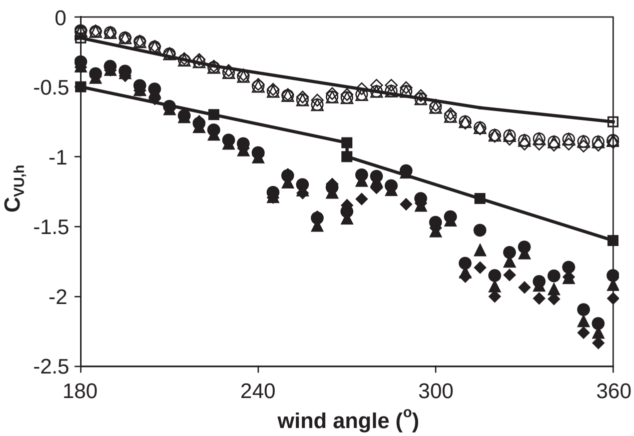

Fig. 4. Peak and mean vertical uplift coefficients, referenced to the 9.8 m (32 ft) eave height, for different analysis parameters. Minimum values from Stathopoulos [10] included for comparison: ●, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, minimum; ▲, current experiment, Stathopoulos tap density, $f = 95$ Hz, $T = 65$ s, minimum; ♦, current experiment, all taps included, $f = 200$ Hz, $T = 100$ s, minimum; ■, Stathopoulos minimum, 1:250 scale; ○, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, mean; △, current experiment, Stathopoulos tap density, $f = 95$ Hz, $T = 65$ s, mean; ◇, current experiment, all taps included, $f = 200$ Hz, $T = 100$ s, mean; □, Stathopoulos mean, 1:250 scale. For clarity, Stathopoulos' data are joined by solid (minimum) and dotted (mean) lines.

where $\hat{L}$ is the peak load, $\hat{C}_L$ is the peak load coefficient, and $\hat{V}_h$ is the peak velocity referenced to mean roof height, which is defined as $\hat{V}_h = \bar{V} + g\bar{\bar{V}}$, where $\bar{V}$ is the mean roof height mean velocity, $\bar{\bar{V}}$ is the root mean square (standard deviation) of the velocity fluctuations, and g is a peak factor, taken as a nominal value of 3.0 for these bay loads. The load, L, in Eq. (2) is taken as vertical uplift (VU) or horizontal thrust (HT) for this comparison.

The mean and equivalent mean coefficients are shown in Figs. 5 and 6 for the horizontal thrust and vertical uplift, respectively. For both sets of data, the mean and equivalent mean horizontal thrust coefficients match at the maximum response, although for the other wind angles they do not, with the equivalent means being larger. Fig. 6, for the vertical uplift, shows somewhat different behavior. In this case the mean and equivalent means match reasonably well over the range of wind angles (except between 300° and 360°). The two experiments also match at the points where there are data. It is clear from this figure that the 45° resolution of the earlier experiments was not sufficient to capture the variation of loading with wind angle.

The peak factor, taken as 3.0 here, is a significant variable in the comparison of mean and equivalent mean coefficients. The results of the comparison here could change, depending on the value of peak factor assumed.

Overall, the comparison between the two experiments is excellent with the new data matching the old when turbulence levels and data acquisition parameters are accounted for. The turbulence level is the dominant factor in the differences in the extreme values of the loads, although tap resolution, filter frequency, sampling time and resolution of wind angles recorded, and possibly the integral scale, play a role.

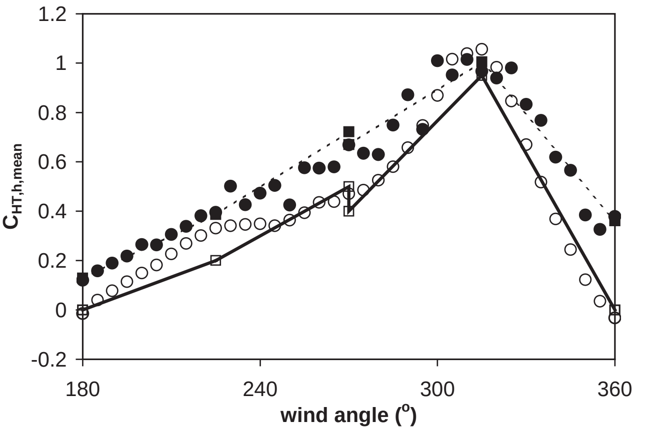

Fig. 5. Mean and equivalent mean horizontal thrust coefficients referenced to the 9.8 m (32 ft) eave height. Stathopoulos data points taken from [10]: ●, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, from maximum; ■, Stathopoulos from maximum, 1:250 scale; ○, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, mean; □, Stathopoulos mean, 1:250 scale. For clarity, Stathopoulos' data are joined by solid (from maximum) and dotted (mean) lines.

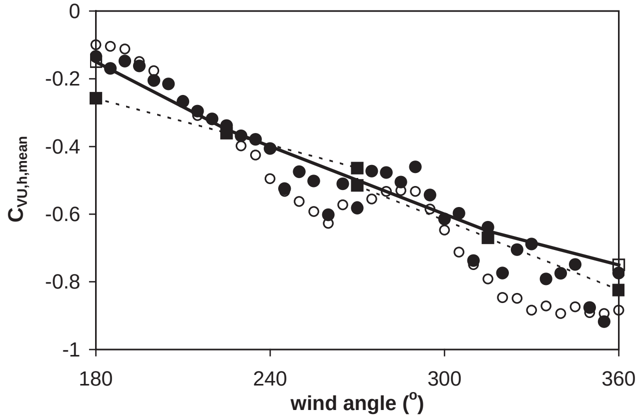

Fig. 6. Mean and equivalent mean vertical roof uplift coefficients derived from peak coefficients (minimum) referenced to the 9.8 m (32 ft) eave height. Stathopoulos data points taken from Ref. [10]: ●, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, from minimum; ■, Stathopoulos from minimum, 1:250 scale; ○, current experiment, Stathopoulos tap density, $f = 44$ Hz, $T = 65$ s, mean; □, Stathopoulos mean, 1:250 scale. For clarity, Stathopoulos' data are joined by solid (minimum) and dotted (mean) lines.

4. The wind load provisions

4.1. General comments

Four wind load provisions were chosen for comparison with the wind tunnel data: the ASCE 7-02, the AS/NZS (2002), the ENV (1995), and the NBCC (1995). In order to compare the structural response coefficients calculated using the wind tunnel data and different building code specifications, these coefficients were re-normalized to reflect the same storm conditions. The storm condition chosen for comparison is defined through a 3-s gust velocity measured in an open country terrain at a height of 10 m; this is the design storm condition specified by the ASCE 7-02. The definition of open country terrain, based on roughness length (z_0) values, varies with design standard. This was dealt with on an individual code basis, as discussed in the next section. The structural responses calculated from the wind tunnel data and all building code provisions are compared in subsequent sections through their equivalent GC_{pf} values, $(GC_{pf})_{eq}$, which are the pressure coefficients for low-rise buildings used in the ASCE 7-02. A brief review of how these equivalent pressure coefficients were obtained is presented below. Further details can be found in Ref. [18].

