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AN ANALYTICAL MODEL FOR THE ALONGWIND DESIGN WIND LOAD OF TALL BUILDINGS

Chii-Ming Cheng[1], Ming-Shu Tsai[2] and Yuan-Lung Lo[3]
[1] *Director, Wind Engineering Research Center, Tamkang University Tamsui, Taipei County 251, Taiwan, cmcheng@mail.tku.edu.tw*
[2] *Research Associate, Wind Engineering Research Center, Tamkang University, Tamsui, Taipei County 251, Taiwan, austine@mail.tku.edu.tw*
[3] *Doctoral program, Department of Socio-cultural Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, loren@load.k.u-tokyo.ac.jp*

ABSTRACT

An analytical model for tall buildings' alongwind Equivalent Static Wind Loads is proposed. The basic assumptions, procedures and the parameters used in this model are mainly based on the results of wind tunnel investigation. In this model, the mean and RMS wind pressures on the leeward face are uniformly distributed. A moment effect based correlation reduction factor for background component is introduced to amend the difference of spatial correlation between ESWL and dynamic wind load. Building mode shape and inertia force distribution are adopted in the derivation of the resonant part of ESWL. The proposed model is compared with the current Taiwan building code and the results from Finite Element analysis of two prototype tall buildings. The result indicates that the proposed model with minor adjustment can yield reasonably accurate estimation of alongwind design wind load for tall buildings.

KEYWORDS: TALL BUILDINGS, ALONGWIND, EQUIVALENT STATIC WIND LOADS, GUST LOADING FACTOR, ANALYTICAL MODEL, WIND TUNNEL DATA.

Introduction

For most of the wind codes in the world, the alongwind design wind load of a tall building at height z adopted the equivalent static wind load (ESWL) format, which is based on the gust loading factor approach. Recently, modification has been proposed mainly in two areas: (i) adopting the moment-based gust loading factor (MGLF) to replace the traditional displacement based gust loading factor (DGLF) (Zhou and Kareem 2001); (ii) the resonant part of ESWL having the span-wise distribution similar to the inertia force. The second modification will make significant difference on design wind load, especially for the resonant part dominated flexible tall buildings. Many current alongwind design wind loads are calculated based on the following assumptions: (a) using drag coefficient, C_D, and wind velocity pressure at height z, (b) using the quasi-steady and strip theories to formulate the dynamic wind load for both windward and lee-ward side of wind load. However, wind tunnel measurements suggest that the quasi-steady and strip theories are valid for the windward side only. The leeward side is under the influence of the wake flow, therefore exhibits different characteristics from the windward side.

The Equivalent Static Design Wind Load (ESWL)

If the wind loads on the windward and leeward sides of isolated rectangular shaped buildings are normalized to the local wind pressure and building height wind pressure, respectively, then both the mean and RMS wind loads vary only slightly along the building height, as shown in Figure 1. Based on these laboratory observations, the following assumptions are used in the following derivation of building ESWL.

(1)The mean and dynamic wind forces on the windward face follow the strip theory strictly; the wind forces on the leeward face assumed to be uniform. (2)The windward pressure coefficients, C_W, is constant with respect to the local wind speed, *U(z)*; the leeward pressure coefficient, C_l, is constant with respect to wind speed at building height, U_H. (3)The lateral and longitudinal (windward vs. leeward) coherences at 2/3 of building height are used as the general form for entire building. (4)The spatial correlation effect on the background part of equivalent static wind load is amended by a moment-based correlation reduction factor. (5)The resonant part is distributed based on the distribution of the inertia force. (6)Building has uniformly distributed mass and fundamental mode shape of $\phi(z)=(z/H)^{\beta}$.

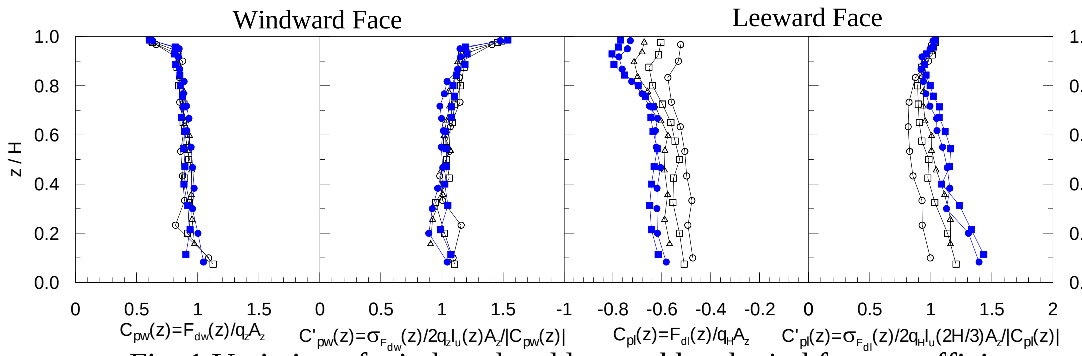

Fig. 1 Variation of windward and leeward local wind force coefficients.
(*BL-B*; *D/B=1*; $H/\sqrt{BD}$ =○:3, □:4, △:5, ●:6, ■:7)

