Along-Wind Load Effects on Tall Buildings: Comparative Study of Major International Codes and Standards

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Abstract: Most international codes and standards provide guidelines and procedures for assessing the along-wind effects on tall structures. Despite their common use of the ''gust loading factor'' (GLF) approach, sizeable scatter exists among the wind effects predicted by the various codes and standards under similar flow conditions. This paper presents a comprehensive assessment of the source of this scatter through a comparison of the along-wind loads and their effects on tall buildings recommended by major international codes and standards. ASCE 7-98 (United States), AS1170.2-89 (Australia), NBC-1995 (Canada), RLB-AIJ-1993 (Japan), and Eurocode-1993 (Europe) are examined in this study. The comparisons consider the definition of wind characteristics, mean wind loads, GLF, equivalent static wind loads, and attendant wind load effects. It is noted that the scatter in the predicted wind loads and their effects arises primarily from the variations in the definition of wind field characteristics in the respective codes and standards. A detailed example is presented to illustrate the overall comparison and to highlight the main findings of this paper.

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Introduction

Most international codes and standards utilize the ''gust loading factor'' (GLF) approach for assessing the dynamic along-wind loads and their effects on tall structures. The concept of the GLF for civil engineering applications was first introduced by Davenport (1967), following the statistical treatment of buffeting in aeronautical sciences (Liepmann 1952). Several modifications based on the first GLF model by Davenport followed, which include Vellozzi and Cohen (1968), Vickery (1970), Simiu and Scanlan (1996), and Solari (1993a, b). Variations of these models have been adopted by major international codes and standards.

Although a similar theoretical basis is utilized in these formulations, considerable scatter in the predictions of codes and standards has been reported (e.g., Loh and Isyumov 1985; Ferraro et al. 1989). Lee and Ng (1988) compared some of the international codes, mainly focusing on the GLF. Discrepancies in the definitions of wind spectrum and wind correlation among the various codes and standards were noted in this study. In a subsequent study, Jesien et al. (1993) made similar observations. More recently, Kijewski and Kareem (1998) compared different international codes and standards with experimental data obtained in a wind tunnel using a high-frequency base balance. Their comparison also included the across-wind and torsional responses. Despite these studies, an in-depth investigation concerning the underlying sources of this scatter has not been conducted, motivating this study. Furthermore, with the globalization of the construction industry and the prospect of developing unified international standards, it is becoming increasingly important to better understand the underlying differences.

This paper presents a comprehensive comparative study of the along-wind loads and their effects on tall buildings utilizing major international codes and standards: ASCE 7-98 (ASCE 1999), AS1170.2-89 (Australian Standards 1989; Holmes et al. 1990), NBC-1995 (NRCC 1995), RLB-AIJ-1993 (AIJ 1996), and Eurocode-1993 (Eurocode 1995). In order to provide a self-sufficient document, the derivation of GLF for the along-wind response is briefly reviewed to highlight the salient features and their respective roles in the overall framework used in the estimation of wind load effects. The comparison in this study considers the definition of wind characteristics, associated mean wind loads, GLF, equivalent static wind loads (ESWL), and attendant wind load effects. An example is given to highlight this comparison and the main findings of this study.

Gust Loading Factor

Following the concept of the GLF approach (Davenport 1967), the peak ESWL on tall buildings provided in codes and standards is described by a product of the mean wind force and an appropriate amplification factor

$$\hat{P}^T(z) = G^\tau \cdot \overline{P^\tau}(z) \quad (1)$$

where $\hat{P}^T(z)$ = peak ESWL at height z during observation time T, usually one hour (1 h) or 10 minutes (10 min) for most civil engineering applications; superscript τ = averaging time used to evaluate the mean wind velocity; and $\overline{P^\tau}$ = mean wind force with averaging time τ

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$$\overline{P^{\tau}}(z)=q(z)\cdot C_d\cdot B \quad (2)$$

in which C_d=drag force coefficient; B=width of the building normal to the oncoming wind; and $q(z)=1/2\rho\overline{V}(z)^2$=mean wind velocity pressure, where ρ=air density and $\overline{V}(z)$=mean wind velocity evaluated at height z above ground. The gust factor G^{τ} is given by

$$G^{\tau}=G_Y^T/G_q^{\tau}(T) \quad (3)$$

in which G_Y^T=GLF for displacement and $G_q^{\tau}(T)$=gust factor (GF) for wind velocity pressure. The displacement GLF takes into account the correlation structure of random wind field, wind-structure interaction, and the dynamic amplification introduced by the structure. Following the current practice in the GLF approach (Davenport 1967), it can be evaluated by

$$G_Y^T=\hat{Y}^T(z)/\overline{Y^T}(z) \quad (4)$$

where $\hat{Y}^T$ and $\overline{Y^T}$=peak and mean wind-induced displacement response, respectively. For the sake of completeness and quick reference, a general derivation of GLF based on displacement is provided in Appendix I. It is noted that, in this formulation, the averaging time for the mean wind velocity is equal to the observation time. This implies that the mean wind velocity and the mean wind load or response have the same averaging time. Although this is the case for some codes (e.g., RLB-AIJ-1993; NBC-1995), the mean wind velocity with a shorter averaging time, e.g., 3 seconds (3 s), is also used in some codes (e.g., ASCE 7-98; AS1170.2-89). The following GF is used to convert the mean wind-velocity pressure to an appropriate averaging period when the mean wind velocity or pressure with a shorter averaging time is used as an input in determining the mean wind load or response

$$G_q^{\tau}(T)=\overline{q^{\tau}}/\overline{q^T} \quad (5)$$

where q=wind velocity pressure. Several representative models of GF for wind velocity or wind pressure are provided in Appendix II. Using the result given by Durst (1960) and assuming T=1 h, GFs for the basic mean wind velocity at a 10-meter (10 m) height in the open country terrain are $G_v^{3\ \mathrm{s}}$ (1 h)=1.51 and $G_v^{1\ \mathrm{h}}$ (1 h)=1.00, respectively. Using a simple square law, the corresponding GFs for the wind-velocity pressure are $G_q^{3\ \mathrm{s}}$ (1 h)=2.28 and $G_q^{1\ \mathrm{h}}$ (1 h)=1.00.