4.2. ASCE 7-02

The design wind-induced pressure for low-rise buildings is given in the ASCE 7-02 as

$$p_{\mathrm{ASCE}} = GC_{\mathrm{pf}}\tfrac{1}{2}\rho V^2_{10\ \mathrm{m,o.c.,3\,sec\,gust}}\, K_{zt}\, K_{\mathrm{d}}\, K_h I, \tag{3}$$

where GC_{pf} is the pressure coefficient specified for low-rise buildings [1, Figs. 6–10, p. 56], ρ is the air density, $V_{10\,\mathrm{m,o.c.,3secgust}}$ is the 3-s gust wind speed obtained at a height of 10 m in an open country terrain, K_{zt} is the topographic factor, K_d is the wind directionality factor, K_h is the velocity pressure exposure factor evaluated at mean roof height, h, and I is the importance factor. The velocity pressure exposure factor re-references the design velocity pressure (measured in an open exposure at a height of 10 m) to mean roof height for the terrain in which the structure is to be located, matching the ASCE 7-02 reference of the pressure coefficients (GC_{pf}) to mean roof height dynamic pressure. When dealing with rougher exposures, this exposure coefficient reduces the design velocity measured in the open exposure resulting in lower peak pressures. In order to obtain equivalent pressure coefficients ($(GC_{pf})_{eq}$), the design pressures calculated for matching storm conditions using other code provisions and the wind tunnel coefficients were set equal to p_{ASCE}.

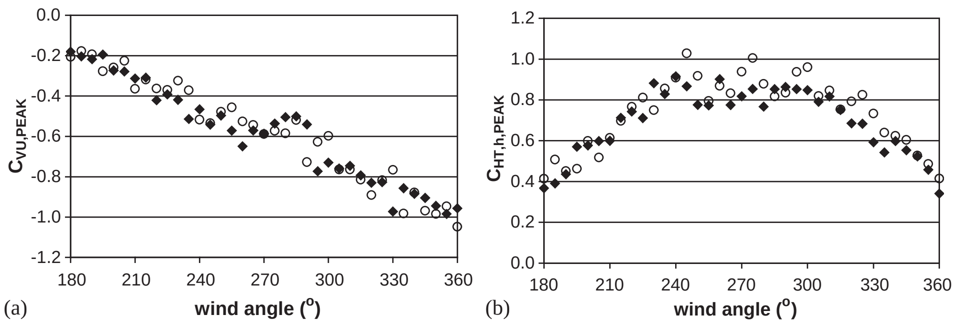

Fig. 7. Peak response coefficients, referenced to eave height peak dynamic pressure, on the 12.2 m eave height 1:12 roof slope model for (a) vertical uplift on the end bay and (b) horizontal thrust on bays W3, W8, and R3; ◆, from the open country exposure experiment; ○, from the suburban exposure experiment.

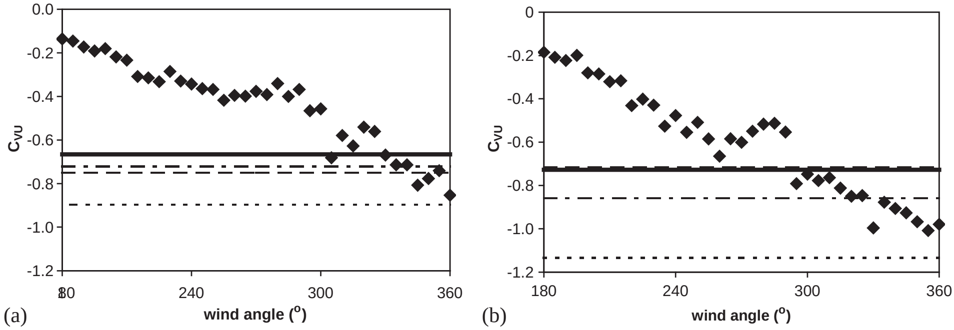

Fig. 8. Vertical uplift response coefficients on bay R1 of (a) 4.9 m (16 ft) and (b) 12.2 m (40 ft) eave height, 1:12 roof slope, open exposure: ◆, wind tunnel; solid line, ASCE 7-02; long dashes, NBCC (1995); short dashes, ENV (1995); long–short dashes, AS/NZS (2002).

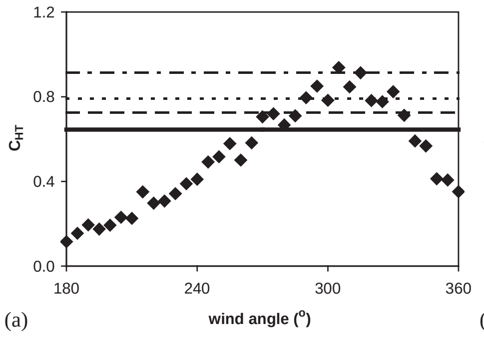

Fig. 9. Horizontal thrust response coefficients on bay R1 of (a) 4.9 m (16 ft) and (b) 12.2 m (40 ft) eave height, 1:12 roof slope, open exposure: ♦, wind tunnel; solid line, ASCE 7-02, long dashes, NBCC (1995); short dashes, ENV (1995); long–short dashes, AS/NZS (2002).

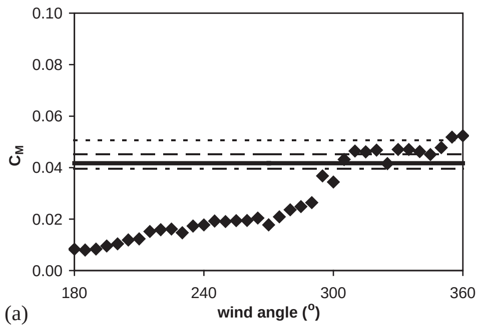

Fig. 10. Moment response coefficients at predominantly windward knee of 3-pinned frame 1 for (a) 4.9 m (16 ft) and (b) 12.2 m (40 ft) eave height, 1:12 roof slope, open exposure: ♦, wind tunnel; solid line, ASCE 7-02, long dashes, NBCC (1995); short dashes, ENV (1995); long–short dashes, AS/NZS (2002).

The roughness length for the open country terrain is specified in the ASCE 7-02 as 0.02 m for the open country terrain [1, p. 278], within the lower (0.01 m) and upper (0.15 m) limits set by the standard. This differs from the value of 0.03 m used in the current experiment, based on ESDU [19]. Interestingly, the roughness length specified in the ASCE 7-98 [20] is 0.01 m for open country exposure, although the values of GC_{pf}, basic velocity and power law exponents are the same between the two standards; i.e. the pressure coefficients or velocities were not changed to account for the changes in turbulence level and mean velocity with the change of roughness length. In light of this, and since the ASCE 7-02 does not use the roughness length value or associated turbulence intensities to determine a design wind pressure for low buildings, the pressure coefficients were not increased to account for the rougher terrain when compared with the wind tunnel pressure coefficients. The implications of this will be discussed later in the paper.

4.3. Wind tunnel data

The equation used to determine the $(\mathrm{GC_{pf}})_{\mathrm{eq}}$ values from the wind tunnel data was

$$\left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}}=\frac{\frac{1}{2}\rho V^2_{h,z_o,\ \mathrm{meanhrly}}C_\mathrm{p}}{\frac{1}{2}\rho V^2_{10\ \mathrm{m,o.c.,3secgust}}K_{zt}K_hK_\mathrm{d}I}=F_\mathrm{WT}\cdot C_\mathrm{p}, \tag{4}$$

where C_p is the peak pressure coefficient obtained from the wind tunnel test referenced to the mean speed at the mean roof height, and $V_{h,z_o,\mathrm{meanhrly}}$ is the mean hourly velocity referenced to mean roof height in either the open or suburban exposure, characterized by z_0. The mean hourly velocity measured in the wind tunnel at the mean roof height was re-referenced to the velocity at 10 m in the open country terrain using the ESDU item 82026 [16] mean hourly velocity profiles, assuming geostrophic height was the value specified in Ref. [16] (note that this is a different approach than that used in Ref. [18][1]). To use the ESDU velocity profiles to re-reference to open country terrain, a value of roughness length is required; z_0 was set to 0.03 m for open country in order to match the wind tunnel simulation. Note that the directionality factor, K_d, from the ASCE 7-02 was assumed to be 1.0 for this case only, as the wind tunnel data was not reduced in any way to account for the directionality effects on peak loads. The wind tunnel pressure coefficients were referenced to the mean roof height dynamic pressure for the appropriate exposure. The factor F_WT in Eq. (4) accounts for all of the differences between the pressure coefficients from the wind tunnel experiment and those specified in the ASCE 7-02.