In order to conforming to the current building wind code, the gust response factor approach is adopted to develop the alongwind ESWL. The ESWL at height z can be expressed in the following form:

$$D(z)=\bar{F}_D(z)+F_D(z)=G(z)\bar{F}_D(z) \tag{1}$$

where z is height, $D(z)=$ alongwind ESWL, $\bar{F}_D(z)=$ mean component of ESWL, $G(z)=$ gust response factor, $g_D=$ peak factor, $F_D(z)=$ dynamic component of ESWL, which can be further divided into the background part, $F_{D,B}(z)$, and the resonant part, $F_{D,R}(z)$:

$$F_D(z)=\sqrt{g_B^2F_{D,B}^2(z)+g_R^2F_{D,R}^2(z)} \tag{2}$$

Where g_B and g_R are peak factors for background part and resonant part, respectively.

$$g_B=3.4;\ g_R=\sqrt{2\ln(f_0T)}+0.5772/\sqrt{2\ln(f_0T)}\ ;\ T=3600s$$

The mean wind load has the form of,

$$\bar{F}_D(z)=\frac{1}{2}\rho U_H^2B\left[(z/H)^{2\alpha}C_W+C_l\right] \tag{3}$$

The ESWL for the RMS of the background part is

$$F_{D,B}(z)=\lambda_Q\rho U_H^2BI_{2/3H}\left[(z/H)^{\alpha}C_W+C_l\right] \tag{4}$$

The ESWL for the RMS resonant part is

$$F_{D,R}(z)=\lambda_R\left(2\beta+1\right)\left(\rho U_H^2BI_{2/3H}\right)(z/H)^{\beta}\left[\pi f_0\chi_R(f_0)S_u^*(f_0)/(4\xi)\right]^{\frac{1}{2}} \tag{5}$$

The Gust Loading Factor can be expressed as $G(z)=1+F_D(z)/\bar{F}_D(z)$, in which

$$\frac{F_D(z)}{\bar{F}_D(z)}=2I_{2/3H}\frac{\left\{g_B^2\lambda_Q^2\left[(z/H)^{\alpha}C_W+C_l\right]^2+\left[g_R^2\lambda_R^2\left(2\beta+1\right)^2(z/H)^{2\beta}\pi f_0\chi_R(f_0)S_u^*(f_0)/(4\xi)\right]^2\right\}^{1/2}}{(z/H)^{2\alpha}C_W+C_l} \tag{6}$$

Case Study: Comparison Of Building Design Wind Loads

Descriptions Of Test Buildings

Two prototype rectangular shape buildings were used for the comparative studies, as shown in Table 1. The commercial software, MIDAS, was used to build FE models and carry out the subsequent dynamic analyses.

Table 1 Parameters of Test Buildings

case	depth *D(m)*	width *B(m)*	height *H(m)*	*D/B*	$H/A^{1/2}$	density *(kg/m³)*	no. of story	dampin g ratio	fundamental frequency $f_0(Hz)$	β of $(z/H)^{\beta}$
1	17.32	51.96	90	1/3	3	276	25	0.01	0.401	0.95
2	17.32	51.96	180	1/3	6	276	50	0.01	0.210	1.40

The instantaneous pressure data of wind tunnel test was applied directly to the structural nodes as the input wind loads for the FE analysis. Each level of pressure data on the pressure models in wind tunnel test represents wind load acting on more than one story of the prototype buildings. Since no extra interpolating scheme was used to adjust the wind load time history, it should be noted that the time history analysis tends to be conservative due to the effect of higher span-wise correlation in the wind tunnel data. The modal superposition scheme of the lowest 10 modes was used instead of direct integration for the time efficiency. It was found that the difference of the maximum base shear between two methods is about 1%. It was also found that using only fundamental mode would result in base shear a few percentages less than the direct integration. Since it is difficult to differentiate the weighting between background and resonant component in the time domain analysis, the resonant adjustment coefficient λ_R=1.00 was used in this study.

