Dynamic Wind Effects Provisions in Codes and Standards and Wind Tunnel Data:

A Comparative Study

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ABSTRACT

An evaluation and comparison of six of the world's major building standards is conducted in this study, with specific discussion of their estimations of the alongwind, acrosswind, and torsional response, where applicable, for a given building. The codes highlighted by this study are those of the United States, Japan, Australia, the United Kingdom, Canada, and Europe. In addition, the response predicted by using the measured power spectra of the alongwind, acrosswind, and torsional responses for several building shapes tested in a wind tunnel are presented for comparison with those predicted by the standards.

Introduction

Under the influence of dynamic wind loads, typical high-rise buildings oscillate in the alongwind, acrosswind, and torsional directions. The alongwind motion primarily results from pressure fluctuations on the windward and leeward faces, which generally follows the fluctuations in the approach flow, at least in the low frequency range. Therefore, alongwind aerodynamic loads may be quantified analytically utilizing quasi-steady and strip theories. The dynamic effects are customarily represented by a random-vibration-based "Gust Factor Approach." However, the acrosswind motion is introduced by pressure fluctuations on the side faces which are influenced by fluctuations in the separated shear layers and wake dynamics. This renders the applicability of strip and quasi-steady theories rather doubtful. Similarly, the wind-induced torsional effects result from the imbalance in the instantaneous pressure distribution on the building surface. These load effects are further amplified in asymmetric buildings as a result of inertial coupling. Due to the complexity of the acrosswind and torsional responses, physical modeling of fluid-structure interactions remains the only viable means of obtaining information on wind loads, though recently, research in the area of computational fluid dynamics is making progress in numerically generating flow fields around bluff bodies exposed to turbulent flows.

Clearly, a disadvantage to physical modeling is the time, cost, and resources required to conduct a wind tunnel analysis. Furthermore, in a preliminary design stage, a number of building shapes are evaluated and estimates of their response due to wind are calculated, using the resulting response as a criteria to "weed out" aerodynamically unfavorable building shapes. Wind tunnel testing of all of these models would not be feasible. Thus, major building standards and codes around the world have begun to develop empirical relationships to produce an approximate procedure to determine the acrosswind dynamic response in preliminary design, with the understanding that further wind tunnel testing during the final design may be necessary. Thus far, only Japan, Australia, and Canada have provided such expressions in their current standards, with Japan providing such an expression for the torsional response as well. Understandably, the development of generalized equations for dynamic response, based on wind tunnel testing, have served as a cost-effective and time-saving tool in daily design.

Six major building standards are examined in this study: the Australian Standard (1989), the National Building Code of Canada (1995), the European Prestandard (1995), the British Standard (1995), the U.S. ASCE7-95 Standard, and the Architectural Institute of Japan (AIJ) Recommendations for Loads on Buildings (1996). A comparison of their treatment of dynamic effects and an assessment of their ability to predict the alongwind, acrosswind, and torsional accelerations at the top of a model building is conducted. The acceleration predicted by these standards are compared to data from wind tunnel tests conducted by the second author. In total, the paper provides a guided tour regarding the usage of the standards and a critical evaluation of the codes' treatment of dynamic effects.

Discussion of Existing Standards

General

Many aspects involved in the estimation of wind loads are held in common by the various codes and standards. Instead of commenting on them repeatedly, they will be highlighted here. First, all the standards break the terrain of any given site down into 3 to 5 categories which will affect the wind characteristics at that location. The design wind speed used in analysis by each of the codes is typically the product of the basic wind speed and factors to account for the geographic location, topographical effects, surface roughness, etc. The standards all derive the reference pressure from this wind velocity.

As for the treatment of dynamic effects, the essential similarity among the codes is their use of the gust factor approach[1,2] to handle the fluctuating components of the structural response due to wind. A gust factor based on extreme value excursion statistics represents the most probable extreme velocity value or its resulting load effect is used for determining equivalent static loadings. This approach relies on stochastic dynamics theory to translate the dynamic amplification of loading, caused by turbulence and dynamic sensitivity of the structure, into an equivalent static loading. The maximum expected wind speed or attendant load effects during an interval T may then be expressed as the summation of the mean value, with the RMS value multiplied by a statistically-derived peak factor.