The ASCE 7-02 assumes a gust power law velocity profile, whereas ESDU [16] mean velocity profiles were used to re-reference the wind tunnel dynamic pressures when moving between different exposure conditions. It is important to discuss the effects of these assumptions on the resulting response pressure coefficients, and thus the comparisons made in this paper. The velocity ratio in Eq. (4) can be broken down into:

$$\begin{aligned}&\left(\frac{V_{h,z_0,\mathrm{meanhrly}}}{V_{10\ \mathrm{m},z_0=0.03\ \mathrm{m,3secgust}}}\right)^2\\&\quad=\left(\frac{V_{10\mathrm{m},z_0=0.03\ \mathrm{m,meanhrly}}}{V_{10\ \mathrm{m},z_0=0.03\ \mathrm{m,3secgust}}}\right)^2\cdot\left(\frac{V_{10\ \mathrm{m},z_0,\mathrm{meanhrly}}}{V_{10\ \mathrm{m},z_0=0.03\ \mathrm{m,meanhrly}}}\right)^2\cdot\left(\frac{V_{h,z_0,\mathrm{meanhrly}}}{V_{10\ \mathrm{m},z_0,\mathrm{meanhrly}}}\right)^2.\end{aligned} \tag{5}$$

The first ratio on the right-hand side of Eq. (5) was taken from ASCE 7-02 (Fig. C6-2). The last two ratios on the right-hand side of Eq. (5) act like an exposure

[1]In Ref. [18], matching was carried out at a reasonable, yet arbitrary, reference height of 500 m. Matching at ESDU's specified geostrophic height essentially recognizes that this is a form of matching parameters within the ESDU quasi-analytical model and its use is required to assure the characteristics of flow near the ground for different z_o's are properly matched. The relationship between 10 m height speeds in different terrain roughness introduces considerable uncertainty, particularly when it is noted that transition from one fully homogeneous terrain to another requires tens of kilometres and is almost impossible to conclusively verify experimentally.

Table 1
Ratio of wind tunnel exposure coefficients (E_c) to ASCE 7-02 exposure coefficients (K_h) for all mean roof heights and exposures investigated

Mean roof height (m)	Open exposure	Suburban exposure
	E_c/K_h	E_c/K_h
4.9	0.88	0.78
7.3	0.95	0.92
9.8	0.99	1.01
12.2	1.03	1.14
6.4	0.93	0.88
8.8	0.98	0.98
11.3	1.01	1.05
13.7	1.04	1.10

coefficient, E_c, for the wind tunnel data, and were calculated using ESDU [16]. The ASCE 7-02 exposure factor, K_h, varies with exposure (i.e. the characteristic z_0 value). The ratio of the wind tunnel exposure coefficient to the K_h value is of interest, as it is a difference introduced by the assumptions made in this analysis. Values for this ratio are shown in Table 1. Where the ratio is less than 1.0, the wind tunnel coefficients were reduced by the velocity profile assumption, and were increased if the ratio is greater than 1.0. From Table 1, it is suggested that the wind tunnel response coefficients were reduced significantly for the lowest mean roof height by the velocity profile assumption, especially for the suburban exposure. The match is best for the second highest eave height for both roof slopes. The ESDU [16] mean velocity profiles were considered to represent the full-scale velocity profiles in the two exposure conditions better than the gust power law profile used in the ASCE 7-02.

4.4. NBCC (1995)

The $(GC_{pf})_{eq}$ values were determined from the NBCC (1995) by

$$(GC_{pf})_{eq} = \frac{\frac{1}{2}\rho V^2_{10\text{ m,o.c.,meanhrly}}(C_e)_{NBCC} C_p C_g}{\frac{1}{2}\rho V^2_{10\text{m,o.c.,3secgust}} K_{zt} K_h K_d I} = F_{NBCC} \cdot C_p C_g, \tag{6}$$

where $(C_e)_{NBCC}$ is the exposure factor, C_pC_g is the combined gust pressure coefficient relevant to the structural load under consideration (taken from Ref. [8] Structural Commentary B, Fig. B-7, p. 20), and $V_{10\text{ m,o.c.,meanhrly}}$ is the mean hourly wind velocity obtained at a height of 10 m in an open country terrain, which is the design velocity condition specified in the NBCC (1995). If all of the factors used between the two codes were identical (e.g., directionality coefficients, exposure coefficients, design velocity, etc.) then the resulting pressure coefficient would be equal to GC_{pf} (i.e., F_{NBCC} would be equal to unity). The NBCC (1995) allows no change in exposure factor for a change in terrain for low buildings, i.e., the design velocity is not reduced for suburban terrain conditions. The pressure coefficients in the NBCC (1995) were based only on wind tunnel data in an open exposure [10]. This is one major difference between the NBCC (1995) and the ASCE 7-02, where the exposure coefficient does vary with exposure for the design of low buildings. Therefore, only the value of K_h varies in Eq. (6) for the calculation of the equivalent $\mathrm{GC_{pf}}$ coefficients for a suburban exposure. The roughness lengths associated with the open country and suburban terrain in the NBCC (1995) were not specified, and therefore no adjustment was made for a difference in terrain between the ASCE 7-02 and the NBCC (1995). The effects of the different parameters on the NBCC (1995) pressure coefficients are represented by the factor F_{NBCC}.

4.5. AS/NZS (2002)

The $(\mathrm{GC_{pf}})_{\mathrm{eq}}$ values were determined from the AS/NZS (2002) using

$$\left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}} = \frac{\frac{1}{2}\rho V^2_{10\ \mathrm{m,o.c.,3secgust}}\left(M_{\mathrm{d}} M_{z,\mathrm{cat}} M_{\mathrm{s}} M_{\mathrm{t}}\right)^2 K_{\mathrm{a}} K_{\mathrm{c}} K_{\mathrm{l}} K_{\mathrm{p}} \mathrm{Cp_e}}{\frac{1}{2}\rho V^2_{10\ \mathrm{m,o.c.,3secgust}} K_{zt} K_h K_{\mathrm{d}} I} = F_{\mathrm{AS}} \cdot \mathrm{Cp_e}, \quad (7)$$

where M_{d} is the directionality multiplier, taken here as 1.0 as specified for use when the wind direction is not known [8, Table 3.2, p. 14]; $M_{z,\mathrm{cat}}$ is the terrain/height multiplier used to re-reference the dynamic pressure to the mean roof height of the building in the specified exposure; M_{s} is the shielding multiplier, taken here as 1.0; M_{t} is the topographic multiplier, taken here as 1.0; K_{a} is the area reduction factor, taken here as 0.80 for all responses where the tributary area is $\geq 100\,\mathrm{m}^2$ (the only exception to $K_{\mathrm{a}} = 0.80$ is the horizontal thrust for the 4.9 m (16 ft) eave height, where $K_{\mathrm{a}} = 0.81$); K_{c} is the combination factor, specified for use when wind pressures act on two or more surfaces of the building and contribute simultaneously to the structural effect, and was taken as 1.0 since $K_{\mathrm{c}} \geq 0.8/K_{\mathrm{a}}$(Clause 5.4.3, p. 32); K_{l} is the local pressure factor for cladding, and was taken as 1.0; K_{p} is a reduction factor for permeable cladding, and was taken as 1.0; $\mathrm{Cp_e}$ is the external pressure coefficient (referenced to mean roof height, taken from Tables 5.2(A), 5.2(B), 5.2(C), and 5.3(A), p. 30–31). Note that the directionality reduction factor specified in the AS/NZS (2002) of 1.0 is significantly different from the value of 0.85 used in the ASCE 7-02. This causes the AS/NZS (2002) response coefficients to be larger than those from the ASCE 7-02 by 15% before the differences in specified pressure coefficients are taken into consideration. The roughness length associated with the open country exposure in the AS/NZS (2002) is specified as 0.02m [8, Table 4.2(B), p. 19]. Since the value of roughness length is not explicitly used in the calculation of design wind pressures in this standard, no adjustment was made to account for a difference in roughness length between the AS/NZS (2002) and the ASCE 7-02. The effects of the different parameters on the AS/NZS (2002) pressure coefficients are represented by the factor F_{AS}.

