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Aero-Data Based Wind Resistant Design of Rectangular Shaped Tall Buildings

Jenmu Wang[1] and Chii-Ming Cheng [2]

[1]Associate Professor, Department of Civil Engineering, Tamkang University,
New Taipei City 25137, Taiwan, wang@mail.tku.edu.tw

[2] Professor, Department of Civil Engineering, Tamkang University
New Taipei City 25137, Taiwan, cmcheng@mail.tku.edu.tw

***Abstract*:** *This article presents the development of a wind tunnel aero-data based wind resistant design procedure for tall buildings. The objective is to provide more accurate design wind loads than the current wind code is capable of. The major works involve conducting large amount of wind tunnel experiments of rectangular tall buildings and formulating calculation models for alongwind, acrosswind and torsional design wind loads. The main challenge of the work is to be able to provide enough incentives to justify the extra effort needed from engineers. On the other hand, the tradeoff between wind load accuracy and calculation complexity needs to be carefully considered. Therefore, the development of artificial neuron networks and easy-to-use computer programs to facilitate the engineering application of the methodology were performed.*

Keywords: *Design Wind Loads, Aerodynamic Database, Artificial Neural Networks, Wind Tunnel, Building Wind Code, Web Programming*

1. Introduction

Wind effects on high-rise buildings include wind load on structural system, cladding pressure, habitants' serviceability and pedestrian level wind environment. Wind load acting on structural system, which could be essential for certain high-rise buildings, should be evaluated base on accurate buildings' response estimations. For most of the tall buildings, the design wind loads are determined by elaborate physical modeling via wind tunnel experiment. Prior to wind tunnel experiment, the building geometry and structural system are decided, in other words, the two most important factors that affecting buildings' wind loads are set and, in most case, will be costly to change. At the present, wind code is used to provide preliminary design wind loads. However, wind code is constructed based on the wind loads data of isolated square (or rectangular) shaped buildings. It could be very conservative for tall buildings other than rectangular shape or buildings with shielding effect. On the other hand, it could be underestimated for very tall buildings, buildings with flexible structural systems or some particular interfering effects from adjacent buildings. If preliminary design wind loads can be obtained handily and with reasonable accuracy, then it could be used interactively with the building design process. So, the objective of this research project is to build a wind tunnel aero-data based wind resistant design guide for tall buildings, which has an intermediate function between wind code and actual wind tunnel simulation.

Adopting aerodynamic database to assist wind resistant design has been promoted and developed in many wind engineering institutes, such as Kareem [1] and his associates Zhou et al [2] at University of Notre Dame, Tamura and his associates [3] at TPU, Kopp and Chen [4] at NIST, Cheng [5] and Wang [6] at Tamkang University (TKU). The construction of a database of rich and accurate contents is a tedious work. But the real challenge is how to put these data into good use. The following sections of the paper describe the wind tunnel experiments, the design wind load calculation procedure and the aero-data based coefficient and parameter estimation methods. Also, the resulted computer programs are presented and the examined cases are discussed at the end.

2. Wind Tunnel Tests

All wind tunnel tests were conducted in an open-circuit, suction type wind tunnel with test section of 17m(L) × 2m(W) × 1.5m(H). Three turbulent boundary layer flows, designated by BL-A, BL-B, BL-C, with power law index α=0.32, 0.25, 0.15, respectively, were generated to represent wind profiles over urban, suburban and open country terrains. During model testing, velocity at model height, UH, was taken as the normalization factor for the reduced velocity, $Ur=U_H/f_0D$. Blockage ratio is less than 5%, therefore, its effect ignored. Reynolds number for the upper half of the testing model was kept greater than 4×10^4 which is higher than Re,cr$\fallingdotseq 2\times10^4$ required for Reynolds number similarity.

The geometry variations of the pressure models are: 13 sets of aspect ratios for H/ = 1 to 7; 13 sets of side ratios for D/B= 1/5 to 5/1. Acrylic pressure models and high speed electronic pressure scanner system were used in this set of wind tunnel experiment. A typical experiment setup is shown in Figure 1. For models with aspect ratio 7, 380 pressure taps were installed on 15 levels along the model height; and 9 levels, 230 pressure taps for models with aspect ratio 3. The sampling rate was 200Hz and the sample length was 287 seconds. Besides the conventional mean and RMS base force coefficients and spectra, local force characteristics and various force coherences were studied.