For example, the expected value a random response is given by:

$$\bar{X}_{max} = \bar{X} + g\sigma_x \tag{1}$$

$$G = \frac{\bar{X}_{max}}{\bar{X}} = 1 + g\frac{\sigma_x}{\bar{X}} \tag{2}$$

where g is the peak factor, σ_x is the RMS value of X, and G is the gust factor. σ_x is typically evaluated in terms of the background and resonant response. In the formulation of wind loads, typically the quadratic term introduced by the fluctuating component of wind is ignored. Should this term be retained, it would influence the description of the peak factor which otherwise is derived based on Gaussian assumptions. Detailed treatment of the modeling and contribution of this quadratic term is given in Kareem, et. al[3].

Finally, it should also be noted that while all of the standards reference their wind speed at 10 m above ground in a flat, open exposure, the standards use gusts of different duration. The British and Canadian standards use the mean hourly wind speed in design, while the European Prestandard and AIJ Recommendations both use a 10 minute mean wind velocity. The ASCE7-95 Standard references a 3 second gust, as does the Australian Standard, though this wind is later converted within both standards to a mean hourly wind in subsequent calculations related to the gust effect factor. As a result, the velocities must be adjusted properly for an adequate comparison of their performance.

In this study, the peak and RMS accelerations estimated by each standard were found using their most detailed dynamic procedure, thus, while all the standards provide a simplified procedure, only the detailed dynamic procedure is discussed herein.

Australian Standard (1989)

In the Australian Standard[4], both an alongwind and acrosswind response may be found following the determination of the design hourly wind speed ($\bar{V}_z$) and the free-stream hourly mean dynamic wind pressure ($\bar{q}_z$). The alongwind response of tall buildings and towers is to be determined by the gust factor approach, based upon a fundamental mode of vibration, which has an approximately linear mode shape. The use of the gust factor allows for a quick determination of the peak base overturning moment, found simply by multiplying the mean base overturning moment by the gust factor (G). This mean base overturning moment is found by summing the moments which are the result of mean pressures on the windward and leeward faces of the building. The gust factor defined as:

$$G = 1 + r\sqrt{g_v^2 B(1+w)^2 + (g_f^2 SE)/\zeta} \tag{3}$$

where r is a roughness factor, g_v is the peak factor for upwind velocity fluctuation taken as 3.7, B is the background factor which measures the slowly varying background component of the fluctuating response caused by the lower frequency wind speed variations, g_f is the peak factor, S is a size factor to account for the correlation of pressures over a structure, E is a spectrum of turbulence in the approaching wind stream, ζ is the structural damping capacity as a function of the critical damping ratio, and w is a factor to account for the second order effects of turbulence intensity, given by:

$$w = \frac{g_v r\sqrt{B}}{4} \tag{4}$$

where the roughness factor, r, is equivalent to twice the longitudinal turbulence at the building's height, h.

Unlike many of the other codes considered, the Australian Standard also provides some estimation of acrosswind effects, with the peak acceleration ($\hat{a}_c$) at the top of a building (with nearly constant height) given by:

$$\hat{a}_c = \frac{(1.5 g_f \bar{q}_h b)}{m_o}(0.76 + 0.24k)\sqrt{(\pi C_{fs})/\zeta} \tag{5}$$

where terms previously not defined are: $\bar{q}_h$, the hourly mean dynamic wind pressure at the building height, h, b is the breadth of the structure normal to the wind, k is the exponent from representation of the fundamental mode shape as $\psi(z) = \left(\frac{z}{h}\right)^k$, C_{fs} is the acrosswind force spectrum coefficient generalized for a linear mode, and m_o is the average mass per unit height of the structure. The cross-wind force spectrum coefficients may be taken from actual spectra plotted as a function of non-dimensionalized frequency provided in the standard for various ratios of height to width to depth for turbulence intensities of 0.12 and 0.20 at 2/3 of the building's height. These may be used to determine the spectrum coefficient with interpolation allowed for building's not specifically corresponding to one of the spectra provided.

An additional provision is supplied for the combination of alongwind and acrosswind responses, yielding an expression for scalar structural effects such as axial loads in columns, which sums the load effect of the mean response in both the alongwind and acrosswind directions with another term involving the sum of the squares of other related parameters including the gust factor for the alongwind response.