The above discussion clarifies the important role of averaging time in this comparative study. On the one hand, when $\tau=T$, the wind load model in Eq. (1) reduces to the general GLF model by Davenport (1967). On the other hand, when using the mean wind velocity with a shorter averaging time, G in Eq. (1) may be significantly less than the GLF in Eq. (4). Therefore, it is important to compare the results based on similar averaging times. A summary of the averaging time for the basic wind velocity or pressure, GLF, ESWL or wind-induced response employed in codes and standards is given in Table 1.

All procedures for estimating GLF and ESWL in major codes and standards are based on the preceding expressions, including Appendix I and II, but differ in their modeling of the wind field and structural dynamic characteristics. These details have led to a large scatter in the predicted values of the GLF and wind load effects based on distinct formulations. Furthermore, as a result of several mathematical manipulations that have been introduced by individual codes and standards, the final expressions for the GLF do not follow exactly the same form as outlined in the Appendixes. For a quick reference, the procedures for the GLF in the current major codes and standards are summarized in Table 2. It is noted that ASCE 7-98 and Eurocode are based on a similar background (Solari 1993a; Solari and Kareem 1998), which has resulted in very similar formulations in these codes. To facilitate a convenient comparison, the expressions in Table 2 are rewritten from the original expressions in the codes and standards to make the displacement GLF follow the format presented in Eq. (22) or Eq. (24) later in the paper and subsequently referred to as the standard form in Appendix I.

Table 1. Averaging Time in Codes and Standards

	ASCE 7	AS1170.2	NBC	RLB-AIJ	Eurocode
Basic wind velocity or basic wind pressure	3 s	3 s[a]	1 h	10 min	10 min[b]
Gust-loading factor	3 s	1 h	1 h	10 min	3 s
Wind-induced response	1 h	1 h	1 h	10 min	10 min

[a]Although the basic wind velocity is defined as 3 s gust in AS1170.2, it is converted to the 1 h mean wind velocity to evaluate the gust-loading factor and the wind-induced response of dynamic structures.

[b]Using an exposure coefficient, the 10 min basic wind velocity or pressure is transformed to the 3 s gust wind pressure, which is then multiplied with the 3 s gust-loading factor to obtain the equivalent static wind loads.

Description of Wind Characteristics in Codes and Standards

In the formulation of the GLF approach, the GLF, ESWL and wind load effects depend on the mean wind velocity profile, turbulence intensity, wind spectrum, turbulence length scale, and correlation structure of the wind field. An overview of the definition or description of these wind characteristics in codes and standards is provided in this section.

Basic Wind Velocity/Pressure

The basic wind velocity in most codes and standards is based on wind measurements at 10 m height in an open terrain associated with different mean recurrence intervals and averaging times. The basic wind velocity is converted to the design reference wind velocity for a particular site by introducing the influence of local environment, directionality, mean recurrence interval, and significance factors associated with the planned structure as shown below

$$V=V_0\cdot C_{\mathrm{direction}}\cdot C_{\mathrm{shield}}\cdot C_{\mathrm{importance}}\cdot C_{\mathrm{return}} \quad (6)$$

where V_0=basic mean wind velocity; $C_{\mathrm{direction}}$=directionality factor; C_{shield}=shielding factor; $C_{\mathrm{importance}}$=building importance factor; and C_{return}=a factor for adjusting wind mean recurrence interval. For the sake of simplicity, these factors are ignored in this study.

Mean Wind Velocity Profile

Generally, the wind velocity distribution along the height is influenced by the local topography, surrounding terrain, and averaging time. The local topography may have a speed-up effect on the wind profile, which is ignored in this discussion for simplicity. The averaging time also influences the wind-velocity profile. For example, the 3 s gust has a flatter distribution than the 1 h mean wind velocity. AS1170.2 and ASCE 7 provide mean wind-

Table 2. Calculation of Gust-Loading Factors in Codes and Standards

	ASCE 7	AS1170.2	NBC	RLB-AIJ	Eurocode
G[a]	$0.925\left(\frac{1+r\sqrt{g_Q^2\mathbf{B}+g_R^2\mathbf{R}}}{1+g_v\cdot r}\right)$[a,c]	$1+r\sqrt{g_V^2\mathbf{B}(1+w)^2+g_f^2\mathbf{R}}$[d]	$1+g_f r\sqrt{\mathbf{B}+\mathbf{R}}$	$1+g_f r\sqrt{\mathbf{B}+\mathbf{R}}$	$\frac{1+g_f r\sqrt{\mathbf{B}+\mathbf{R}}}{1+3.5r}$[c]
T	3,600 s	3,600 s	3,600 s	600 s	600 s
$\overline{z}$	$0.6H$	H	H	H	$0.6H$
r	$r=1.7I_{\bar{z}}$[e]	$r=2\cdot I_{\bar{z}}$	$r=\sqrt{2K/C_{eH}}$[f]	$r=(3+3\alpha)/(2+\alpha)\cdot I_{\bar{z}}$[g]	$r=2I_{\bar{z}}$
g	$g_Q=g_V=3.4$ $g_R=g_R(T,f_1)$[h]	$g_V=3.7$; $g_f=\sqrt{2\ln(T\cdot f_1)}$	$g_f=g_R(T,\upsilon)$;[g] $\upsilon=f_1\sqrt{SE/(SE+\zeta\mathbf{B})}$	$g_f=\sqrt{2\ln(T\cdot\upsilon)+1.2}$ $\upsilon=f_1\sqrt{\mathbf{R}/(\mathbf{B}+\mathbf{R})}$	$g_f=g_R(T,\upsilon)$[h] $\upsilon=\sqrt{(\upsilon_0^2\mathbf{B}+f_1^2\mathbf{R})/(\mathbf{B}+\mathbf{R})}$
B	$\frac{1}{1+0.63\left(\frac{B+H}{L_{\bar{z}}}\right)^{0.63}}$	$\frac{1}{1+\frac{\sqrt{36H^2+64B^2}}{L_H}}$	$\frac{2}{3}\int_0^{914/H}\frac{1}{1+\frac{xH}{457}}\frac{1}{1+\frac{xB}{122}}\frac{x}{(1+x^2)^{4/3}}dx$	$1-\frac{1}{\left\{1+5.1\left(\frac{L_H}{\sqrt{HB}}\right)^{1.3}\left(\frac{B}{H}\right)^{k}\right\}^{1/3}}$	$\frac{1}{1+0.9\left(\frac{B+H}{L_{\bar{z}}}\right)^{0.63}}$
E[i]	$9.5N_1/(1+10.3N_1)^{5/3}$[e]	$0.6N_1/(2+N_1^2)^{5/6}$	$2N_1^2/3(1+N_1^2)^{4/3}$	$4N_1/(1+71N_1^2)^{5/6}$	$6.8N_1/(1+10.2N_1)^{5/3}$
S	$R_H R_B(0.53+0.47R_D)$[j]	$\frac{1}{\left[1+3.5\frac{f_1H}{V_H}\right]\left[1+4\frac{f_1B}{V_H}\right]}$	$\frac{1}{\left[1+\frac{8f_1H}{3V_H}\right]\left[1+\frac{10f_1B}{V_H}\right]}$	$\frac{0.84}{\left[1+\frac{2.1f_1H}{V_H}\right]\cdot\left[1+\frac{2.1f_1B}{V_H}\right]}$[k]	$R_H R_B$[j]

