Building Economics of Wind-Engineered Tall Structures –
Part 1: Empirical Response Formulae of Corner-modified Buildings

K. T. Tse, K.C. S. Kwok and P. A. Hitchcock,
CLP Power Wind/Wave Tunnel Facility, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R.China
C. M. Chan,
Department of Civil Engineering, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R.China
R.O. Denoon
CPP, Inc., Colorado, USA

Abstract: This paper investigates the impact and value of wind engineering modifications on the building economics of tall structures. Economic factors often influence design decisions more than any other single factor and should be well understood. Aerodynamically efficient plan shapes are shown to be an effective means of suppressing cross-wind loads, and hence construction cost, but may come at the cost of reducing both the size and value of saleable/rentable floor area. Therefore, it is not straightforward for engineers to decide on the size and type of corner modifications with regard to both the structural responses and the effects on economic rewards. A series of wind tunnel tests of building models with different corner modifications was conducted at the CLP Power Wind/Wave Tunnel Facility, The Hong Kong University of Science and Technology. In Part 1 of this study, details and the methodology for the high-frequency force balance (HFFB) tests are presented. Empirical formulae are also proposed to relate the cross-wind responses to the building dimensions. In Part 2, the construction costs and financial returns of tall buildings will be discussed. The empirical formulae proposed in Part 1 will also be employed to assess optimal building dimensions with respect to financial profits.

1.0 INTRODUCTION

It has been proved that modifying the shape of tall buildings can significantly affect cross-wind loading and hence the wind-induced response. Kwok and Bailey (1987), Kwok (1988), Melbourne (1989), and Melbourne and Cheung (1998) studied modifying the building planforms by rounding or chamfering corners and modifying the building shape further to polygonal plan forms. Tapering, cutting corners or progressively removing corners were also found to reduce wind-induced responses. Further studies of corner modifications and introducing vertical slots have been conducted by Dutton and Isyumov (1990), Miyashita el al. (1993) and Kawai (1998) for nominally square planform buildings to reduce wind-induced vibrations, although without any consideration of the effects that these modifications will have on other building issues. The impact of tall building shape on the street level wind environment has also been investigated by a number of researchers (Jamieson et al., 1992; Stathopoulos, 1985; Uematsu et al., 1992).

A tall building's aerodynamic efficiency may be improved by employing various corner modifications and treatments. However, an aerodynamically efficient plan shape may come at the cost of usable floor area that, in turn, may require additional compensatory storeys, which obviously increase the wind loads and construction cost again. A less-efficient planform in terms of interior space-planning may also recoup lower rental or sales returns. On the other hand, additional upper level storeys, have the potential to increase revenue. Therefore it is not straightforward to decide on the size and type of corner modification.

The purpose of the current study is to determine the cross-wind loads of nominally square buildings with different sizes of recessed and chamfered corners while increasing the number of storeys to maintain the same usable floor area. Empirical formulae, which are to be employed in the optimization formulation in Part 2, are then proposed relating the wind-induced cross-wind response to the number of storeys, which in turn is intrinsically related to the size of the corner modifications.

2.0 WIND TUNNEL TESTS

2.1 Building models

The building models used for the current study were variations of a 1:400 scale reference building, having a basic square shape with dimensions equivalent to 48 × 48 × 240 m (B × D × H). Different sizes of corner modification were sequentially introduced to the reference building and are listed in Table 1. To maintain the same usable floor area, additional storeys were required to compensate for the floor area lost in the corner modifications, resulting in changes in building height and natural frequency. Schematic diagrams of the building models with modified corners and different heights are illustrated in Figure 1.

Table 1. Building Characteristics

storey, N	H (m)	Freq (Hz)	chamfer	recess
60	240	0.208	0% (REF)	0% (REF)
61	244	0.205	9% (CH1)	6% (RE1)
62	248	0.202	13% (CH2)	9% (RE2)
63	252	0.198	15% (CH3)	
64	256	0.195		13% (RE3)
66	264	0.189	21% (CH4)	
67	268	0.187		16% (RE4)
70	280	0.179	27% (CH5)	19% (RE5)

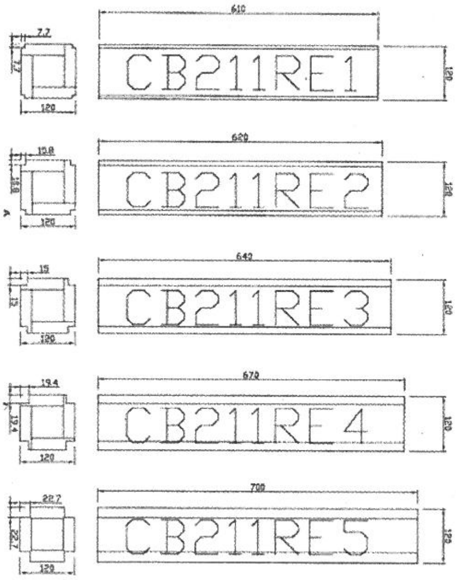

Figure 1. schematic diagrams of recessed corners

The modelled buildings have aspect ratios (H/B) ranging from 5 to nearly 6, and prototype scale natural frequencies, n, ranging from 0.208 to 0.179 Hz, which are based on a commonly-used equation for steel buildings (Tamura et al., 2000; Suda et al., 1996),

$$n = 50/H, \qquad (1)$$

Assuming that the mean wind speed at building height for serviceability design is about 40 m/s, their reduced frequencies range from just above 0.2 to nearly 0.25.