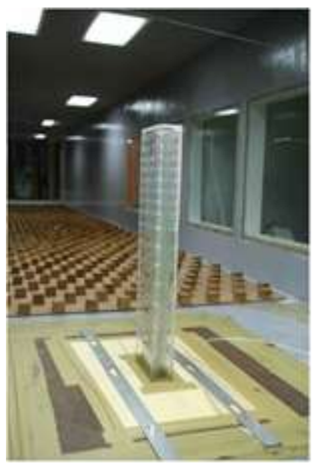

Fig. 1: Experimental Setup in the Wind Tunnel I at TKU

3. Design Wind Load Models

This section explains the wind load calculation procedure developed, which consists of three parts, alongwind, acrosswind and torsional wind loads.

3.1. Alongwind Design Wind Load

During the development of the present model, the wind load is divided into two parts, i.e., windward and leeward force coefficients, C_{DW} & C_{DL}, are used to replace the single drag coefficient, C_D. The basic assumption is that mean and dynamic wind forces on the windward face follow the strip theory and quasi-steady theorem; the wind force on the leeward face is assumed to be constant with respect to the reference wind speed, U_H. The mean component of the alongwind design wind load can be expressed in the form of

$$\overline{F}_D(z) = 1/2\rho U_H^2 B((z/H)^{2\alpha} C_{DW} + C_{DL}) \quad (1)$$

Where ρ is air density, B is building width and α is power law exponent.

The Equivalent Static Wind Load (ESWL) for the RMS of the background part can be expressed by:

$$F_{D,B}(z) = \lambda_D \rho U_H^2 B I_{2/3H}((z/H)^{\alpha} D_{DW} + C_{DL}) \quad (2)$$

λ_D is a reduction factor to account for the imperfect spatial correlation of fluctuating wind loads between the windward-leeward faces and along the building height.

The equivalent static load for the RMS resonant part is assumed to have same distribution as the inertia force. Assuming the building mass is uniformly distributed and model shape has the form of $\varphi(z)=(z/H)\beta$, the resonant component of wind load at height z, $F_{D,R}(z)$, can be expressed as:

$$F_{D,R}(z) = (2\beta+1)(\rho U_H^2 B I_{2/3H})(z/H)^{\beta}(\pi f_0 \chi_R(f_0) S_u(f_0)/4\xi)^{1/2} \quad (3)$$

Where $S_u(f_0)$ is a normalized wind velocity spectrum, and $\chi_R(f)$ is an aerodynamic admittance function in the generalized coordinate. $\chi_R(f)$ is a complex function of several flow field and structural parameters can be acquired through lengthy calculations.

The alongwind design wind load is:

$$D(z) = \overline{F}_D(z) + (g_B^2 F_{D,B}^2(z) + g_R^2 F_{D,R}^2(z))^{1/2} \quad (4)$$

3.2. Acrosswind And Torsional Design Wind Load

The acrosswind design wind load $W_L(z)$ for a rectangular building at height z can be calculated as follow:

$$W_L(z) = (g_{L,B}^2 F_{L,B}^2(z) + g_{L,R}^2 F_{L,R}^2(z))^{1/2} \quad (5)$$

The background part of the fluctuating wind load $F_{L,B}(z)$ at height z is calculated according to the following equation:

$$F_{L,B} = q(H)\lambda_L C_L(z) D \quad (6)$$

The resonant part of the fluctuating wind load $F_{L,R}(z)$ at height z is calculated according to the following equation:

$$F_{L,R}(z) = (2\beta+1)(1/H)(z/H)^{\beta}(\pi f_a S_{F_L}(f_a)/4\xi)^{1/2} \quad (7)$$

where $C_L(z)$ is the fluctuating lift coefficient at height z; λ_L is the space correlation correcting factor for $C_L(z)$; and $S_{FL}(f_a)$ is the normalized acrosswind lift force spectrum value corresponding to the natural frequency of a structure in acrosswind direction.