While the peak and RMS accelerations in the alongwind direction are not specifically given by the standard, they may be found in the commentary by Holmes, et al.[5] In this reference, it is assumed that the peak displacement may be estimated by dividing the peak moment found in the standard by M_I:

$$\hat{x} = \frac{\hat{M}}{M_I} = \frac{\hat{M}}{\frac{1}{3}\rho b d h^2 (2\pi n_1)^2} \tag{6}$$

where ρ is the building density and n_1 is the fundamental frequency in the alongwind direction.

Commentary: This standard also does an excellent job of explaining what the parameters in each expression represent and their working units. The expressions and tables are easy to follow, making the calculation of the gust factor and the corresponding overturing moments and accelerations not incredibly taxing. Also to the credit of this standard, it does provide a means to estimate the acrosswind response of a structure using cross-wind force spectrum coefficients generalized for a linear mode; however, the force spectrum must be determined from a provided spectra for only a limited number of aspect ratios. As a result, interpolation must be used if the desired aspect ratio does not correspond to those provided. As wind tunnel tests on several buildings of varying dimension have shown, the spectra can vary greatly, so the use of interpolation on the given spectra makes any estimates of the acrosswind response merely approximate. This margin for error could be eliminated if empirical expressions could be developed to provide the cross-wind force spectrum coefficient for any aspect ratio.

Architectural Institute of Japan (AIJ) Recommendations

As true of the other standards considered, the AIJ Recommendations[6] employs the gust factor approach, which, for the purposes of this study, will be determined by Detailed Procedure II, in which the resonant response generated by the fluctuating wind force is not negligible. Once the mean wind pressure is determined, Detailed Procedure II may then be used to find the gust factor, given various assumptions in the estimation of the alongwind response, including that of a linear fundamental mode, negligible aerodynamic damping, and a power law representation of the mean wind speed and turbulence intensity. The gust factor may then be expressed as:

$$G_f = 1 + g_f r_f \sqrt{B_f + R_f} \tag{7}$$

where g_f is the peak factor discussed previously, r_f is a factor for the fluctuating wind speed, and B_f and R_f are the background excitation and resonance factors, respectively, that, while typically expressed by multiple integrals, have been estimated by approximate expressions. After determining these parameters, the designer may then refer to appropriate techniques to determine the alongwind displacements and acceleration. Since strip theory fails to predict the acrosswind and torsional responses, they must be instead defined from empirical expressions. The acrosswind vibration and its resulting load are estimated using the data of RMS overturning moments in that direction derived from wind tunnel tests for rectangular buildings of various aspect ratios up to 6. From this, an expression for the acrosswind RMS acceleration was developed:

$$\sigma_{a_y} = 3 q_H C_L' \frac{B}{m} \frac{z}{H} \sqrt{R_L} \tag{8}$$

where q_H is the dynamic wind pressure, C_L'is the RMS overturning moment coefficient in the acrosswind direction, B is the building width, m is the mass per unit height, z is the height at which the RMS acceleration is being calculated, H is the full building height, and R_L is given by:

$$R_L = \frac{\pi F_L}{4 n_f} \tag{9}$$

where F_L is the wind force spectrum factor and n_f is the critical damping ratio for the first translational mode.

The wind force spectrum factor is shown in the standard to agree reasonably with those of wind tunnel studies.

The empirical expression for the torsional response was also based on a set of wind tunnel studies paralleling those mentioned above. In this case, the experimental data was collected on the response angle acceleration, and a non-dimensional expression for this acceleration was introduced which applies only to buildings which have negligible eccentric effects. Following the same assumptions of the acrosswind analysis yields a torsional response angle acceleration:

$$\sigma_{a_\theta} = \frac{2\rho C_T' n_o^2 \sqrt{BD}}{L\rho_b \sqrt{n_f}} K_T U^{*(\beta_T + 2)} \tag{10}$$

where ρ is the air density, ρ_b is the building density, L is the larger of B (building width) and D (building depth), n_o is the natural frequency for the first torsional mode, n_f is the critical damping ratio for the first mode, C_T' is the RMS torsional moment coefficient, K_T and β_T are reduced coefficients for response angle acceleration, and U^* is a non-dimensional design wind speed at reference height ($U_H/(n_o\sqrt{BD})$).