4.6. Eurocode (1995)

The $(\mathrm{GC_{pf}})_{\mathrm{eq}}$ values were determined from the ENV (1995) using

$$\left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}} = \frac{\frac{1}{2}\rho V^2_{10\ \mathrm{m},z_o,10\ \mathrm{min}}(C_\mathrm{e})_{\mathrm{EU}}\mathrm{Cp_e}}{\frac{1}{2}\rho V^2_{10\ \mathrm{m,o.c.,3secgust}}K_{zt}K_hK_\mathrm{d}I} = F_{\mathrm{ENV}} \cdot \mathrm{Cp_e}, \tag{8}$$

where $(C_\mathrm{e})_{\mathrm{EU}}$ is the exposure factor from the ENV (1995) to be calculated at the same reference height as the pressure coefficients, $\mathrm{Cp_e}$ is the external pressure coefficient to be used (referenced to ridge height for low-rise buildings, taken from Ref. [9], Table 10.2.4, p.53), and $V_{10\ \mathrm{m},z_o,10\ \mathrm{min}}$ is the 10-min mean wind velocity measured at a 10 m height. The z_0 value for the open country terrain was specified as 0.05 m, which differs from the value of 0.03 m. The ENV (1995) is the only standard investigated here that explicitly uses values of z_0 in the calculation of the design pressure (in the calculation of $(C_\mathrm{e})_{\mathrm{EU}}$). Therefore, the ESDU item 82026 [16] mean hourly velocity profiles were used to re-reference the velocity to the open country terrain specified by a $z_0 = 0.03$ m. The differences in the manner in which the velocity profiles from the code provisions are manipulated between the different exposures are thus incorporated into the $(\mathrm{GC_{pf}})_{\mathrm{eq}}$ values. Note that the directionality reduction factor specified in the ENV (1995) of 1.0 is significantly different from the value of 0.85 used in the ASCE 7-02, but is the same as that in the AS/NZS (2002) standard. Again, this causes the ENV (1995) response coefficients to be larger than those from the ASCE 7-02 by 15% before the differences in specified pressure coefficients are taken into consideration. The factor F_{ENV} reflects the difference in the pressure coefficients specified by the two code provisions.

4.7. Discussion on code definitions

The figures in the following section depict the response coefficients calculated from the building codes and the wind tunnel data. In all four building codes investigated herein, pressure coefficients were specified for wind with a direction predominantly parallel to the ridge and wind predominantly perpendicular to the ridge. Response coefficients were calculated using the code coefficients for both wind directions (parallel and perpendicular to the ridge), and the maximum value of response (positive or negative) determined from each code provision is presented here for all wind angles as a single value. There are two reasons for this: firstly, these responses are compared with the maxima obtained from the wind tunnel data, and secondly, an engineer using the building code provisions for structural design would only use the maximum response value.

The assumption made in the NBCC (1995), the AS/NZS (2002), and the ASCE 7-02 standards is that the pressure coefficients referenced to dynamic pressure at mean roof height do not vary with building height. The regions over which the external pressure coefficients are applied do vary with the building dimensions. In contrast, the ENV (1995) pressure coefficients vary with both the area and the roof ridge height. For the open country exposure, the NBCC (1995) and the ASCE 7-02 response coefficient values are nearly identical for all responses. The responses were calculated for the NBCC (1995) code using the prescribed 'edge' zone and ignoring the option presented in the code to simply use the first bay as the edge zone, which can be used for structures with frames [7, Commentary B, Note (7) to Fig. B-7, p.20]. The detailed edge zone was used because it was thought to adequately represent these code specifications.

The largest responses were calculated on the end frame (frame 1) and the end bays (bays W1, W10, and R1; see Fig. 1(b)). The response coefficients calculated using the wind tunnel data from the suburban exposure simulation were larger in magnitude than those from the open exposure when referenced to the lower dynamic pressure in the suburban exposure. However, when the response coefficients obtained in the suburban exposure experiment were re-referenced to the same dynamic mean roof height pressure in the open exposure, the peak response coefficients were similar in magnitude as those obtained in the open exposure. Fig. 7 compares the peak response coefficients for the 1in12 roof slope model for the 12.2 m eave height obtained in both the suburban and open country simulations, referenced to the peak dynamic pressure for (a) the vertical uplift on the end bay and (b) the horizontal thrust on the middle bay (regions W3, W8 and R3 in Fig. 1(b)). Generally, the response coefficients, referenced to the peak dynamic pressure, are similar regardless of exposure, although the match was better between values larger in magnitude. This limited analysis generally supports the approach taken by ASCE [1], AS/NZC [8], and ENV [9], where there is a velocity reduction for terrains rougher than open country, however it brings about the question of why the 'effective' set of coefficients in these standards do not compare equally with the wind tunnel response coefficients in both exposures. The effects of terrain on peak response coefficients are discussed further in Section 5.

5. Results

5.1. Effects of building height (1:12 roof slope)

Figs. 8–10 illustrate the variation of response coefficients calculated using the wind tunnel data with wind angle for (a) the lowest eave height investigated (4.9 m) and (b) the highest (12.2 m). For comparison purposes, response coefficients calculated using the wind load provisions from the different building codes investigated are also shown in these figures. Tables 1–4 summarize many of the results, while a complete analysis is presented in Ref. [18]. As discussed earlier, the present analysis varies slightly from that presented in Ref. [18] by the way in which the pressure coefficients were re-referenced between different exposures; as a result values presented here are slightly different than those in Ref. [18]. Appendix A provides the details of the equations and assumptions used for the calculation of the responses.