[a]Expressions for GLF in this table are not necessarily reproduced from the original codes and standards, but are rewritten in the standard form [refer to Eq. (22) or Eq. (24)].

[b]0.925 is an adjustment factor used to make the wind load in the updated code consistent with the former version.

[c]Numerator is the displacement GLF and the denominator is the GF for the wind velocity pressure.

[d]w is an approximate consideration of the quadratic wind velocity term (Vickery 1995).

[e]A 3 s low-pass filter has been included (Solari and Kareem 1998).

[f]K is provided for different terrains in NBC.

[g]A 0.75 factor is used to account for nonuniform load distribution (RLB-AIJ 1994).

[h]$g_R(T,f_1)$; see Eq. (23) by substituting relevant parameters.

[i]$E=f_1S_v(f_1)/\sigma_v^2$ and $N_1=f_1L_{\bar{Z}}/\overline{V_{\bar{Z}}}$.

[j]$R_l=1/\eta-1/2\eta^2(1-e^{-2\eta})$ for $\eta>0$; and $R_l=1$ for $\eta=0$. R_H, $\eta=4.6f_1H/V_{\bar{Z}}$; R_B, $\eta=4.6f_1B/V_{\bar{Z}}$; and R_D, $\eta=15.4f_1D/V_{\bar{Z}}$.

[k]Aerodynamic admittance function is equal to 0.84 at zero frequency.

velocity profiles based on both 3 s and 1 h averaging times, whereas NBC, RLB-AIJ, and Eurocode utilize averaging times of 1 h, 10 min, and 10 min for the mean velocity profiles, respectively.

There are two kinds of basic wind-velocity profile descriptions, i.e., the logarithmic and the power law. AS1170.2 and Eurocode use the logarithmic profile, whereas all others use a power-law profile. Nevertheless, the wind profiles provided in the codes and standards discussed here can be expressed in terms of the following general power law:

$$V(z)=V_0\cdot b\cdot(z/10)^{\alpha} \quad (7)$$

where b and α=constants depending on the terrain type. For an open terrain case (exposure C) at 10 m height, b is equal to unity since the basic wind velocity is defined for this exposure. Coefficients b and α for all exposures provided in codes and standards are summarized in Table 3.

When using 3 s reference velocity $\hat{V}_0^{3\text{ s}}$, the mean wind velocity profiles in codes and standards can also be expressed as

Table 3. Mean Wind Velocity Profiles in Codes and Standards [Eq. (7)]

	ASCE 7				AS1170.2 (fitted)				NBC		RLB-AIJ		Eurocode (fitted)	
	3 s		1 h		3 s		1 h		1 h		10 min		10 min	
	b	α	b	α	b	α	b	α	b	α	b	α	b	α
A	0.66	0.20	0.30	0.33	0.76	0.14	0.29	0.28	0.43	0.36	0.39	0.35	0.55	0.29
B	0.85	0.14	0.45	0.25	0.91	0.10	0.45	0.20	0.67	0.25	0.58	0.27	0.77	0.21
C	**1.00**	0.11	0.65	0.15	**1.04**	0.07	0.58	0.16	**1.00**	0.14	0.79	0.20	**1.00**	0.16
D	1.09	0.09	0.80	0.11	1.18	0.04	0.69	0.13			**1.00**	0.15	1.17	0.12
E											1.23	0.10		

Note: Basic wind velocity refers to the condition where the coefficient b is equal to unity, which is shown in bold in this table.

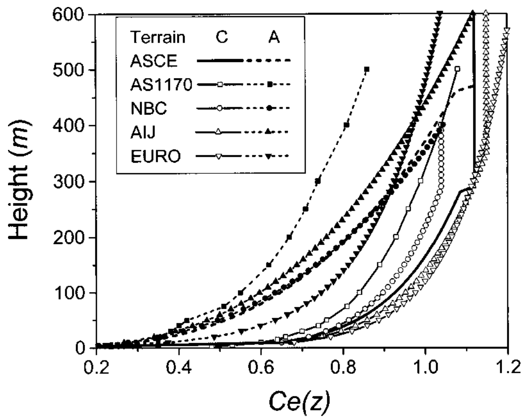

Fig. 1. Mean wind velocity profiles in codes and standards [Eq. (8)]; in terms of 3 s gust basic wind velocity. *A*: large city center; *C*: open country terrain. Note: Open country terrain corresponds to exposure *C* in codes and standards, except for AIJ standard, in which exposure *D* is used. Refer to Table 3.