Commentary: The AIJ recommendations are fashioned more as a “teaching code,” providing a detailed description of the procedure alongside the steps themselves. The code does an excellent job of developing the theory behind the expressions presented and defining their range of validity. The standard should commended on being the only to provide expressions for both the acrosswind and torsional RMS accelerations; however, a methodology for determining the displacements and accelerations for the alongwind direction needs to be more clearly defined in the standard. Also, it is not obvious how one should go about determining the design pressures for categories other than II and III, which may be treated by the simplified analysis provided.

National Building Code of Canada (1995)

As with the standards discussed previously, the National Building Code of Canada[7] defines two separate procedures for the estimation of wind loads on structures - a simplified or detailed procedure. The detailed analysis is an equivalent procedure based on wind tunnel test results and should be used for light-weight buildings or those of extreme height, with low frequencies or suffering from low damping, and proceeds as follows.

Once the reference wind pressure is determined, the pressure due to wind, which provides the static pressure intended to produce the same load effect as the dynamic resonant response to the actual fluctuating component of the wind, may be determined. Then, the alongwind acceleration may be determined from the reference wind pressure (q) by:

$$a_D = g_p \sqrt{\frac{KsF}{C_e\beta_D}} \left(\frac{3.0}{2 + \alpha}\right) \left(\frac{(C_e q)}{D\rho_B}\right) \tag{11}$$

where s is size reduction factor, F is gust energy ratio at the natural frequency, C_e is the exposure factor, β_D is the first mode alongwind fraction of critical damping, and α is the boundary layer exponent for a particular terrain.

Having recognized that while the primary deflection may be in the alongwind direction, the acrosswind direction acceleration significantly affects occupant comfort and serviceability, the Canadian Standard provides an expression for this acceleration at the top of the building based on a variety of wind tunnel studies. In order to determine the peak acrosswind acceleration, the following formula is provided:

$$a_w = n_w^2 g_p \sqrt{WD} \left(\frac{a_r}{\rho_B g \sqrt{\beta_W}}\right) \tag{12}$$

where n_w and β_W are the first modal frequency and ratio of critical damping, respectively, in the acrosswind direction, W and D are the dimensions of the building plan, g is the acceleration due to gravity, g_p is the peak factor, ρ_B is the average building density, and a_r is defined as:

$$a_r = 78.5x10^{-3}\left[\frac{V_H}{n_w\sqrt{WD}}\right]^{3.3} \tag{13}$$

where V_H is the mean wind speed at the top of the building.

Commentary: A large part of the detailed procedure pulls required values from figures, allowing much room for human error, especially in the log-log plots. However, to the credit of this standard, its authors did recognize the significance of acrosswind response when considering issues of occupant comfort and serviceability and has provided expressions for the acrosswind acceleration to address this, though the torsional response is neglected. While empirical expressions for the torsional response are available in Canadian wind literature, they have not been made part of the standard.

European Prestandard (1995)

The European Prestandard[8] is quite similar to the other standards referenced using quasi-static pressures or forces are equivalent to the extreme effects of wind. While two analysis schemes are presented in the prestandard, only the detailed analysis, corresponding to a dynamic factor (C_d), i.e. gust factor, greater than 1.2, is described herein.

Annex B in the standard treats the detailed analysis, based on the nondimensional power spectral density function (R_N), in full for buildings that have an uncoupled alongwind fundamental mode, obey a linear elastic assumption, and fit one of the corresponding standardized cases presented. Otherwise, a wind tunnel analysis must be performed. The annex provides an expression for the RMS acceleration of the building in the alongwind direction as:

$$\sigma_{a_x} = \frac{\Phi_{1,x}(z)\rho b C_f V_m^2(z_{equ})}{m_{1,x}} Iv(z_{equ}) R_x K_x \tag{14}$$

where $\Phi_{1,x}(z)$ is the fundamental alongwind mode shape, ρ is the air density, b is the building width, C_f is the averaged alongwind force coefficient, $V_m(z_{equ})$ is the mean wind velocity at the building's equivalent height (0.6 building height), $Iv(z_{equ})$ is the alongwind turbulence intensity at the equivalent height, $m_{1,x}$ is the alongwind fundamental modal mass, R_x is the resonant response part, and K_x is a nondimensional coefficient. The dynamic (gust) factor is given by:

$$C_d = \frac{1 + 2gI_v(z_{equ})\sqrt{Q_o^2 + R_x^2}}{1 + 7(I_v(z_{equ}))} \tag{15}$$

where g is the peak factor, Q_o is the background response part, and R_x is the resonant response part.