2.2 Test setup

High-frequency force balance models were fabricated from a composite of an aluminium core and medium-density foam skins to provide model/balance natural frequencies greater than 70 Hz, which is approximately 3 times higher than the building natural frequency in model scale.

The simulated wind model corresponded to AS/NZS 1170.2:2002 (Australian/New Zealand Standard 2002) Category 2 terrain. It was established using a combination of trip boards and roughness elements over a 21m fetch length. In order to achieve a minimum Reynolds number of 5×10^4, as recommended by AWES-QAM-1-2001 for a building model with sharp corners, the tests were carried out at velocity scale of approximately 1:4, resulting in a time scale of about 1:100. Similarly, the frequency ratio was 100:1 and the sampling frequency was 400 Hz. Measurements were taken at every 22.5° from 0° to 90°, where 0° corresponds to wind normal to the building face.

3.0 RESULTS

3.1 Normalized PSDs

The magnitudes of the power spectral densities (PSDs) of cross-wind base over-turning moments, shown in Figure 2, were normalized by the same quantity for each building configuration, $M_o^2 = (\rho U^2 B H^2/2)^2$, where U is the mean wind speed at the reference building height, B is the reference building breadth, and H is the reference building height. Reduced frequencies were determined using building breadths and mean wind speeds at building heights corresponding to each specific building configuration tested, thereby allowing the critical reduced frequencies to be identified easily.

It can be seen that the critical reduced frequency shifts from ~0.09 (reference building) to

~0.11 (recess-cornered buildings) and the peak PSD magnitudes decrease significantly with the introduction of recess corners. Although the recessed corners are effective in disrupting vortex shedding, the effectiveness of increasing the recess size is gradually offset by the increased building height necessary to maintain useable floor area. The efficiency of large recess corners, i.e. approximately 19%, was significantly diminished as the normalized PSD of RE5 approaches that of the reference building.

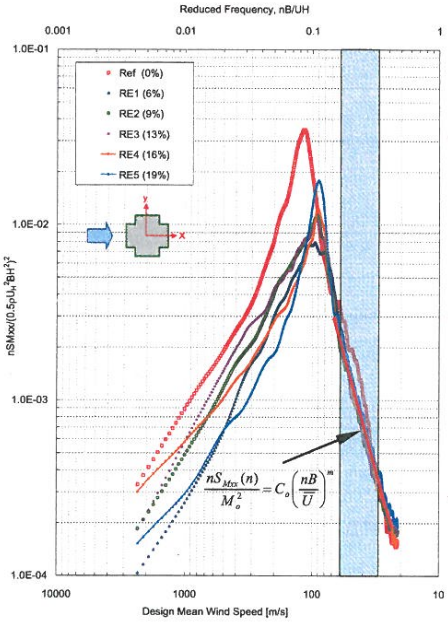

Figure 2. Normalized cross-wind loads PSDs

3.2 *Cross-wind responses*

The PSDs of the dynamic components of the measured base moments were used in conjunction with the dynamic properties (mass distribution, natural frequency, damping and mode shape) to evaluate analytically the prototype scale cross-wind dynamic responses. In this preliminary study, it was assumed that the natural frequency is inversely proportional to the building height (50/H), building mass is uniformly distributed, mode shapes are linear and uncoupled, and the structural damping ratio was set to be 2% of critical for the purposes of demonstrating the process.

PSDs of cross-wind response are presented in Figure 3. The resonant response peaks were found to shift towards 0.1Hz and their magnitudes gradually increased. The total dynamic cross-wind responses were separated into background and resonant components and are listed in Table 2. The cross-wind background responses of the modified building configurations were found to be reduced by over 20%. In contrast, the resonant responses increase gradually from just above 80% of the reference building response (for RE1) to even greater than that of the reference building (120% for RE5). Hence the total response, which is dominated by the resonant response, follows the trend of the resonant response.