Wind load time history equivalent to 1 hour in prototype was use in each case of time domain analysis. The sums of column shear at each story that corresponds to the maximum base shear were calculated and compared with the wind code and the present analytical model. Since the background part and the resonant part can not be differentiated in the time domain analysis. To avoid the possible deviation from the effects of peak factors, g_B and g_R, the peak values of time domain analysis are obtained from multiplying the RMS response with the same peak factors used in the analytical model.

Comparison Of Design Wind Loads

Shown in Figure 2 are the comparisons of the story shear of two prototype buildings with side ratio *D/B=1/3*, in urban, suburban and open terrain flow fields i.e., *BL-A*, *BL-B* and *BL-C*, respectively. The comparisons includes story shear calculated from: (i) the proposed model, (ii) Taiwan building wind code (similar to ASCE7-02) and, (iii) wind tunnel data + FE model. Figure 2 shows that, for both the 90m and 180m tall buildings in urban flow field, BL-A, building story shear predicted by the proposed model agrees quite well with the FE model. The story shear of both buildings estimated according to the current Taiwan building wind code are significantly less than the other two methods. For open terrain flow field, data shows that base shear predicted by the proposed model is 10~15% less than the FE analysis for both prototype buildings.

Ideally, an ESWL procedure should be slightly conservative to be adopted into building wind code; and some leaning-to-conservative assumptions are made during model development for this reason. The predictions of the proposed ESWL model less than the FE analysis in some cases are mainly due to two reasons: (i) a value greater than 1.0 should be used for the resonant adjustment coefficient, λ_R, (ii) in the FE analysis, the wind load time history obtained from wind tunnel test is higher than the actual wind load due to the perfect special correlation between two consecutive level of pressure taps. The difference between proposed model and FE analysis becoming large in the open terrain flow field is likely due to that the span-wise correlation in *BL-C* is significantly less than *BL-A* and *BL-B*. In term of the coefficient of the span-wise coherence function, C_Z is found to be 8 and 14 for the 90m and 180m buildings in *BL-C* flow field, compare to C_Z =4.5 and 7 in *BL-A*, and C_Z =5.5 and 8 in *BL-B*. Consequently, the effect of higher span-wise correlation of wind load time history becomes more noticeable in *BL-C*.

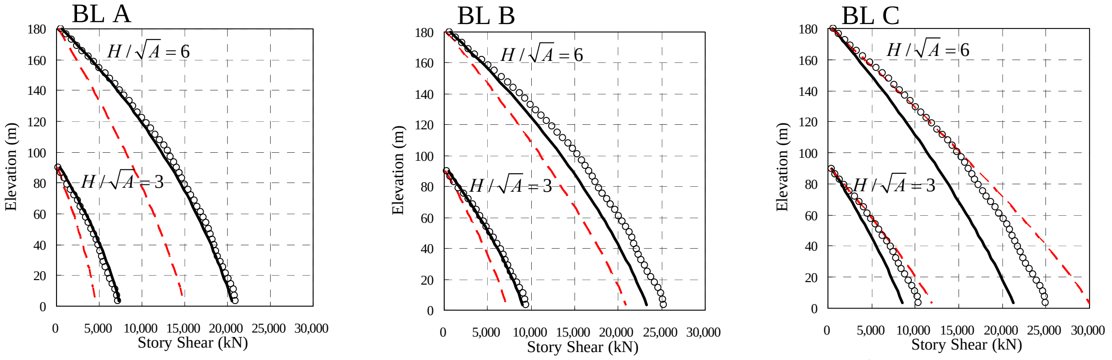

Fig.2 Comparisons of building story shear.(—:Present; ---:Wind Code;◯:Wind Tunnel＋F.E.)

Conclusions

A modified analytical model for tall buildings' alongwind design wind loads is proposed. The basic assumptions, procedures and the parameters used in this proposed model are mainly based on the results of wind tunnel investigation. In this model, the mean and RMS wind pressures on the leeward face are uniformly distributed. A moment effect based correlation reduction factor for background component is introduced to amend the difference of spatial correlation between ESWL and dynamic wind load. Building mode shape and inertia force distribution are adopted in the derivation of the resonant part of ESWL. The Finite Element models of two prototype tall buildings were constructed for comparative studies. The story shear based on the proposed model is then compared with the current Taiwan building code and the results from detailed Finite Element analysis. The result indicates that the proposed model with minor adjustment can yield reasonably accurate and yet slightly conservative estimation of alongwind design wind load for tall buildings.

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