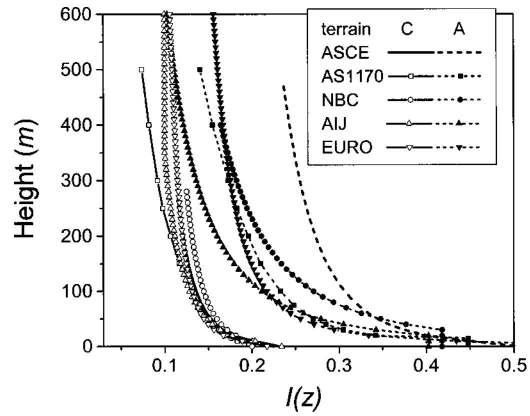

Fig. 2. Turbulence intensity profiles in codes and standards [Eq. (9)]; *A*: large city center; *C*: open country terrain

$$C_e(z)=\overline{V}(z)/\hat{V}_0^{3\ \mathrm{s}} \tag{8}$$

This information is included in both ASCE 7 and AS1170.2. For other codes and standards that do not use 3 s gust as the reference wind velocity, Eq. (32) of the Appendix is used to relate the mean wind velocity to the 3 s gust. For example, in the case of NBC, $T=1$ h. Considering exposure C at the 10 m height and assuming $I=0.2$, the velocity gust factor $G_{V_0}^{3\ \mathrm{s}}$ (1 h)=1.58. Similarly, by setting $T=10$ min, $G_{V_0}^{3\ \mathrm{s}}$ (10 min)=1.48 can be used to convert the 10 min mean wind velocity in RLB-AIJ and Eurocode to 3 s gust. The mean wind profiles provided by each code and standard for exposures C and A (large city centers) are shown in Fig. 1.

From both Table 3 and Fig. 1, considerable differences between the mean wind-velocity profiles among different codes and standards can be noted. Clearly, this will have a significant impact on the mean wind load estimates. The mean wind velocity will also indirectly influence the GLF, thus impacting estimates of the overall wind load effects.

Turbulence Intensity Profile

The turbulence intensity profile can also be expressed in terms of a power law

$$I(z)=c\cdot(z/10)^{-d} \tag{9}$$

where c and d=constants depending on the terrain type. These coefficients, as provided in the codes and standards, are summarized in Table 4. Fig. 2 illustrates a comparison of these profiles for exposures A and C.

From Table 4 and Fig. 2, significant differences in the description of the turbulence intensity can be noted. These variations will affect both the background and the resonant GLF components, without a significant influence on the mean wind loads.

Wind Spectra, Turbulence Length Scales, and Correlation Structure

Table 5 lists wind spectra and definitions of turbulence length scales given in the codes and standards. It is interesting to note that AS1170.2, NBC, and RLB-AIJ all prescribe a length scale formulation independent of terrain, though data in Counihan (1975) suggest that it is a decreasing function of terrain toughness. Fig. 3 provides wind spectra for exposures A and C for the case of a 200 m tall building. The reference height, turbulence length scale, and wind velocity for each spectrum are given in Table 6. The difference in the definition of the wind spectrum primarily influences the resonant component of GLF and the associated acceleration response, whereas there is a marginal influence on the background component of the GLF.

As shown in the derivation of the displacement-based GLF in Appendix I, the correlation structure of the fluctuating wind velocity is reflected in the background factor and the aerodynamic admittance function or size reduction factor. A comparison of size reduction factors used in codes and standards is provided in Fig. 4. Once again, the variations in size reduction factors are noteworthy.

Application of Gust Loading Factor to Wind Load Effects

Although all current codes and standards follow the preceding outline, it is interesting that the ESWL obtained using the tradi-

Table 4. Turbulence Intensity Profiles in Codes and Standards [Eq. (9)]

	ASCE 7		AS1170.2 (fitted)		NBC (derived)[a]		RLB-AIJ		Eurocode (fitted)	
Terrain	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
A	0.450	0.167	0.453	0.300	0.621	0.360	0.402	0.400	0.434	0.290
B	0.300	0.167	0.323	0.300	0.335	0.250	0.361	0.320	0.285	0.210
C	0.200	0.167	0.259	0.300	0.200	0.140	0.259	0.250	0.189	0.160
D	0.150	0.167	0.194	0.300			0.204	0.200	0.145	0.120
E							0.162	0.150		

[a]Turbulence intensity profile is not explicitly available in NBC. The data herein are derived by rewriting the code procedure in the standard form.

Table 5. Wind Spectra and Turbulence Length Scales in Codes and Standards

	Wind spectra (unified)	Turbulence length scale (m)
ASCE 7	$\frac{fS_\nu(f)}{\sigma_\nu^2}=\frac{6.868x}{(1+10.302x)^{5/3}}, \quad x=\frac{f\cdot L_{\bar{z}}(\bar{z})}{\bar{V}(\bar{z})}$	$L_{\bar{z}}=l(\bar{z}/10)^{\bar{\varepsilon}}$ l and $\bar{\varepsilon}$ depend on terrain
AS1170.2	$\frac{fS_\nu(f)}{\sigma_\nu^2}=\frac{4x}{6.677(2+x^2)^{5/6}}, \quad x=\frac{L_H f}{\bar{V}_H}$	$L_H=1{,}000(H/10)^{0.25}$; A measure of turbulence scale
NBC	$\frac{fS_\nu(f)}{\sigma_\nu^2}=\frac{2x^2}{3(1+x^2)^{4/3}}, \quad x=\frac{1{,}200f}{\bar{V}_H}$	1,220; A length scale, Davenport (1967)
RLB-AIJ	$\frac{fS_\nu(f)}{\sigma_\nu^2}=\frac{4x}{(1+70.8x^2)^{5/6}}, \quad x=\frac{fL_H}{\bar{V}_H}$	$L_H=100(H/30)^{0.5}$
Eurocode	$\frac{fS_\nu(f)}{\sigma_\nu^2}=\frac{6.868x}{(1+10.302x)^{5/3}}, \quad x=\frac{f\cdot L_{\bar{z}}(\bar{z})}{\bar{V}(\bar{z})}$	$L_{\bar{z}}=300(\bar{z}/300)^{\bar{\varepsilon}}$ $\bar{\varepsilon}$ depends on terrain