The torsional design wind load $W_T(z)$ for a rectangular building at height z can be calculated as follow:

$$W_T(z) = (g_{T,B}^2 F_{T,B}^2(z) + g_{T,R}^2 F_{T,R}^2(z))^{1/2} \quad (8)$$

The background part of the fluctuating torsional wind load $F_{T,B}(z)$ at height z is calculated according to the following equation:

$$F_{T,B} = q(H)\lambda_T C_T(z) BD \quad (9)$$

The resonant part of the fluctuating torsional wind load $F_{T,R}(z)$ at height z is calculated according to the following equation:

$$F_{T,R}(z) = (2\beta+1)(1/H)(z/H)^{\beta}(\pi f_T S_{F_T}(f_t)/4\xi)^{1/2} \quad (10)$$

where $C_T(z)$ is the fluctuating moment coefficient at height z; λ_T is the space correlation correcting factor for $C_T(z)$; and $S_{FT}(f_t)$ is the normalized torsional wind force spectrum value corresponding to the natural frequency of a structure in torsional direction.

4. Estimations on Functions and Parameters

Artificial neural networks (ANNs) were used to estimation the wind force coefficients and spectral values required for using the wind load calculation equations in the above section. In terms of wind force coefficient estimation, neural networks were used to train, simulate and forecast wind coefficients using terrain exposure, side ratio and aspect ratio as inputs. The neural networks investigated include BP (Back Propagation), RBF (Radial Basis Function) and GR (General Regression) neural networks. According to our evaluation, RBFNN has the best results [7]. The network architectures shown in Figure 2 are our current alongwind force coefficient modification schema.

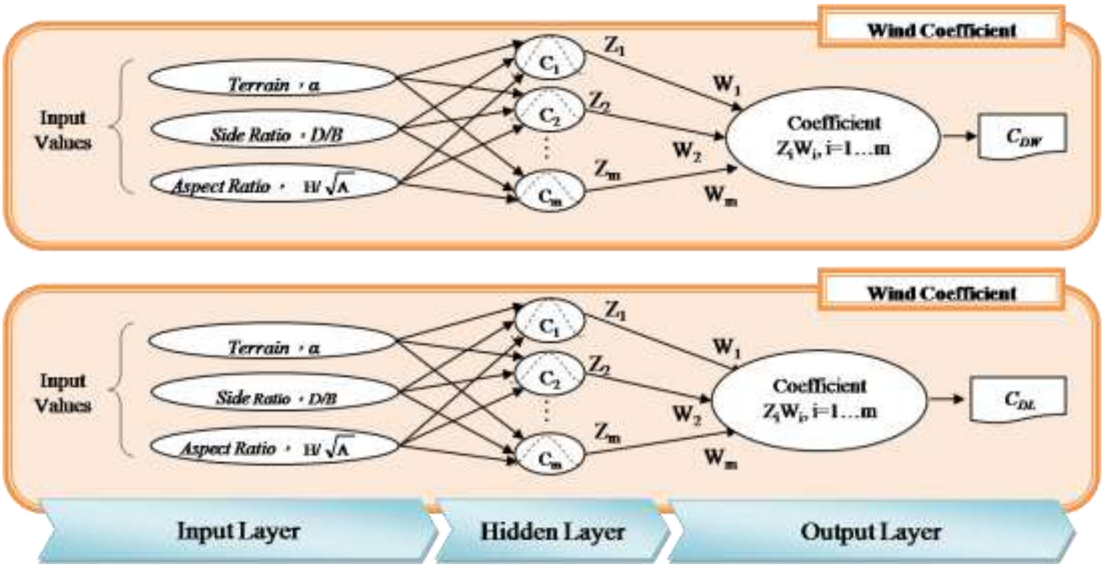

Fig. 2: The ANN Schema for Alongwind Force Coefficient Prediction

For predicting the wind force spectra of high-rise buildings under specific conditions, usually the known values are: terrain exposure, aspect ratio and side ratio. The intended output is the spectrum value at a particular non-dimensional frequency. After extended study of using ANNs to predict wind force spectra [8], the following conclusions have be reached. Alongwind, acrosswind and torsional spectra should be trained independently owning to the different characteristics among them. After numerous trials, Radial Basis Function Neural Networks (RBFNN) was selected and the network architecture (see Figure 3) finally set with four neurons, terrain exposure, aspect ratio, side ratio and non-dimensional frequency for the input layer, and one output, the spectrum value of the corresponding frequency. A fixed Gaussian function was used in our RBFNN. For the wind load calculation procedure presented in this paper, alongwind spectrum is not required. Therefore, a total of 12 ANNs were trained for acrosswind spectra, and another 12 ANNs are required to estimate torsional spectra.