Commentary: The calculations required to determine the RMS acceleration in the European Standard are numerous, requiring multiple equations with many terms which must be calculated from other equations scattered throughout the text. Since expressions are not compact and confined to a particular section, the procedure becomes tedious at times. Once again there are also some questions of accuracy when terms read off of graphs are applied, since there may be some human error in reading off these values. Especially since there is no expression for the dynamic factor in the simplified analysis, forcing its value to be determined from the provided figures. In addition, a shortcoming of this standard is its failure to treat the acrosswind and torsional response.

British Standard (1995)

Consistent with the other standards considered, the British Standard Part 2's[9] Standard method uses equivalent static loads to represent the effect of fluctuating loads for buildings not susceptible to dynamic excitation. The response of mildly dynamic structures may be calculated by the procedure in Annex C; however, British Standard Part 2 is not suggested for buildings taller than 300 m or having calculated dynamic augmentation factors (C_r) greater than 0.25. Such structure's response should be determined by other appropriate methods. For buildings that do meet the criteria, the following expression[10] for the dynamic augmentation factor may be applied:

$$C_r = \frac{1 + (S_g^2 - 1)\left(\sqrt{\frac{K_h K_b}{60}}\right)}{S_g^2} \tag{16}$$

where S_g is the gust factor, based on structural size and surrounding terrain, and K_h and K_b are parameters depending on the building height, location, and structural system. A simplified form Eqn. 16, based on curve fits, is also provided. Although for $C_r<0.25$ the procedure provided in the British Standard works best, calibration studies have shown that this static approach can be approximately used for values up to 1.5; however, designers are encouraged to consult a full dynamic analysis for buildings with C_r values over 1.4.[10]

Once the design pressure, found by multiplying the reference pressure by an external pressure coefficient and a size effect factor to account for non-simultaneous action of gusts across a surface, and this dynamic factor have been determined, overall loads may be found by[10]:

$$P = 0.85\left(\sum P_{front} - \sum P_{rear}\right)(1 + C_r) \tag{17}$$

where $\sum P_{front}$ is the horizontal component of surface loads summed over the windward walls and roofs and $\sum P_{rear}$ is likewise for the leeward walls and roofs. For dynamically sensitive structures, common practice in the United Kingdom is to refer to the procedure outlined in ESDU (Engineering Sciences Data Units) to estimate the structural response.

Commentary: The British Standard appears to be a very hands on, straight forward code that only provides a means to determine the pressures on buildings for a very simplified approach, with no sufficiently detailed procedure provided. The code only applies to a specific group of structures that are not significantly susceptible to dynamic effects, for which only the alongwind loads are found. Should the target structure exhibit any wind-sensitive characteristics or not fit one of the prescribed building types, the code is no longer valid and an appropriate alternative dynamic analysis must be consulted.

ASCE7-95 Standard

Chapter 6 of the ASCE7 Standard[11] provides a procedure for wind-sensitive structures, while encouraging wind tunnel testing for structures that deviate significantly from a uniform rectangular prism, are highly flexible with low natural frequencies, subject to buffeting but the wake of upwind structures, or subjected to accelerated flow caused by channeling or local topographic features. Once the wind velocity pressure is determined in a manner common to all the standards, taking into account topographic factors, application of the gust factor approach may begin.

An expression to determine the gust factor, G, is defined as:

$$G = (1 + 2gI_{\bar{z}}\sqrt{Q^2 + R^2})/(1 + 7I_{\bar{z}}) \tag{18}$$

where g, the peak factor is taken as approx. 3.5, $I_{\bar{z}}$ is the intensity of turbulence at height $\bar{z}$, Q is the background response, and R is the resonant response factor. Though identical to the dynamic factor in the European Standard, each standard has distinct expressions for the parameters involved due to differences in the averaging period of the wind. The RMS acceleration is given by:

$$\sigma_{a_x}(z) = \frac{0.85\phi(z)\rho bhC_{fx}\bar{V}_{\bar{z}}^2}{m_1} I_{\bar{z}}KR \tag{19}$$

where previously undefined terms include: $\phi(z)$, the fundamental mode shape; ρ, the air density; b, the building width; h, the building height; C_{fx},the mean alongwind force coefficient; $\bar{V}_{\bar{z}}$,mean hourly wind speed at height $\bar{z}$; m_1, the modal mass; and K, a factor with an expression provided in the standard. Similarly, the standard also provides an expression for the maximum top displacement.