The vertical uplift response coefficients were observed to increase for larger eave heights for both roof slopes in both exposures. The 'artificial' increase of the wind

Table 2
Peak response coefficients in open country terrain for end bays and end frames on the building with the 1:12 roof slope

Response		Eave height (m)			
		4.9	7.3	9.8	12.2
Vertical uplift	Wind tunnel	−0.85	−0.87	−1.00	−1.01
	ASCE 7-02	−0.67	−0.73	−0.73	−0.73
	ENV(1995)	−0.90	−1.01	−1.08	−1.13
	AS/NZS (2002)	−0.72	−0.83	−0.85	−0.86
Horizontal thrust	Wind tunnel	0.94	1.10	1.15	1.09
	ASCE 7-02	0.65	0.75	0.78	0.81
	ENV(1995)	0.79	0.92	1.02	1.10
	AS/NZS (2002)	0.91	0.97	1.00	1.07
2-pin moment windward knee	Wind tunnel	0.026	0.034	0.045	0.058
	ASCE 7-02	0.022	0.028	0.037	0.047
	ENV(1995)	0.026	0.029	0.035	0.049
	AS/NZS (2002)	0.019	0.023	0.035	0.049
3-pin moment windward knee	Wind tunnel	0.052	0.064	0.078	0.091
	ASCE 7-02	0.042	0.052	0.062	0.073
	ENV(1995)	0.051	0.058	0.064	0.070
	AS/NZS (2002)	0.040	0.043	0.054	0.072
2-pin moment at ridge	Wind tunnel	−0.032	−0.037	−0.038	−0.042
	ASCE 7-02	−0.024	−0.026	−0.027	−0.028
	ENV(1995)	−0.030	−0.033	−0.034	−0.033
	AS/NZS (2002)	−0.021	−0.025	−0.024	−0.024
2-pin moment leeward knee	Wind tunnel	0.026	0.032	0.040	0.044
	ASCE 7-02	0.019	0.021	0.022	0.024
	ENV(1995)	0.026	0.029	0.033	0.037
	AS/NZS (2002)	0.020	0.021	0.022	0.023
3-pin moment leeward knee	Wind tunnel	0.051	0.061	0.069	0.074
	ASCE 7-02	0.038	0.042	0.044	0.044
	ENV(1995)	0.051	0.058	0.064	0.068
	AS/NZS (2002)	0.040	0.043	0.045	0.046

tunnel response coefficients for the largest eave height due to the velocity profile assumptions made when manipulating the data (see Table 1 and Section 4.3) is only 3% for the 1in12 building in the open exposure. However, the reduction of the response coefficients for the lowest eave height is 12%, which is significant; this should be noted for the following comparisons. Fig. 8 shows the vertical uplift response coefficients calculated using the wind tunnel data and the four wind load

Table 3
Peak response coefficients in open country terrain for 2nd bay and frame on the building with the 1:12 roof slope, open country terrain

Response		Eave height (m)			
		4.9	7.3	9.8	12.2
Vertical uplift	Wind tunnel	−0.44	−0.53	−0.59	−0.66
	ASCE 7-02	−0.69	−0.69	−0.69	−0.69
	ENV(1995)	−0.58	−0.61	−0.69	−0.75
	AS/NZS (2002)	−0.47	−0.51	−0.60	−0.73
Horizontal thrust	Wind tunnel	0.74	0.91	1.01	1.03
	ASCE 7-02	0.52	0.57	0.60	0.61
	ENV(1995)	0.81	0.94	1.05	1.13
	AS/NZS (2002)	0.91	0.97	1.00	1.07
2-pin moment windward knee	Wind tunnel	0.014	0.021	0.033	0.043
	ASCE 7-02	0.017	0.022	0.028	0.036
	ENV(1995)	0.018	0.024	0.035	0.049
	AS/NZS (2002)	0.014	0.023	0.036	0.049
3-pin moment windward knee	Wind tunnel	0.026	0.034	0.046	0.061
	ASCE 7-02	0.032	0.039	0.048	0.056
	ENV(1995)	0.028	0.041	0.053	0.070
	AS/NZS (2002)	0.025	0.049	0.054	0.071
2-pin moment at ridge	Wind tunnel	−0.016	−0.019	−0.022	−0.023
	ASCE 7-02	−0.018	−0.020	−0.021	−0.021
	ENV(1995)	−0.019	−0.020	−0.020	−0.022
	AS/NZS (2002)	−0.015	−0.019	−0.021	−0.024
2-pin moment leeward knee	Wind tunnel	0.014	0.018	0.023	0.032
	ASCE 7-02	0.015	0.016	0.017	0.018
	ENV(1995)	0.017	0.019	0.022	0.025
	AS/NZS (2002)	0.013	0.017	0.020	0.022
3-pin moment leeward knee	Wind tunnel	0.027	0.034	0.038	0.047
	ASCE 7-02	0.029	0.032	0.033	0.033
	ENV(1995)	0.025	0.037	0.040	0.042
	S/NZS (2002)	0.026	0.033	0.039	0.042

provisions for the 1:12 roof slope. Fig. 8(a) shows that the ASCE 7-02 and the NBCC (1995) uplift response coefficients match the peak values relatively well for the lowest eave height. However, the uplift response coefficients calculated using these provisions do not increase with eave height, as do those calculated using the wind tunnel data, the AS/NZS (2002) and the ENV (1995). (Note that the AS/NZS (2002) response coefficients do not increase with eave height as much as those from

Table 4
Peak response coefficients in suburban terrain for end bays and end frames on the building with the 1:12 roof slope

Response		Eave height (m)			
		4.9	7.3	9.8	12.2
Vertical uplift	Wind tunnel	−0.79	−0.79	−1.03	−0.90
	ASCE 7-02	−0.66	−0.73	−0.73	−0.73
	NBCC(1995)	−0.94	−0.87	−0.84	−0.80
	ENV(1995)	−1.07	−1.23	−1.32	−1.38
	AS/NZS (2002)	−0.72	−0.83	−0.82	−0.82
Horizontal thrust	Wind tunnel	0.94	1.00	1.02	1.03
	ASCE 7-02	0.65	0.75	0.78	0.81
	NBCC(1995)	0.91	0.93	0.95	0.92
	ENV(1995)	0.95	1.12	1.26	1.35
	AS/NZS (2002)	0.92	0.97	0.97	1.03
2-pin moment windward knee	Wind tunnel	0.024	0.032	0.039	0.052
	ASCE 7-02	0.022	0.029	0.037	0.047
	NBCC(1995)	0.030	0.035	0.043	0.052
	ENV(1995)	0.031	0.036	0.043	0.060
	AS/NZS (2002)	0.020	0.023	0.034	0.047
3-pin moment windward knee	Wind tunnel	0.050	0.057	0.067	0.081
	ASCE 7-02	0.038	0.042	0.062	0.073
	NBCC(1995)	0.052	0.051	0.073	0.081
	ENV(1995)	0.061	0.071	0.078	0.085
	AS/NZS (2002)	0.040	0.043	0.053	0.069
2-pin moment at ridge	Wind tunnel	−0.032	−0.032	−0.036	−0.034
	ASCE 7-02	−0.024	−0.026	−0.027	−0.028
	NBCC(1995)	−0.032	−0.032	−0.032	−0.031
	ENV(1995)	−0.036	−0.040	−0.041	−0.041
	AS/NZS (2002)	−0.021	−0.025	−0.023	−0.023
2-pin moment leeward knee	Wind tunnel	0.027	0.029	0.035	0.044
	ASCE 7-02	0.019	0.021	0.022	0.024
	NBCC(1995)	0.026	0.026	0.026	0.026
	ENV(1995)	0.031	0.036	0.041	0.045
	AS/NZS (2002)	0.020	0.021	0.022	0.023
3-pin moment leeward knee	Wind tunnel	0.053	0.054	0.069	0.072
	ASCE 7-02	0.038	0.042	0.044	0.044
	NBCC(1995)	0.052	0.051	0.052	0.049
	ENV(1995)	0.061	0.071	0.078	0.083
	AS/NZS (2002)	0.040	0.043	0.043	0.044

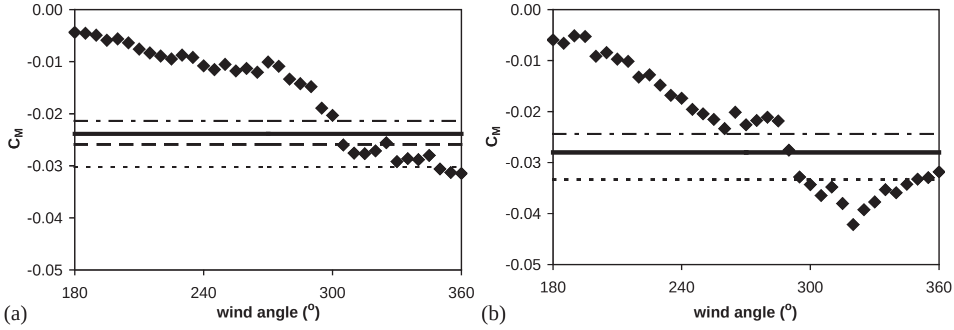

Fig. 11. Moment response coefficients at ridge of 2-pinned frame 1 for (a) 4.9 m (16 ft) and (b) 12.2 m (16 ft) eave height, 1:12 roof slope, open exposure: ♦, wind tunnel; solid line, ASCE 7-02, long dashes, NBCC (1995); short dashes, ENV (1995); long–short dashes, AS/NZS (2002).

the ENV (1995).) Thus, the North American codes generally underestimate the peak uplift response magnitudes significantly for the largest eave height. This is seen in Fig. 8(b), where these two provisions underestimate the peak magnitude of vertical uplift by ~40%.