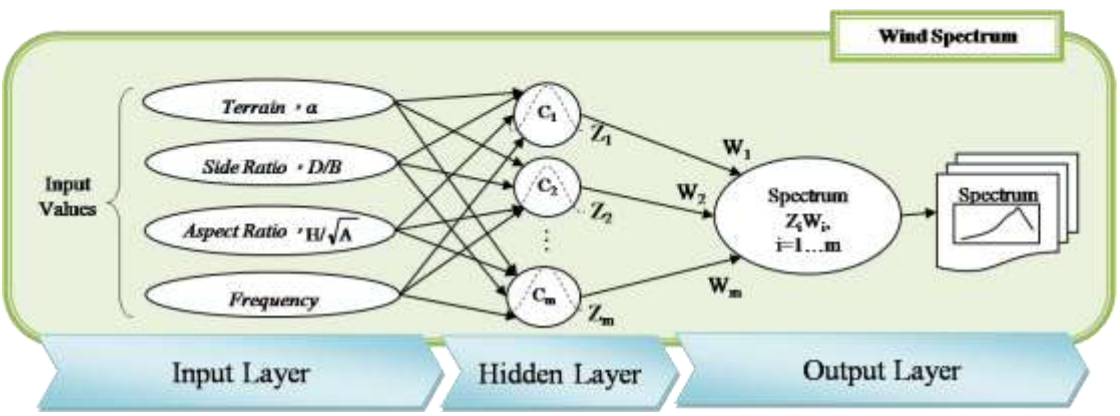

Fig. 3: The ANN Schema for Wind Spectrum Prediction

To ease the burden of using the above mentioned design wind load analysis model, all the equations, functions, and ANNs are coded in Matlab. A friendly user interface is warp around the programs to form a software package. Two versions of the software are provided, a PC and a web version. Shown in Figure 4 are Web Pages for the Aero-Data Based Wind Load Analysis System.