tional GLF formulation in Eq. (1) does not represent the actual ESWL acting on a tall building. Rather, the ESWL given in Eq. (1) follows the distribution of the mean wind load. This is not consistent with the distribution of the inertial force that is proportional to the mass distribution and the mode shape of the building. Although the ESWL in Eq. (1) can ensure accurate estimation of the first mode displacement, it may result in less reliable estimates of other wind effects, e.g., the base shear (Zhou et al. 1999a,b, 2000). A more novel way to correctly use the traditional GLF is to express it in terms of the base bending moment response. As outlined in a new GLF formulation by Zhou and Kareem (1999c, 2001), the actual peak base bending moment response can be estimated by

$$\hat{\mathbf{M}}=G_Y\cdot\bar{M} \tag{10}$$

where $\bar{M}=\int_0^H\bar{P}(z)\cdot z dz=$base bending moment under the mean wind load and $\hat{\mathbf{M}}=$peak base bending moment response. The distribution of the ESWL components can be evaluated from the base bending moment following the procedure provided by Zhou and Kareem (2001). For example, the background ESWL component is given by

$$\hat{\mathbf{P}}_B(z)=G_{YB}\cdot\bar{P}(z) \tag{11}$$

where $G_{YB}=g_B\cdot r\sqrt{\mathbf{B}}$; and for the resonant ESWL component

$$\hat{\mathbf{P}}_R(z)=\frac{m(z)\varphi_1(z)}{\int_0^H m(z)\varphi_1(z)zdz}\cdot\hat{\mathbf{M}}_R \tag{12}$$

where $\hat{\mathbf{M}}_R=G_{YR}\cdot\bar{M}$ and $G_{YR}=g_R\cdot r\sqrt{\mathbf{R}}$. The RMS acceleration can be computed by

$$\sigma_a(z)=\frac{\int_0^H\hat{\mathbf{P}}_R(z)\varphi_1(z)dz}{g_R\cdot\int_0^H m(z)\varphi_1^2(z)dz}\cdot\varphi_1(z) \tag{13}$$

The peak acceleration is obtained by multiplying the RMS acceleration by g_R. The acceleration response depends only on the resonant component of GLF. It is noted that in this section the difference in the averaging time is ignored. This difference can be similarly treated as in the proceeding sections.

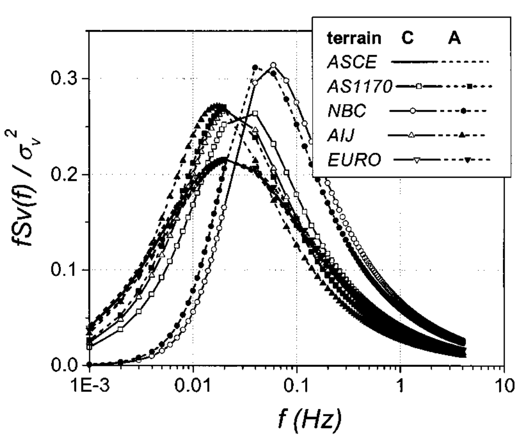

Fig. 3. Wind spectra in codes and standards; Refer to Tables 5 and 6 for involved parameters. *A*: large city center; *C*: open country terrain.

Application of Codes and Standards to an Example Tall Building

A tall building is used as an example to compare the estimates of wind load effects based on the codes and standards considered. The building particulars are $H=200$ m, $B=D=33$ m; $f_1=0.2$ Hz, and linear mode shape in two translation directions; $\zeta=0.01$; $C_d=1.3$; and building density $=180$ kg/m^3. The building is located at the edge of a central business district with exposure *A* on one side and exposure *C* on the other; and the basic 3 s gust wind velocity $=40$ m/s. For simplicity, the effects of the wind direction, topography, shielding, importance, and return period are ignored in the following discussion.

The results obtained by using the procedures in the codes and standards selected here are listed in Table 6. As expected, the averaging time shown in Table 1 manifests significant influence