Figs. 9 (a) and (b) show horizontal thrust response coefficients calculated using the code provisions and the wind tunnel data for the 4.9 and the 12.2 m eave height for the 1:12 roof slope model in the open country terrain. Similar trends noted for vertical uplift (Fig. 8) can be seen here, although the ASCE 7-02 underestimates the peak horizontal thrust response coefficient even at the lowest eave height by about 45%. The NBCC (1995) horizontal thrust response coefficients follow those from the ASCE 7-02 closely, as was shown for the vertical uplift response. The ENV (1995) response coefficients match the peak values better (within 20%) for all eave heights, as does the AS/NZS (within 15%).

Figs. 10 and 11 show moment response coefficients on frame 1 (see Fig. 1(b)) for two of the five bending moments investigated. Fig. 10 shows the moment response coefficients calculated at the predominantly windward knee of the 3-pinned frame system while Fig. 11 shows the peak moment response coefficients at the ridge for the 2-pinned frame system. In this case, the AS/NZS (2002) coefficients are generally the worst match over all eave heights for both moments. The ASCE 7-02 (and consequently the NBCC (1995)) underestimates these moment coefficients, however not as much as the AS/NZS (2002). The ENV (1995) is generally the best match for these responses at all eave heights. The response calculated using the ENV (1995) and the AS/NZS (2002) adequately reproduce the variation of this response with eave height; however, they do not represent the peak response. For the 2-pinned frame, assumptions were made about the relative stiffness ratio between the frame girders and columns (see Appendix A). Because of these assumptions, the moments calculated using the NBCC (1995) and the ASCE 7-02 specifications increase or decrease with eave height, although the pressure coefficients remain the same regardless of building height.

5.2. Summary of observations

5.2.1. End bay

Peak values of all response coefficients on bay R1 and frame 1 (see Fig. 1(b)) are shown in Table 2 for all eave heights investigated of the 1:12 roof slope model in the open country terrain.

(a) *ASCE 7-02 and NBCC (1995)*: In the open exposure, the NBCC and the ASCE 7-02 response coefficients are almost identical, so only the response coefficients from the ASCE 7-02 are shown in the tables (except Table 4). The ASCE 7-02 response coefficients generally underestimate the calculated wind tunnel response coefficients significantly. This underestimation generally increases in magnitude as the eave height increases except for the horizontal thrust response and the 3-pin moment at the windward knee, where the underestimation remains relatively constant for all eave heights (approximately 40–45% and 25%, respectively).

(b) *Eurocode (ENV, 1995)*: Unlike the ASCE 7-02, the pressure coefficients specified in the ENV generally increase for a larger eave height, which is similar to the wind tunnel pressure coefficients; thus, the ENV results in a better match than the ASCE 7-02. For example, the ENV underestimates the wind tunnel moment response coefficients by an average of 13%, whereas the ASCE 7-02 underestimates these same moments by an average of 40%. However, in some cases the ENV provisions overestimate the peak wind tunnel responses, such as the vertical uplift at all eave heights.

(c) *AS/NZS (2002)*: The AS/NZS estimate the vertical uplift and horizontal thrust response coefficients calculated from the wind tunnel data well (less than $\sim$15% difference). The moment responses, however, are not reflected well in the AS/NZS provisions for the end frame for any of the eave heights, with an average underestimation for all moment responses over all heights of $\sim$50%.

5.2.2. Second bay

Response coefficients calculated using the ASCE 7-02, the ENV, the AS/NZS and the wind tunnel data for the second bay/frame from the edge of the 1:12 roof slope model in the open country terrain are shown in Table 3.

(a) *ASCE 7-02*: For every response, the ASCE 7-02 overestimates the response coefficients for the lowest eave height (4.9 m) but underestimates the peak response coefficients for the largest eave height (12.2 m). The relationship between peak responses for the two mid-heights (7.3 and 9.8 m) varies with response.

(b) *ENV (1995)*: The ENV generally overestimates the wind tunnel response coefficients for all heights for all responses except the moments at the largest eave height (12.2 m or 40 ft). This overestimation is most pronounced for vertical uplift. The moments on this frame are generally well reflected by these provisions.

(c) AS/NZS (2002): With few exceptions, the AS/NZS provisions reproduce the response coefficients for the second bay/frame from the edge the best of all provisions investigated here. This includes all responses at all eave heights.

5.2.3. Effects of terrain

The response coefficients calculated from all standards investigated and the wind tunnel data for bay 1 and frame 1 for the 1:12 roof slope model in the suburban exposure are presented in Table 4. A reduction in design velocity pressure is allowed for rougher exposures in all standards but the NBCC. Since the response coefficients calculated using the NBCC differ from those calculated using the ASCE 7-02, they are also shown in Table 4. The mean velocity at eave height in the same storm does decrease with an increase in terrain roughness; however, the peak pressure coefficients referenced to mean roof height dynamic pressure obtained from the wind tunnel increase with exposure roughness, whereas those in the codes do not. When re-referenced to the open country terrain, however, the wind tunnel pressure coefficients obtained in the suburban exposure are slightly smaller in magnitude than those obtained in the open exposure simulation.

As detailed in Section 4.3 and Table 1, the wind tunnel response coefficients were 'increased' due to the assumption made when re-referencing the coefficients to the $(GCp_f)_{eq}$ format. This increase was minimal in most cases, however was significant (14%) for the 12.2 m eave height of the 1:12 building in the suburban exposure. However, the wind tunnel response coefficients were reduced by 22% for the lowest eave height of the 1:12 building in the suburban exposure. This effect of the manipulation of the wind tunnel response coefficients must be taken into account in the comparison presented in this section and in Table 4.

(a) *ASCE 7-02*: The ASCE 7-02 underestimates the peak wind tunnel response coefficients in the suburban exposure. Differences of 10–85% are seen between the ASCE 7-02 and the wind tunnel response coefficients for the largest eave height, and 10–45% differences for the lowest eave height. These differences are similar to those observed in the open exposure.
(b) *NBCC (1995)*: The NBCC response coefficients better match those from the wind tunnel data than the ASCE 7-02 because there are no velocity reduction factors for the suburban exposure; this 'inflates' the response coefficients calculated using the NBCC.
(c) *ENV (1995)*: The ENV provisions match the wind tunnel response coefficients relatively well in the suburban exposure, although they overestimate the peak response coefficients for all responses and building heights. The ENV calculated moment response coefficients generally match those from the wind tunnel best of all the standards.
(d) *AS/NZS (2002)*: As with the open exposure, the AS/NZS response coefficients do not agree with those calculated from the wind tunnel data for the end bay and frame. The difference in magnitude is slightly less for the suburban exposure.