Commentary: The ASCE7 Standard is easy to follow with charts and tables making values readily available without the extensive use of plots to determine values. The use of tabularized data makes interpolation much easier. The commentary provides a detailed discussion of the procedures and a thorough example. Since each of the three procedures only changes the gust factor, leaving the heart of the analysis essentially unchanged, the authors wisely place these alternative procedures for finding the gust factor in the commentary so not to confuse the user. The ASCE7 Standard may be criticized, however, like many of the other standards, for neglecting the acrosswind and torsional response of the structure.

Experimental Procedure

The lack of torsional and acrosswind descriptions in the U.S. standard and several of the other standards discussed has prompted the present research effort to develop such relationships. The research at the University of Notre Dame is based upon the wind tunnel testing, conducted previously by the second author, of rigid balsa wood models mounted on a high frequency force balance, representing 9 typical building shapes shown in Fig. 1, for three different building heights of 16, 20, and 24 inches, in simulated urban and suburban terrain boundary layer flows, thus yielding 54 building/terrain scenarios. The time histories were transformed to corresponding power spectral density functions using FFT. These spectra (Fig. 2(a)) representing the forcing function in the torsional, alongwind, and acrosswind directions, were then non-dimensionalized.

At this time, only the spectral plots were available and thus had to be digitized using a software package, Digimatic$^{\text{TM}}$, so that the data points could be fit with a curve of the following form:

$$Y(x) = \sum_{j=1}^{N}\left(\frac{C_jK_j(1+0.6\beta_j)\beta_j}{\pi}\,\frac{(x/f_j)^{A_j}}{\{1-(x/f_j)^2\}^2 + 4\beta_j(x/f_j)^2}\right) \tag{20}$$

where Y is the non-dimensionalized spectral density, N corresponds to the number of “humps” in the curve, x is the non-dimensionalized frequency on the plot, and the remaining parameters are varied to insure the best possible curve fit. By varying the parameters of this equation, accurate curve fits could be obtained, an example of which is shown in Fig. 2. Note that Fig. 2 (a) shows the original non-dimensionalized spectra (solid line) and Fig. 2(b) shows the data points returned by Digimatic$^{\text{TM}}$ (circles) and the resulting curve fit (solid) obtained by (21).

The result of this effort is then a data base of the empirical curve fits for the alongwind, acrosswind, and torsional response spectra for each of the 27 buildings for both an urban and suburban terrain. While the resulting data and spectra are too numerous to present here, a comparison of the RMS acceleration as predicted by the standards and that predicted by our data is provided for a sample building shown in Fig. 3, accompanied by its relevant structural data (note that the critical damping ratio and first modal frequency are assumed to be the same in both the alongwind and acrosswind directions). For this comparison, the alongwind and acrosswind RMS accelerations for winds measured as a 3-second gust of 70, 75, 80, and 90 mph, 10 m above ground in an open terrain, are compared to the wind tunnel data. Since other standards may use mean hourly and 10 minute gusts for their reference wind velocities, a table, also in Fig. 3, contains the appropriate wind speeds used for each gust duration. Using the most detailed dynamic procedure offered by each standard, estimates of the peak and RMS accelerations were calculated for the alongwind and acrosswind direction. Where expressions for the RMS accelerations were lacking, values were obtained through dividing the peak acceleration by a peak factor. Values for the alongwind response for the British Standard were not provided, as was the case with the AIJ alongwind response, since they must be obtained indirectly once the force distribution on the building is obtained.

Discussion

Fig. 4 displays the RMS accelerations for the alongwind and acrosswind directions, where applicable. Notice that ASCE7-95 most closely matches the alongwind RMS acceleration predicted by the wind tunnel data. It is not surprising that the European and ASCE7 results closely parallel each other, since their procedure for estimating the peak accelerations is nearly identical. In light of this, the Australian Standard appears to significantly overestimate the RMS acceleration, while the Canadian Standard begins to deviate from the wind tunnel data at higher velocities, which may be due to negative aerodynamic damping.