Table 6. Results of Computation using Codes and Standards

		ASCE 7		AS1170.2[a]		NBC		RLB-AIJ		Eurocode	
		A	*C*	*A*	*C*	*A*	*C*	*A*	*C*	*A*	*C*
V_0 (m/s)			40 (3 s)		40 (3 s)		26 (1 h)[b]		27 (10 min)[b]		27 (10 min)[b]
$\overline{z}$ (m)			120		200		200		200		120
$V_{\overline{z}}$ (m/s)		27.5	38.1	26.7	37.3	32.6	39.5	30.4	42.3	30.7	39.3
r		0.506	0.225	0.368	0.210	0.423	0.303	0.276	0.180	0.422	0.254
$L_{\overline{z}}$ (m)		190	250	2115	2115	1220	1220	258	258	197	236
B		0.583	0.624	0.633	0.633	0.300	0.300	0.582	0.582	0.500	0.529
E		0.140	0.144	0.094	0.117	0.170	0.191	0.080	0.100	0.106	0.109
S		0.048	0.079	0.080	0.123	0.077	0.101	0.154	0.212	0.087	0.121
R		0.525	0.889	0.596	1.138	1.031	1.524	0.967	1.655	0.726	1.039
g_f		$g_R=3.79$;	$g_v=3.40$	$g_R=3.63$;	$g_v=3.70$	3.759	3.768	3.209	3.235	3.208	3.225
	3 s	0.447	0.316							0.386	0.315
G_B	10 min							0.676	0.443	0.958[c]	0.596[c]
	1 h	1.214[c]	0.559[c]	1.083	0.618	0.870	0.626				
	3 s	0.472	0.421							0.466	0.442
G_R	10 min							0.872	0.747	1.154[c]	0.835[c]
	1 h	1.283[c]	0.742[c]	1.030	0.813	1.614	1.411				
	3 s	0.990	1.051							1.009	1.073
G	10 min							2.103 (78.2%)[g]	1.868 (100.8%)[g]	2.500[c] (92.9%)[g]	2.026[c] (109.2%)[g]
	1 h	2.691[c]	1.854[c]	2.495 (92.8%)[g]	2.021 (109.2%)[g]	2.833 (105.3%)[g]	2.544 (137.3%)[g]				
$\overline{M}$	3 s	1,035,400	1,465,400								
(kN·m)	10 min							367,810 (86.3%)[g]	833,050 (105%)[g]	528,250 (124%)[g]	837,510 (106%)[g]
	1 h	425,980[d]	790,360[d]	297,600 (69.9%)[g]	644,490 (81.5%)[g]	417,880 (98.1%)[g]	735,690 (93.1%)[g]				
$\hat{\mathbf{M}}$	10 min							773,410	1,556,400	1,320,400	1,696,700
(kN·m)								(75.5%)[g]	(101.1%)[g]	(128.6%)[g]	(110.3%)[g]
	1 h	1,024,808 1,146,260[e]	1,539,848 1,465,015[e]	742,420 (72.4%)[g]	1,302,400 (84.5%)[g]	1,183,900 (115.7%)[g]	1,871,300 (121.1%)[g]				
σ_a	10 min							3.82	7.36	7.27	8.30
(milli-g)								(77.3%)[g]	(117.8%)[g]	(147%)[g]	(133%)[g]
	1 h	4.94 5.52[f]	6.23 5.93[f]	3.23 (65.4%)[g]	5.52 (88.5%)[g]	6.86 (138.4%)[g]	10.54 (168.6%)[g]				

[a]Neglect the correction for the quadratic term.

[b]Wind velocity GFs of 0.65 and 0.676 are used to transfer the 3 s gust wind velocity to those in 1 h and 10 min mean, respectively.

[c]Displacement GLF, computed by neglecting the dominator in the GLF expression.

[d]Computed based on the 1 h mean wind profile in ASCE 7.

[e]Product of the GLF and the mean base bending moment both based on the 1 h averaging time.

[f]Correspond to the base bending moment in e.

[g]Comparing with the result by ASCE 7. For simplicity, the effect of a shorter averaging time (10 min) in RLB-AIJ and Eurocode is not considered.

on both the GLF and the mean wind load estimates. Since the basic wind-velocity pressure GF for the 3 s gust is $G_q^{3\text{ s}}$ (1 h) $=(1.58)^2=2.50$ or $G_q^{3\text{ s}}$ (10 min)$=(1.48)^2=2.19$, the GLFs obtained by using ASCE 7 and Eurocode, based on 3 s averaging time, are significantly less than those by other codes and standards, which are based on a longer averaging time. However, in terms of peak base bending moments and displacement GLFs, which are based on longer averaging time, the difference in the estimates among the codes and standards is considerably reduced.

Since the codes and standards employ quite varied definitions of wind characteristics, it is not surprising to find considerably different results at each step of the wind load effects analysis even when considering a similar averaging time.

With the same input of 3 s basic gust wind velocity, the mean wind loads obtained by each code and standard are quite varied due to their distinct mean wind velocity profiles. This results in disparities in the mean base bending moments. For example, the mean base bending moments in terms of a 1 h averaging time by AS1170.2 are 70 and 81.5% of those given by ASCE 7 for exposures *A* and *C*, respectively.

Regarding the GLF, it is noted that estimates based on ASCE 7 are distinct from those given by Eurocode due to their unique definitions of wind characteristics, although these two codes are both based on a similar closed-form formulation (Solari 1993a; Solari and Kareem 1998). Eurocode neglects the correlation between the windward and leeward wind pressures, which results in

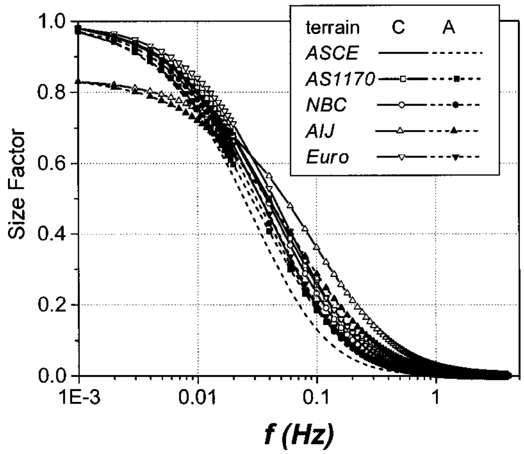

Fig. 4. Size factors in codes and standards; refer to Tables 2 and 6 for involved parameters. *A*: large city center; *C*: open country terrain

larger size reduction factors. This effect, although partly compensated by the decreased gust energy factor and turbulence intensity, combined with higher estimates of mean wind loads, leads to 28.6% and 47% higher estimates of base bending moment and acceleration, respectively, for exposure *A*, if the difference in averaging times between these two codes is ignored.

Comparing with other codes, ASCE 7 prescribes higher turbulence intensity, especially for exposure *A*, which results in greater estimates in both background and resonant GLF components. Coupled with the relatively higher mean wind load, ASCE 7 produces the second largest peak estimates of the base bending moment and acceleration for exposure *A*. In comparison to ASCE 7 and NBC, AS1170.2 provides the lowest estimates of the GLF, base bending moment, and the acceleration since it prescribes lower turbulence intensity, gust energy factor, and mean wind load. However, NBC employs the highest gust energy factor, which yields the largest value of GLF, base bending moment, and acceleration for the exposure *C* case. Meanwhile, the background factor in NBC is apparently less than those by other codes. RLB-AIJ employs the lowest turbulence intensity definition, which leads to the lowest GLF estimates despite the fact that the size reduction factor in this standard is the greatest.