Table 5
Peak response coefficients in open terrain for end bays and end frames on the building with the 3:12 roof slope

Response		Eave height (m)			
		4.9	7.3	9.8	12.2
Vertical uplift	Wind tunnel	−0.85	−0.98	−1.05	−0.91
	ASCE 7-02	−0.72	−0.72	−0.72	−0.72
	ENV(1995)	−0.89	−0.94	−0.99	−0.99
	AS/NZS (2002)	−0.76	−0.83	−0.84	−0.85
Horizontal thrust	Wind tunnel	0.85	0.97	1.05	1.04
	ASCE 7-02	0.55	0.69	0.77	0.83
	ENV(1995)	0.68	0.82	0.99	1.02
	AS/NZS (2002)	0.74	0.82	0.89	0.92
2-pin moment windward knee	Wind tunnel	0.029	0.040	0.051	0.066
	ASCE 7-02	0.022	0.029	0.039	0.051
	ENV(1995)	0.023	0.026	0.039	0.061
	AS/NZS (2002)	0.017	0.021	0.029	0.040
3-pin moment windward knee	Wind tunnel	0.045	0.061	0.076	0.091
	ASCE 7-02	0.033	0.044	0.056	0.071
	ENV(1995)	0.034	0.039	0.053	0.072
	AS/NZS (2002)	0.026	0.031	0.042	0.055
2-pin moment at ridge	Wind tunnel	−0.025	−0.029	−0.035	−0.037
	ASCE 7-02	−0.017	−0.021	−0.023	−0.025
	ENV(1995)	−0.017	−0.019	−0.019	−0.014
	AS/NZS (2002)	−0.014	−0.015	−0.017	−0.020
2-pin moment leeward knee	Wind tunnel	0.023	0.030	0.037	0.033
	ASCE 7-02	0.020	0.023	0.025	0.027
	ENV(1995)	0.023	0.026	0.028	0.034
	AS/NZS (2002)	0.017	0.023	0.019	0.011
3-pin moment leeward knee	Wind tunnel	0.036	0.045	0.052	0.047
	ASCE 7-02	0.029	0.033	0.036	0.038
	ENV(1995)	0.034	0.039	0.043	0.041
	AS/NZS (2002)	0.026	0.033	0.030	0.022

5.2.4. *Effect of roof slope*

Response coefficients for the end bay and frame of the 3:12 roof slope in the open country terrain are shown in Table 5. The response coefficients calculated using the NBCC are represented by the ASCE 7-02 (as in Section 5.2.1) and are not presented in this table.

(a) ASCE 7-02: The ASCE 7-02 underestimates most peak responses, as was seen with the 1:12 roof slope. The degree of underestimation is generally similar between the two roof slopes.
(b) ENV (1995): Generally, the match between the ENV and the peak wind tunnel response coefficients improved at the higher roof slope. This is seen mostly with the area-averaged loads (vertical uplift and horizontal thrust).
(c) AS/NZS (2002): The AS/NZS underestimates the peak wind tunnel response coefficients to a greater degree with the increase in roof slope. This is most prominent for the moment response coefficients.

5.3. Discussion

The analysis presented herein raises several interesting questions. First of all, the effects of terrain roughness deserve further comment. The original Stathopoulos data were obtained in a legitimate open country terrain ($z_0 \sim 0.01$ m), but with a lower roughness than was used in the current experiment ($z_0 \sim 0.03$ m). In fact, the value of roughness length for open country terrain varies from 0.005 to 0.1 m for open country terrain in ESDU item 82026 [16]. The ASCE 7-02 provides a roughness length range of 0.01–0.15 m for Exposure C (open country) and 0.15–0.7 m for the Exposure B (suburban). The increase in roughness leads to higher turbulence levels and a decrease in the mean velocity with a consequent increase in loading (which can be mostly accounted for by quasi-steady theory, as shown above). For a larger change in terrain—from open country ($z_0 \sim 0.03$ m) to suburban ($z_0 \sim 0.3$ m)—the overall loads are about the same because the decrease in the mean roof height speed is offset by the increased turbulence level (see Section 4.7 and Fig. 7). It appears that the NBCC (1995) is sensible in this regard, by considering only open country terrain for simplicity, although clearly, the majority of low buildings are in suburban terrain and are somewhat shielded by other buildings and trees. This latter fact cannot be handled explicitly in building codes, although it can be implicitly, as in the NBCC (1995).

Ratios of peak dynamic pressures (q) calculated using ESDU [15,16] for different roughness length values to that for $z_0 = 0.03$ m are shown Fig. 12 for each of the eave heights investigated here (4.9, 7.3, 9.8, and 12. 2m). The range values used in this figure correspond to the broad range of roughness lengths specified in the ASCE 7-02 and Ref. [16]. There is a significant disparity ($\sim$60%) in peak dynamic pressure between the minimum z_0 (0.005 m) and the maximum value (0.15 m). Even over a relatively small terrain perturbation, say from $z_0 = 0.03$ to 0.01 m results in a 10% increase in the peak speed.

Overall code consistency requires the definition of design wind speeds in carefully specified open country terrains, and that the historical wind speed data on which these wind speeds are based should be corrected to this standard terrain. In practice, this procedure still contains many uncertainties, as was mentioned previously. Although all codes, except the NBCC, specified the roughness length associated with terrain, only the ENV (1995) used the value explicitly in the calculation of structural

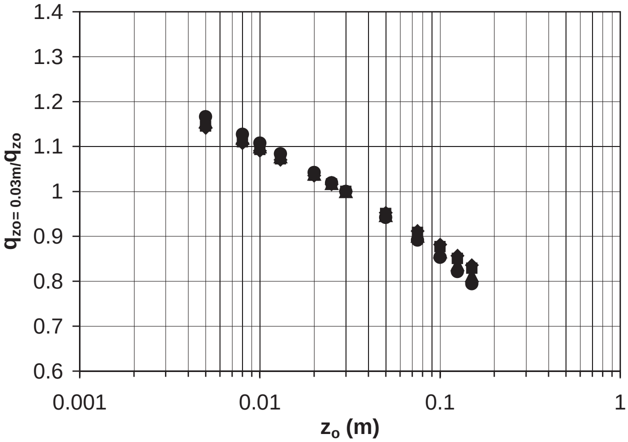

Fig. 12. Ratio of peak (solid symbols) dynamic pressures (q) for roughness length (z_0) values within the range specified for open country terrain [1,16] to the dynamic pressure for $z_0 = 0.03$m for all eave heights investigated: ♦, ratio of peak dynamic pressures, 12.2 m eave height; ▲, ratio of peak dynamic pressures, 9.8m eave height; ■, ratio of peak dynamic pressures, 7.3m eave height; ●, ratio of peak dynamic pressures, 4.9m eave height.

response coefficients on low buildings. The pressure coefficients, velocity profiles, and the basic design velocity values in the ASCE 7 standards did not change from the 1998 to the 2002 edition but the specified z_0 for the open country terrain was increased with no correction made to match. The implication is that only a single z_0 is relevant for a given terrain for design. This makes sense for simplicity, although the particular formulation causes the difficulties encountered here when there is a change in understanding of the terrain.

A second observation is related the large differences between the North American and AS/NZS (2002) provisions, as compared to the ENV (1995). Clearly, the Eurocode makes a much greater effort to envelope the moment responses while the others, based on the responses determined herein, are more concerned with overall aerodynamic loads (uplift and thrust). This difference leads to significantly overestimated responses to uplift loads by the ENV (1995). The moment responses are important for the design of connections which are relatively low cost compared to the higher costs of materials for the building envelope and frames. It would seem to be more effective from a codification point of view to separate these considerations in order to lead to economical, yet reliable, designs. That said, it is clear that the North American provisions do not adequately deal with the changes in loading with roof height, significantly underestimating them for taller buildings. This is reasonable, however, as the Stathopoulos measurements, which provide the basis for the North American provisions, were obtained only for building heights up to 9.8 m (32 ft). Their application to buildings as high as 18m was an extrapolation consistent with code definitions of low buildings, but not supported by experimental evidence.