For the acrosswind direction, most of the standards conservatively estimate the RMS acceleration. Still, of the codes which provide some estimate, the Australian Standard best matches the test data without underestimating the RMS acceleration. It is important to note that for the AIJ Standard, since other estimates of the dynamic pressure were not available, the simplified dynamic pressure for a more open, Category III terrain (as opposed to Category V) was used. The standard states that this may indeed overestimate wind loads for small buildings in Category V (dense urban) terrain: however, for this larger, more flexible building, the response is clearly underestimated.

In addition, a comparison of the torsional response angle acceleration as predicted by the AIJ standard and the wind tunnel data, was conducted. Though a full graphical comparison of these values could not be presented due to restrictions on space, the estimates by the AIJ standard are within 20% of those predicted by the wind tunnel test data, for the same model building but with fundamental natural frequency of 0.35 Hz in the torsional direction.

Conclusion

The use of the gust factor approach in international standards makes it fairly simple to evaluate the response of a structure due to both its mean and fluctuating components, with each standard applying the gust factor approach uniquely. The validity of the assumptions and applications of this widely-accepted theory in various standards has been explored in this study against data collected in a wind tunnel. From this, the following may be concluded:

(1) The European Standard and ASCE7-95 most closely match the alongwind RMS acceleration measured in wind tunnel studies.

(2) Of the standards able to estimate the acrosswind RMS acceleration, the Australian Standard was most

successful in closely matching the data without underestimating.

(3) The torsional response angle approximated by AIJ Recommendations was within 20% of those predicted by the wind tunnel data.

Acknowledgments

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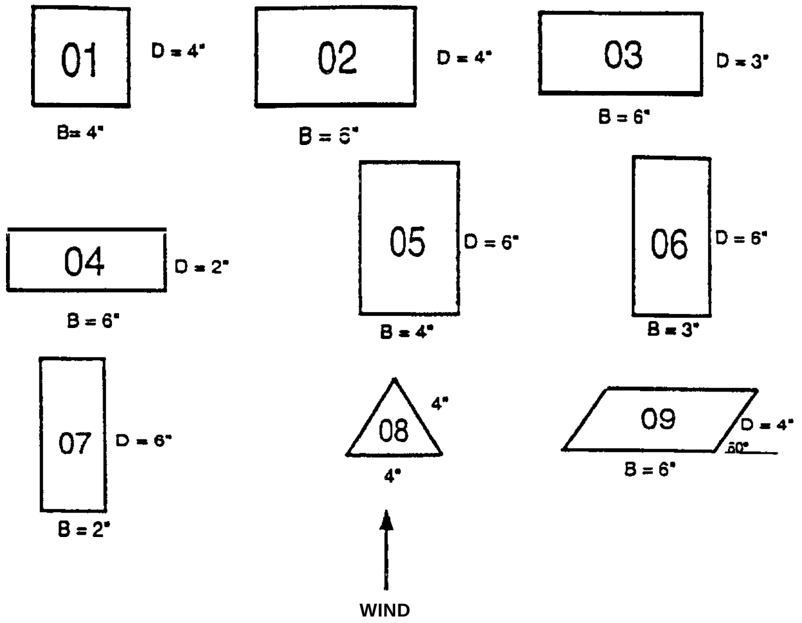
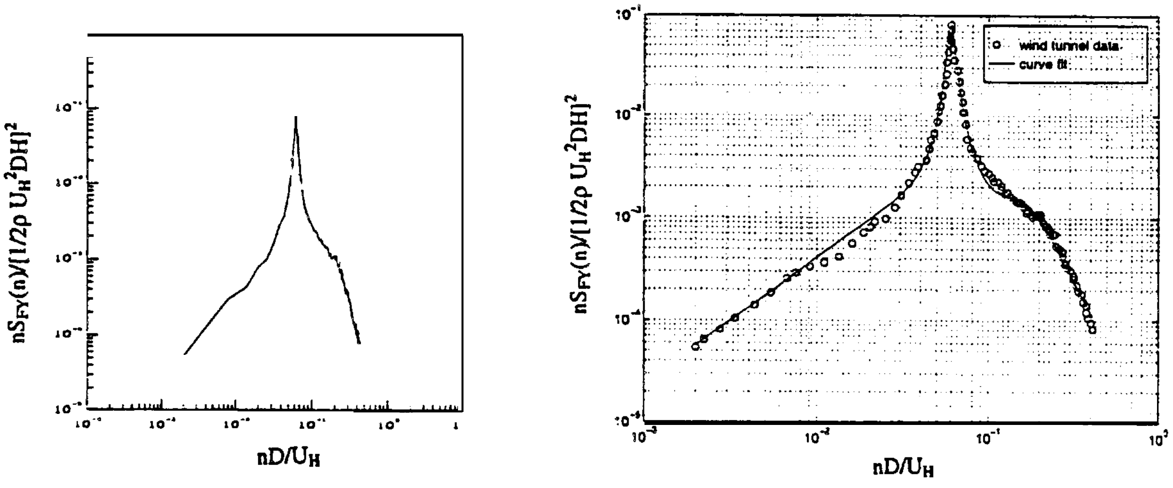