Concluding Remarks

All major international codes and standards are based on the GLF approach for estimating the maximum wind load effects in the along-wind direction; however, each employs unique definitions of wind field characteristics, including the mean wind-velocity profile, turbulence intensity profile, wind spectrum, turbulence length scale, and the wind correlation structure (related to the aerodynamic admittance function using strip and quasi-steady theories). These nuances in the wind field characteristics have resulted in discrepancies not only in the GLF estimates, but also in the mean wind loads, which correspondingly lead to significant variations in the estimates of the ESWL and associated wind-induced load effects.

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Appendix I: Derivation of GLF for displacement

Assuming that the wind-induced displacement response is a Gaussian process, the displacement GLF in Eq. (4) can be expressed as (Davenport 1967)

$$G_Y = 1 + g \cdot \sigma_Y(z)/\overline{Y}(z) \tag{14}$$

For the sake of brevity, the superscript T is omitted in this discussion, implying that the mean wind velocity corresponds to the same averaging time as the observation time. Usually, the mean structural displacement can be approximated in terms of the first mode mean displacement response

$$\overline{Y}(z) = (\overline{P}_1^*/k_1^*) \cdot \varphi_1(z) \tag{15}$$

where $\overline{P}_1^* = \int_0^H \overline{P}(z)\varphi_1(z)dz$; $k_1^* = (2\pi f_1)^2 m_1^*$; $m_1^* = \int_0^H m(z)\varphi_1^2(z)dz$ = generalized load, stiffness, and mass of the first mode, respectively; f_1 = natural frequency of the first mode; $m(z)$ = mass per unit height; and the fundamental mode shape of a tall building can be approximated by $\varphi_1(z) = (z/H)^\beta$, where β = mode shape exponent. This has been assumed to be equal to unity in most codes and standards, since the effect of a nonlinear mode shape on the derivation of the GLF can usually be neglected (Vickery 1970; Zhou et al. 1999b).

Using the quasi-steady and strip theories and neglecting the contribution of the quadratic wind-velocity term, the fluctuating aerodynamic wind force acting on the surface of a tall building can be estimated by

$$\tilde{P}(z,t) = \rho \overline{V}(z) \cdot v(z,t) \cdot C_d \cdot B \tag{16}$$

where $v(z,t)$ is the fluctuating wind velocity. Under the action of this fluctuating wind pressure, the fluctuating displacement in the first mode can also be computed by

$$\sigma_Y(z) = \left(\int_0^\infty S_{\tilde{P}_1^*}(f)df \cdot |H_1(f)|^2/k_1^{*2} \right)^{1/2} \cdot \phi_1(z) \tag{17}$$

where $|H_1(f)|^2 = ([1-(f/f_1)^2]^2 + (2\zeta f/f_1)^2)^{-1}$ = first mode structural transfer function; ζ = critical damping ratio in the first mode; and $S_{\tilde{P}_1^*}(f)$ = power spectral density of the fluctuating generalized wind load, which can be expressed as

$$S_{\tilde{P}_1^*}(f) = \int_0^H \int_0^H \int_0^B \int_0^B \rho^2 C_d^2 B^2 \overline{V}(z_1)\overline{V}(z_2) \cdot R(x_1,x_2,z_1,z_2,f) S_v(z_1,z_2,f)\varphi_1(z_1)\varphi_1(z_2)dx_1dx_2dz_1dz_2 \tag{18}$$

where $R(x_1,x_2,z_1,z_2,f)$ = correlation function of the fluctuating wind pressures and $S_v(z_1,z_2,f)$ = cross-PSD of the fluctuating wind velocity.

Using Eqs. (15) and (17), the fluctuating component of the GLF can be derived as

$$\sigma_Y(z)/\overline{Y}(z)=\left(\int_0^\infty S_{\tilde{P}_1^*}(f)|H_1(f)|^2 df\right)^{1/2} \bigg/ \overline{P_1^*} \tag{19}$$

which shows that the GLF is independent of the mass. The integration in Eq. (19) is usually performed in the background and resonant portions. After some mathematical manipulations, the fluctuating component of the GLF can be derived

$$\sigma_Y/\overline{Y}=2\cdot I_{\overline{z}}\cdot\sqrt{\mathbf{B}+\mathbf{R}} \tag{20}$$

where $I_{\overline{z}}=[(2+2\alpha)/(2+\alpha)]I_H$ in which $I_H=\sigma_v/\overline{V}_H$=turbulent intensity evaluated at the top of the building; $\overline{z}\approx 2H/3$=reference height; $\mathbf{B}=\int_0^\infty \chi(f)\cdot S_v^*(\overline{z},f)df$=background factor; $\mathbf{R}=\pi SE/4\zeta$=resonant factor; $S_v^*(f)$=normalized wind velocity spectrum with respect to the mean-square fluctuating wind velocity, σ_v^2; $E=f_1 S_v^*(\overline{z},f_1)$=gust energy factor

$$\chi(f)=\frac{\int_0^H\int_0^H\int_0^B\int_0^B(z_1/H)^\alpha(z_2/H)^\alpha(z_1/H)(z_2/H)\cdot R(x_1,x_2,z_1,z_2,f)dx_1dx_2dz_1dz_2}{\int_0^H\int_0^H\int_0^B\int_0^B(z_1/H)^\alpha(z_2/H)^\alpha(z_1/H)(z_2/H)dx_1dx_2dz_1dz_2} \tag{21}$$

which represents the aerodynamic admittance function; $S=\chi(f_1)$=size reduction factor, which is a measure of the overall effect of the wind pressure correlation. For an ideal pointlike structure, or when $f\to 0$, the velocity field is fully correlated or $R=1$. Thus, $\chi(f)$ approaches unity and both S and $\mathbf{B}$ are also equal to unity. Meanwhile, since the length scale of turbulence is finite in size, the correlation of wind pressure decreases as the distance increases. Theoretically, when the building size becomes infinitely large, the lack of correlation diminishes the effects of wind, thus S and $\mathbf{B}$ concomitantly approach zero.