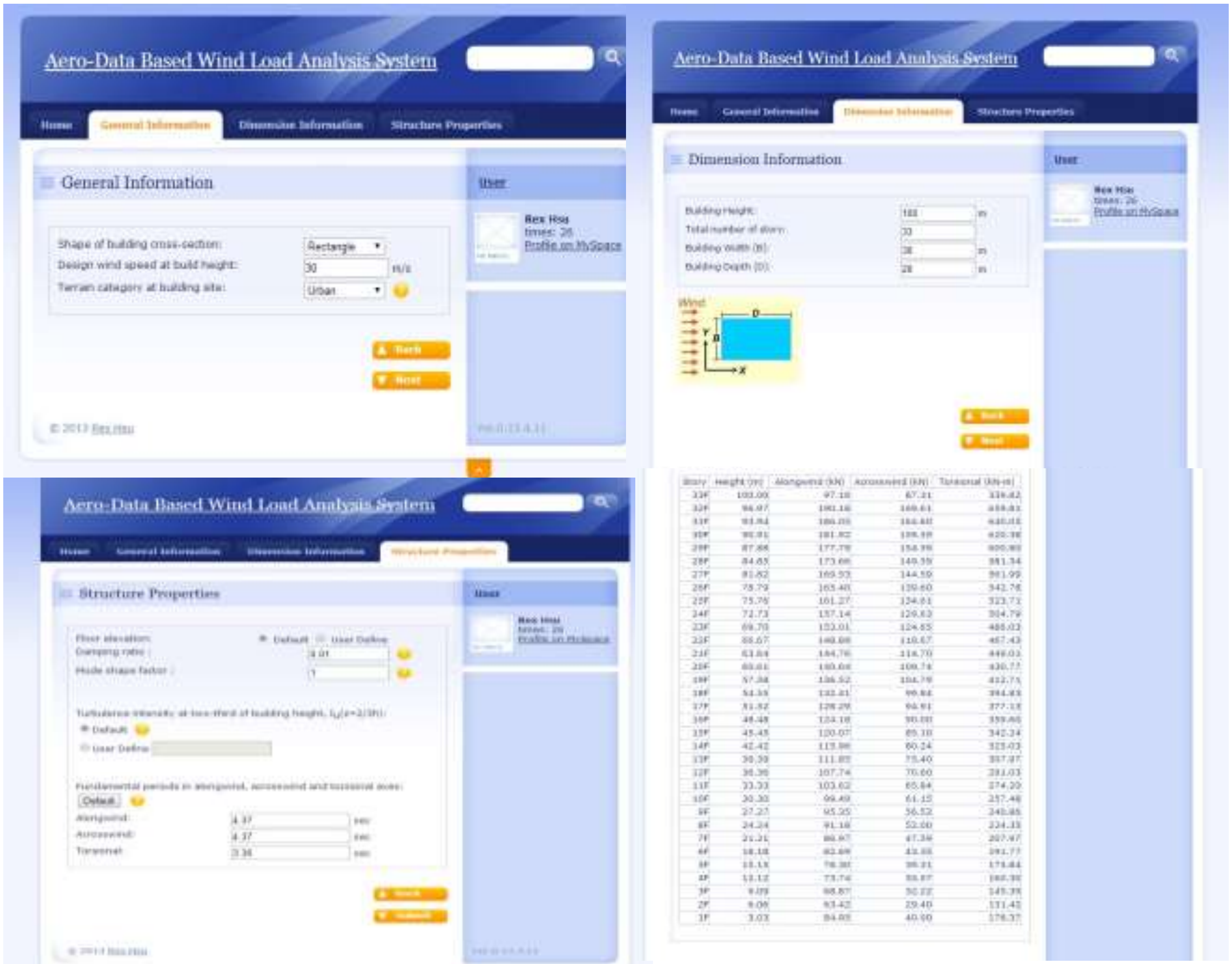

Fig. 4: Web Pages for design wind loads of tall buildings (http://dbwl.wind.org.tw/en)

5. Cases Study

The proposed alongwind design wind load model is compared with design wind load calculated based on the time domain analysis of the wind tunnel measured wind loads. Prototype rectangular shaped buildings of side ratio, D/B=1/5, 1/3, 1/1, 3/1, 5/1, with aspect ratio $H/\sqrt{BD}$ =3, 6, were used for the comparative studies. All buildings have the same cross-sectional area, A=900m^2, i.e., the building heights are, H=90m and 180m. The building density is 276 kg/m^3 and the structural damping is 0.01. The stiffness was adjusted so that the fundamental periods of the test buildings roughly equals to 1/10 of the building stories. Linear mode shape, β=1.0, was used for the proposed model. Shown in Figures 5, 6 and 7 are the comparisons of design wind loads calculated from the present model and design wind loads obtained based on the time domain analyses of applying one hour wind load time history on building finite element models. Generally speaking, the predictions from present model are in good agreement with the results from time domain analysis. The differences between two schemes may come from the following sources:

(1) Aerodynamic assumptions in proposed model,

(2) Linear mode shape used in proposed model is different from the FE model

(3) Linear interpretation scheme used to deploy wind load time history to FE models may cause error in the force spatial correlations, and

(4) Inherent random nature in time domain analysis.

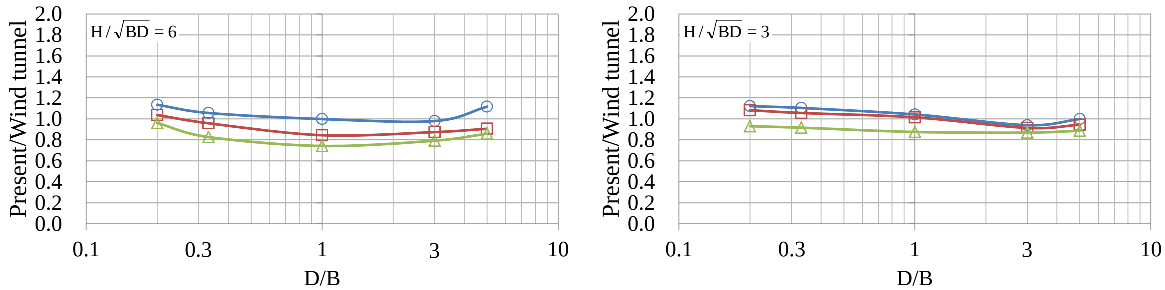

Fig. 5: Comparisons of alongwind base shear between present model and time domain analysis (○BL-A □BL-B ∆BL-C)