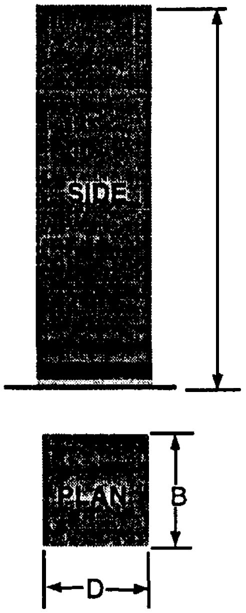
Fig. 1: Nine building cross-sections tested in wind tunnel.



(a)

(b)

Fig. 2: (a) Example spectra from wind tunnel data
(b) Digitized and resulting curve fitted spectra.



BUILDING PROPERTIES
first mode natural frequency=0.2 Hz
first mode critical damping ratio=0.01
mean alongwind force coefficient=1.3
mode exponent=1.0
building density=12 lb/cu.ft. (192.22 kg/cu.m)
air density=0.0024 slugs/sec (1.25 kg/cu.m)
building location= Chicago, IL (urban)
B=100 ft = 30.48 m
D=100 ft = 30.48 m
H=600 ft = 182.88 m

Reference Velocities Used in Comparison of Wind Tunnel Data vs. International Standards

Gust Duration	V_1 m/s (mph)	V_2 m/s (mph)	V_3 m/s (mph)	V_4 m/s (mph)
3 seconds	31.29 (70.00)	33.53 (75.00)	35.76 (80.00)	40.23 (90.00)
10 minutes	21.96 (49.13)	23.32 (52.17)	25.09 (56.13)	28.25 (63.20)
1 hour	20.52 (45.91)	22.00 (49.22)	23.45 (52.46)	26.40 (59.06)

Fig. 3: Model building and wind velocities considered.

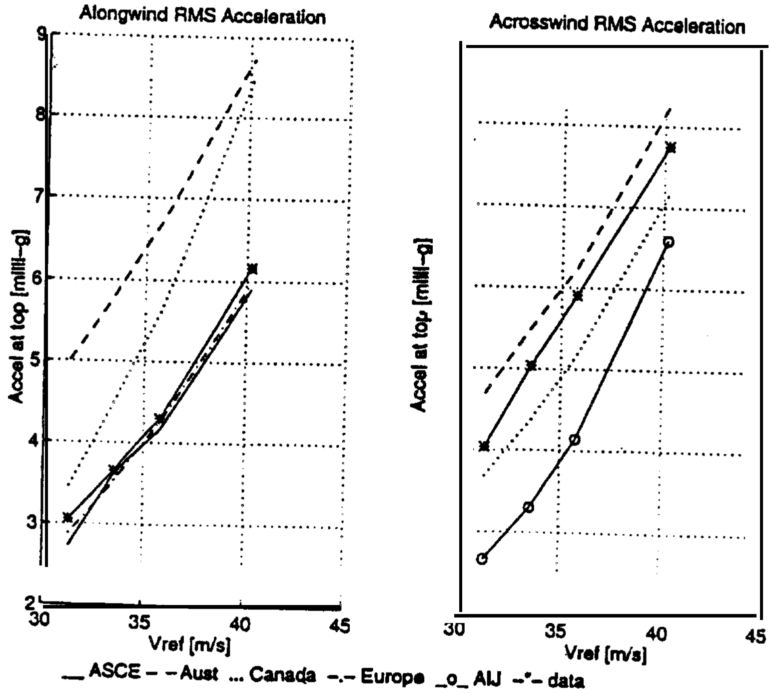


Fig. 4 Comparison of RMS accelerations at model building top predicted by standards and wind tunnel data.