Using Eqs. (14) and (20), the GLF can be expressed as

$$G=1+g\cdot r\cdot\sqrt{\mathbf{B}+\mathbf{R}} \tag{22}$$

in which $r=2I_{\overline{z}}$, and the displacement peak factor g can be computed by

$$g=\sqrt{2\ln(\upsilon T)}+0.5772/\sqrt{2\ln(\upsilon T)} \tag{23}$$

where υ=mean up-crossing rate. Alternatively, Eq. (22) can be expressed in terms of the peak factors associated with the background and resonant response components as given in ASCE 7-98

$$G=1+r\cdot\sqrt{g_B^2\cdot\mathbf{B}+g_R^2\cdot\mathbf{R}} \tag{24}$$

where background peak factor $g_B=g_v$=wind velocity peak factor and g_R=resonant peak factor approximated by setting $\upsilon=f_1$ in Eq. (23).

It is noted that in this study the GLF in Eqs. (22) or (24) is referred to as the standard form in which the following conditions are satisfied:

$$\begin{aligned}&\mathbf{B}\to 1\quad\text{when } B \text{ and } H\to 0\\&\mathbf{B}\to 0\quad\text{when } B \text{ and } H\to\infty\\&S\to 1\quad\text{when } B \text{ and } H\to 0 \text{ or } f\to 0\\&S\to 0\quad\text{when } B \text{ and } H\to\infty \text{ or } f\to\infty\end{aligned} \tag{25}$$

Appendix II: Gust Factors for Wind Velocity/ Pressure

Gust Factor for Wind Velocity

The gust factor for the wind velocity can be defined as

$$G_V^\tau(T)=\overline{V^\tau}/\overline{V^T} \tag{26}$$

The first model for the wind velocity GF is based on the statistical analysis of the meteorological wind-velocity records (Durst 1960). For an open terrain, Durst (1960) provided GFs for some typical averaging times with regard to the mean wind velocity with an observation time of both 10 min and 1 h. Durst's results were employed by ASCE 7-98 in defining the 3 s gust and the 1 h mean wind velocity (Simiu and Scanlan 1996). For exposure C at 10 m height, $G_V^{3\text{ s}}$ (1 h)=1.51 in terms of 1 h mean wind velocity.

The second model is based on wind-velocity spectrum analysis, which introduces a low-pass filter corresponding to the averaging time (Greenway 1979; Solari 1993a). Considering that thewind-velocity fluctuations are a stationary Gaussian process, the gust factor in Eq. (26) can be given by

$$G_V^\tau(T)=[\overline{V^T}+g_v(\tau)\sigma_v(\tau)]/\overline{V^T}=1+g_v(\tau)\cdot I_v(\tau) \tag{27}$$

in which

$$\sigma_v^2(\tau)=\int_0^\infty S_V(f)\kappa(f,\tau)df \tag{28}$$

$$\kappa(f,\tau)=\sin^2(\pi f\tau)/(\pi f\tau)^2 \tag{29}$$

$$n_0(\tau)=\left(\int_0^\infty f^2 S_v(f)\kappa(f,\tau)df \bigg/ \int_0^\infty S_v(f)\kappa(f,\tau)df\right)^{1/2} \tag{30}$$

$$g_v(\tau)=\sqrt{2\ln[n_0(\tau)T]}+0.5772/\sqrt{2\ln[n_0(\tau)T]} \tag{31}$$

A closed-form solution of the wind velocity gust factor was provided by Solari (1993a)

$$G_V^\tau(T)=1+g_v(\tau)\times I\times\sqrt{\mathsf{P}_0(\tau)} \tag{32}$$

in which $I=\sigma_v^T/\overline{V^T}$=turbulence intensity; $g_v(\tau)=\{1.175+2\ln(\tilde{T}\sqrt{\mathsf{P}_1/\mathsf{P}_0})\}^{1/2}$; $\mathsf{P}_0=1/(1+0.56\tilde{\tau}^{0.74})$; $\mathsf{P}_1/\mathsf{P}_0=1/(31.25\tilde{\tau}^{1.44})$; $\tilde{\tau}=\tau\overline{V}_z/L_z$; $\tilde{T}=T\overline{V}_z/L_z$. For ASCE 7 use, $\tau=3$ s, $T=3{,}600$ s, thus $g_v(\tau)=3.41$ and $\mathsf{P}_0=0.723$ (Solari and Kareem 1998). Applying this relationship to the reference wind velocity where I is close to 0.2, the gust factor $G_V^{3\text{ s}}$ (1 h)=1.58. The difference between this approach and Durst's result is 4.6%. Nevertheless, some inconsistencies have been found in other wind exposures (Zhou and Kareem 2002). In ASCE 7-98 code, the gust factor in Eq. (32) is incorporated in the overall GLF as outlined in Eq. (3). The inconsistency due to the application of both spectral model (Solari 1993a) and statistical model (Durst 1960) in ASCE

7 manifests itself in the numerical example. More detailed information can be found in Zhou and Kareem (2002).

AS1170.2-89 and Eurocode employed a similar simplified procedure

$$G_V = 1 + g_v \times I \tag{33}$$

involving peak factors of 3.7 and 3.5, respectively.

Gust Factor for Wind Velocity Pressure

Similarly, when neglecting the contribution of the quadratic fluctuating wind-velocity term, the wind-velocity pressure is also Gaussian. The gust factor for the wind-velocity pressure can then be related to the wind velocity GF by (Solari 1993a)

$$G_q = 2G_v - 1 \tag{34}$$

This formulation was employed by ASCE7-98 and Eurocode.

On the other hand, when simply using the square rule, the wind-velocity pressure GF can be computed by

$$G_q = G_v^2 \tag{35}$$

This relationship is used in AS1170.2. The contribution of the quadratic wind velocity was included in AS1170.2 (Vickery 1995). A detailed consideration of the contribution of the quadratic wind velocity can be found in Zhou and Kareem (unpublished).

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