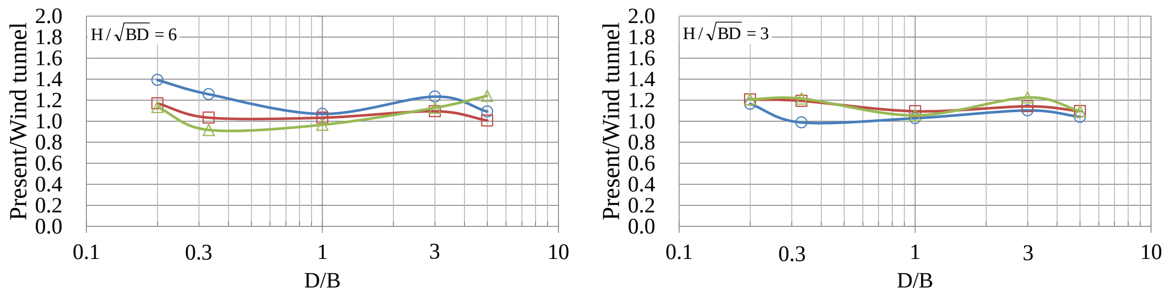

Fig. 6: Comparisons of acrosswind base shear between present model and time domain analysis (○BL-A □BL-B ∆BL-C)

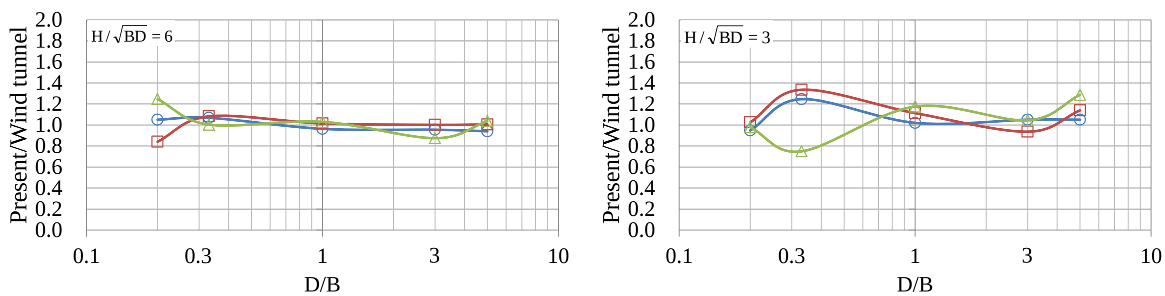

Fig. 7: Comparisons of base torque between present model and time domain analysis (○BL-A □BL-B ∆BL-C)

The present design wind load models were then compared with current building wind code which the alongwind load is similar to ASCE7 and the acrosswind and torsional wind loads are adopted from AIJ recommendations. For alongwind design wind loads, comparing to the proposed model, the current Taiwan building wind code (similar to ASCE7) is at least 20% over-estimated in open country terrain; slightly under-estimated in suburban terrain; significantly under-estimated in urban terrain. For the acrosswind design wind load, Taiwan wind code (similar to AIJ recommendation) is overestimating in open country terrain especially for shallow and tall buildings; in good agreement with present model in suburban terrain for buildings with aspect ratio 1 and above; significantly under-estimated in urban terrain. With regard to torsional design wind loads, the comparisons are as follows: for aspect ratio 3, Taiwan wind code (similar to AIJ recommendation) always underestimates the torsional wind loads; for aspect ratio 6, wind code usually overestimates the torsional wind loads.

6. Conclusions

WERC at TKU has been working on tall building aerodynamic databases for many years. The work reported here expanded the existing aerodynamic database to a much broader building geometric range: $H/\sqrt{BD}$ = 1 to 7 and B/D=1/5 to 5/1. A wind load analysis model was developed based on the established database. To reduce the complexity of calculation, the tedious and complex integrations in the wind load procedures were replaced by pre-calculated functions and parameters, which shorten the computer time from 4-5 minutes to less than 20 seconds. Extra efforts were put to improve the multi-variable regression and ANN models used in wind load procedures to retrieve and adjust the wind loads parameters from the aerodynamic database. A stand-alone PC program and an Internet-based web application with user-friendly interface and build-in design wind load procedures were then built so that the building designer can acquire the design wind loads handily.

Comparing with the results of time domain analysis using wind tunnel time histories and the present design wind load models exhibited satisfactory accuracy. The present design wind load models were then compared with current building wind code. The significant differences shown in the comparing cases suggested that the current building code tends to underestimate the alongwind and acrosswind loads in the terrain category A; overestimate both wind loads in terrain category C. For building aspect ratio less than 3, building wind code significantly underestimate torsional wind load in both terrain categories A and B. In short the current building wind code has its limitations needs to be improved in the future.

7. Acknowledgements

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