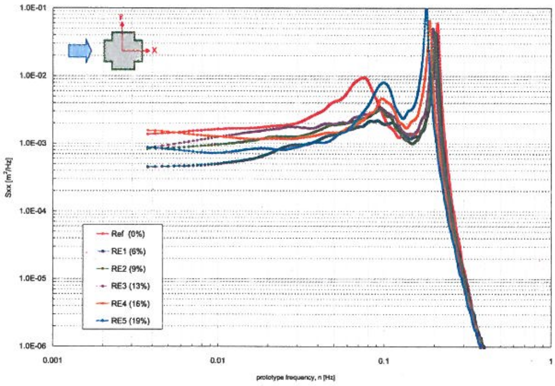

Figure 3. Cross-wind response PSDs

Table 2. HFFB and empirical response values

	cross-wind resp. std. (mm)				
	background		resonant		total
	measured	emp.	measured	emp.	measured
REF	19.6 (1.00)		30.4 (1.00)		36.1 (1.00)
RE1	12.3 (0.63)	12.6	24.8 (0.82)	24.5	27.7 (0.77)
RE2	13.8 (0.71)	14.2	25.2 (0.83)	25.2	28.8 (0.78)
RE3	14.6 (0.75)	15.0	26.9 (0.88)	26.6	30.6 (0.85)
RE4	14.2 (0.72)	14.5	30.0 (0.99)	30.4	33.2 (0.92)
RE5	15.1 (0.77)	15.5	36.1 (1.19)	36.5	39.2 (1.08)

3.3 *Empirical formulae*

To understand the combined effect of corner modifications and additional storeys with regard to the financial returns, optimization is one available tool that allows design variables to be expressed in an explicit form. Therefore, it is necessary to relate the size of corner modifications to the cross-wind responses which are basically interrelated with the construction cost.

The total dynamic cross-wind responses can be considered as comprising background dynamic response, due mainly to approaching wind characteristics, and resonant dynamic response attributed to the structural dynamic properties, as expressed in Equation (2) below. Empirical formulae were derived to relate the cross-wind background dynamic response and resonant dynamic response to the number of storeys which in turn is a function of size of the recess corners.

$$\begin{aligned}\sigma_\xi^2 &= \frac{1}{k^{*2}}\int_0^\infty |H(n)|^2 \frac{S_{Mxx}(n)}{h^2}dn \\ &\cong \frac{1}{(hk^*)^2}\int_0^\infty S_{Mxx}(n)dn + \frac{S_{Mxx}(n_o)}{(hk^*)^2}\int_0^\infty |H(n)|^2 dn \\ &= \sigma_{\xi,BG}^2 + \sigma_{\xi,res}^2 \end{aligned} \qquad (2)$$

where, $k^* = m^*\omega = \dfrac{\rho A \Delta h}{3}\left(\dfrac{2\pi\eta}{N\Delta h}\right)^2$

Based on the HFFB test results the standard deviation of the base overturning moment σ_{Mxx} is modelled as a 3rd order polynomial in terms of the number of storeys, N. Hence,

Background, $\sigma_{\xi,BG}^2 = \dfrac{\sigma_{Mxx}^2}{(hk^*)^2}$

$$\boxed{\sigma_{\xi,BG}^2 = \frac{9N^2\left(a_3N^3 + a_2N^2 + a_1N + a_0\right)^2}{16\pi^4\eta^4\rho_s^2A^2}} \qquad (3)$$

Considering a reduced frequency range of 0.15 – 0.3 highlighted in Figure 2, the normalized spectra are exponentially related to the reduced frequency, therefore:

$$\frac{nS_{Mxx}(n)}{M_o^2} = C_o\left(\frac{nB}{\overline{U}}\right)^m$$

Then, $S_{Mxx}(n) = C_1\overline{U}^{4-m}n^{m-1}$

Resonant, $\sigma_{\xi,res}^2 = \dfrac{S_{Mxx}(n)}{(hk^*)^2}\dfrac{n\pi}{4\zeta}$

$$\boxed{\sigma_{\xi,res}^2 = \frac{9C_1\overline{U}^{4-m}}{64\pi^3\eta^{5-m}\rho_s^2A^2\Delta h^m\zeta}N^{2-m}} \qquad (4)$$

where $N, \eta, \rho_s, A, \Delta h, \zeta$ and $\overline{U}$ are number of storeys, frequency coefficient, structural density, usable floor area, storey height, damping ratio, and design mean wind speed at building height, respectively. The empirical values are listed in Table 2 and are accurate to within 5% over the following parameter ranges: a) $30 < \overline{U} < 45$ m/s; b) $40 < \eta < 60$; c) $200 < \rho_s < 400$ kg/m², and d) $0.01 < \zeta < 0.03$.

4.0 CONCLUSIONS

The influence of the recess and chamfered corners and additional storeys on the building responses were identified, which are expected to be strongly correlated with the construction cost. Further investigation is required into their effect on the returns on investment for a tall building which, after all, is the primary financial concern of almost all building developers. Indeed, it is not an easy task for a structural or wind engineer to decide on the size and type of corner modification with regard to the effect on financial returns. Therefore, empirical formulae were derived for use in Part 2 of this study to establish optimal building dimensions. Building economics of corner-modified structures will also be discussed.

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