Finally, the analysis of the end frame in the current work neglected any support provided by an end wall to the end frame. This simplifying assumption is not overly realistic and penalizes standards such as the AS/NZS (20020) that provide an excellent match for the interior frames, while apparently significantly underestimating end frame loads which are amplified by the assumption.

6. Conclusions

The purpose of the present work was to perform a detailed analysis of wind load provisions and compare the results to new data acquired at UWO. These data were obtained from wind tunnel tests of two gable-roofed low buildings with full-scale plan dimensions of 38.1 m (125 ft) by 24.4 m (80 ft), for two roof slopes (1:12 and 3:12) at four eave heights (4.9 m (16 ft), 7.3 m (24 ft), 9.8 m (32 ft), and 12.2 m (40 ft)). The models of these buildings were constructed at a geometric scale of 1:100. Two upstream terrains were simulated: an open exposure ($z_0 = 0.03$ m) and a suburban exposure ($z_0 = 0.3$ m).

The data were first compared to the historically significant data of Stathopoulos [10]. The vertical uplift and horizontal thrust coefficients were compared and the current data set was manipulated in a similar manner to Stathopoulos' to avoid possible differences introduced by filtering frequency, tap density, and length of time series. The turbulence intensities for the open country simulations in both experiments were significantly different. This large difference in turbulence intensity was taken into account by deriving "equivalent mean" coefficients where the peak response was referenced to the peak velocity. When comparing both mean and equivalent response coefficients, the two data sets matched well. However, when the peak response coefficients are compared between the two experiments, there was a significant difference in peak values. This is attributed primarily to the higher turbulence intensities in the current experiments, although the other parameters do have an effect.

Seven structural responses were calculated on an assumed structural system and the current data were compared with the wind load provisions for low buildings from the ASCE 7-02, the AS/NZS (2002) the ENV (1995), and the NBCC (1995). The primary conclusions are:

1. The ASCE 7-02 and the NBCC (1995) generally underestimate the peak response coefficients calculated on the end bay and frame in the open exposure, regardless of roof slope. This underestimation generally increased with building height, as the magnitudes of the peak wind tunnel response coefficients increased with eave height while the pressure coefficients specified did not. This underestimation was less pronounced for the response coefficients on bays R2, W2, and W9 and frame 2, and in the rougher exposure.
2. The NBCC (1995) response coefficients are the same as those from the ASCE 7-02 for the open country exposure, as these two provisions were derived from the same data set [18]. However, the NBCC (1995) does not allow a reduction in

velocity with a rougher exposure. This resulted in a better match between the NBCC (1995) and the wind tunnel response coefficients than noted with the ASCE 7-02 in the suburban exposure.
3. The ENV (1995) response coefficients match those from the wind tunnel better than the North American codes. However, the ENV (1995) tends to overestimate the peak area-averaged response coefficients (vertical uplift and horizontal thrust), and most notably for the smaller eave heights and the interior bay and frame. This standard underestimates the moment response coefficients the least on the end frame of all the standards studied.
4. The AS/NZS (2002) response coefficients typically underestimate those from the wind tunnel data, especially for the end frame and bays. This underestimation is most significant when comparing moment response coefficients. However, with few exceptions, this standard best captures the interior bay structural response coefficients. Consideration of the support provided by end walls may validate this standard, but was not considered in the current analysis.
5. The definition of accepted roughness length is broad, particularly for the open country exposure (ASCE 7-02, ESDU [12]). The turbulence intensities associated with this range of roughness lengths can result in significantly different pressure coefficients, as was shown with the comparison with the current experiment and the Stathopoulos [10] data set.

The current investigation only considered one building dimension and two roof slopes but clearly points out the deficiencies in the current wind load provisions. The current test program also has data in other building dimensions and roof slopes. Further recommendations are expected once these data have been analyzed.

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Appendix A. Definitions of pressure and structural load coefficients

Seven structural loads were calculated using the time series obtained from the wind tunnel testing. These responses were selected to envelope the major structural actions important to designing a building with frames of a uniform spacing. Two area-averaged loads were calculated: vertical uplift (vertical shear) and horizontal thrust (horizontal shear). These area-averaged loads were assumed to act on areas between the frames (bays), i.e. not on frames, and therefore did not depend on any assumed structural system. Five moments were calculated: the moments at the ridge and at both knees of a frame pinned at the base, and the moments at the frame knees for a frame pinned at the base and at the ridge. Assumptions had to be made regarding the frame system for the 2-pinned moment, as discussed below. All loads were calculated assuming a frame spacing of 7.6 m (25 ft). The pressure coefficients used in these equations for the calculation of the code responses were those provided by the different code provisions.

The area-averaged response pressure coefficients were determined by integrating the pressure time series obtained at each tap location weighted by the ratio of the tributary area of the tap to the total area being considered. The vertical uplift coefficients were obtained by

$$C_{\mathrm{vu}} = \frac{\sum w_{\mathrm{i}} b_{\mathrm{i}} \left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}}}{WB} \tag{A.1}$$

where w_i and b_i are the tributary width and breadth associated with the tap, respectively, $(\mathrm{GC_{pf}})_{\mathrm{eq}}$ is the design pressure coefficient made equivalent to that in the ASCE 7-02 (see Section 4 of this paper), W is the building width (24.4 m, or 80 ft), and B is the bay width (7.6 m). Horizontal thrust is the total horizontal shear acting on the vertical planes of the structure opposite each other over the ridge (i.e. windward face and leeward face). Note that these windward and leeward faces include the vertical projection of the roof; i.e. the horizontal component of the pressures acting perpendicular to the roof were included in the horizontal thrust calculation. The horizontal thrust response pressure coefficients were determined by

$$C_{\mathrm{HT}} = \left(\frac{\sum w_i b_i \left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}}}{WB}\right)_{\mathrm{windwardface}} - \left(\frac{\sum w_i b_i \left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}}}{WB}\right)_{\mathrm{leewardface}}, \tag{A.2}$$

where the variables are as defined above.

All of the moment response pressure coefficients were determined by

$$C_{\mathrm{M}} = \frac{\sum w_i b_i I_{\mathrm{L}} I_{\mathrm{M}} \left(\mathrm{GC_{pf}}\right)_{\mathrm{eq}}}{W^2 B}, \tag{A.3}$$

where I_{M} is the moment influence coefficient at each tap location along the frame relating the local frame load to the moment in question. It varies with each different moment to be determined and with each structural system assumed. I_{L} is the linear influence coefficient relating the pressure on the surface to the local load on the frame. The value of bay width, B, used in Eq. (A.3) was 7.6 m for the end frames, and 15.2 m for the interior frames, since this was the width contributing to the response.

To calculate the moment influence coefficients on the 2-pinned frames, the stiffness of the frame girders relative to the stiffness of the columns was assumed to be unity. In order to keep this stiffness ratio constant, the moment of inertia of the column cross section was varied. The ratio of the girder moment of inertia to that of the column $\left(\text{i.e. } I_{\mathrm{g}}/I_{\mathrm{c}}\right)$ was taken as the ratio of the building width (24.4 m, 80 ft) to the eave height. These ratios were 5.0, 3.3, 2.5, and 2.0 for eave heights of 4.9, 7.3, 9.8, and 12.2 m, respectively.

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