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Wind Induced Noise and Vibration Design Issues of Mega-tall Buildings

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ABSTRACT

Aurecon's building sciences team has worked on a range of "mega-tall" buildings including currently Santiago Calatrava's Dubai Creek Harbour (DCH) Tower (~1km), Gensler's Shanghai Tower (630m), Woods Bagot's Nakheel Tower (not constructed, ~1km) and Skidmore, Owings and Merrill's Burj Khalifa (~830m). This paper will outline some interesting noise and vibration design issues specific to these types of buildings related to aerodynamic modifications of the form to reduce structural loads and control serviceability response. Specifically introduction of cross or oblique openings and internal noise effects due to building motion.

1. Introduction

The Council for Tall Buildings and Urban Habitat (CTBUH) notes that a "tall building" is a building that exhibits some element of "tallness" in one or more of the following categories: Height relative to context; Proportion; Building Technologies. CTBUH also defines "supertall" and "megatall" buildings as being those more than 300m and 600m in height respectively. The tallest 20 buildings in the years 2000, 2010 and 2020 have average heights of 375m, 439m and 598m respectively, and within 2 decades (2000-2020) the height of the world's tallest building has more than doubled (CTBUH).

As building height has increased, the interplay between architectural and structural form, with consideration of wind effects has become more crucial, not only with regard to design for strength but also serviceability. Various methods of modifying the aerodynamic shape of tall buildings have been explored by various researchers to reduce along-wind and across-wind response, including horizontal shape (eg. Rectangular, circular, triangular, elliptical, Y-shape etc), vertical shape (eg. Taper, Helix), edge effects (eg. Corner modifications), openings (eg. Cross, Oblique) and composite (being any combination of these modifications).

As noted by Griffis (2003), every building or other structure must satisfy:

- **Strength Limit State**, such that each member is proportioned to carry the design loads to resist buckling, yielding, instability, fracture, etc.;
- **Serviceability Limit State** such that the behavior under load (eg. deflection, vibration, and corrosion) does not reduce amenity.

2. Strength Limit State

Code based design methods, and wind tunnel methods are well established to determine structural loads, however only recently have aerodynamic and flow characteristics of tall buildings with various unconventional configurations been summarised well by Tanaka et al (2013). A summary of maximum mean and fluctuating drag (along-wind) and lift (across-wind) moment coefficients is provided in Figure 1 below. Of particular interest is the effects of cross and oblique openings at reducing the mean across-wind response, with significant reductions in the fluctuating across-wind response.

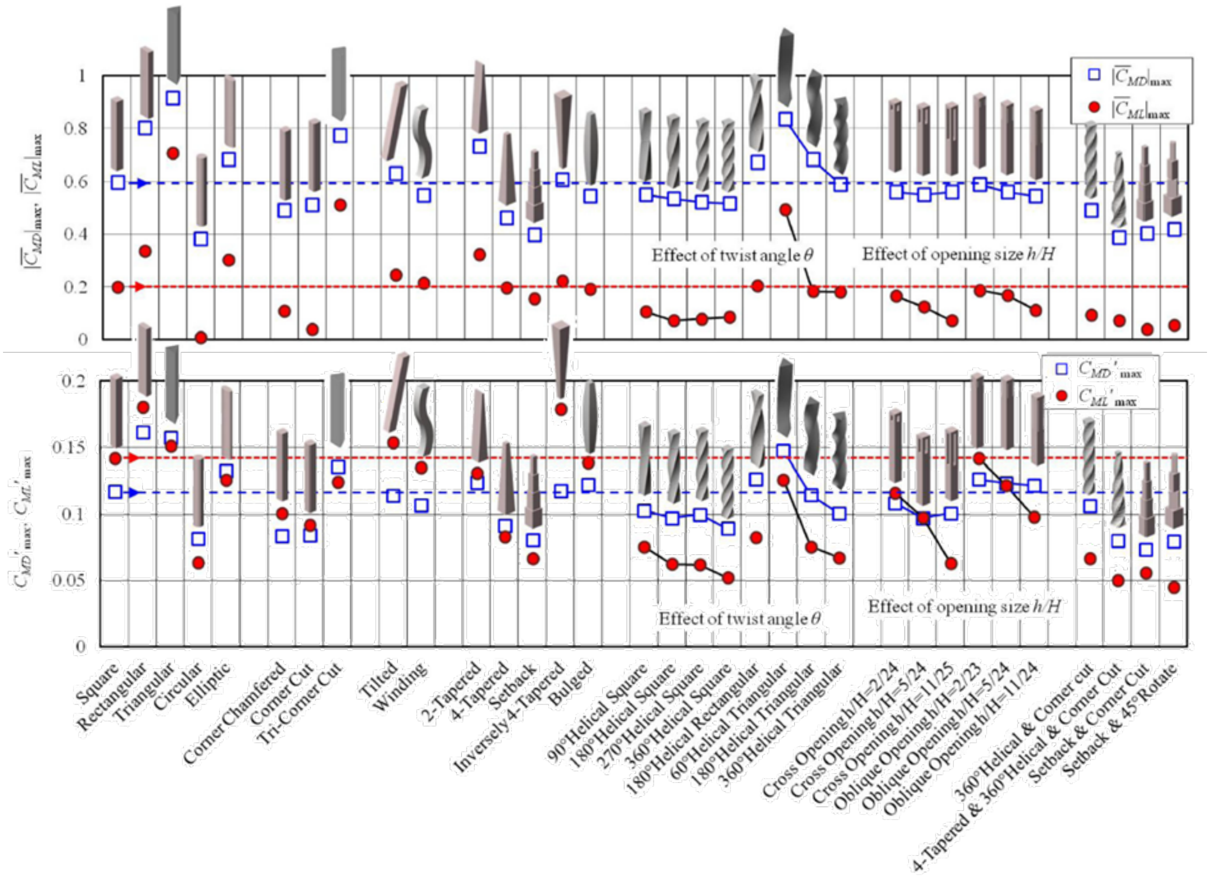

Figure 1 Comparison of maximum mean overturning moment (upper) and maximum fluctuating overturning moment (lower); Tanaka et al (2013).

The use of cross-openings was included in the design of Nakheel's 1km tower in Dubai, with both cross and oblique openings included in the design of Incheon tower as reported by Lim et al (2013) to reduce across-wind response. However, the inclusion of openings through building elements in the upper levels of super-tall and mega-tall buildings has the potential to generate significant noise.

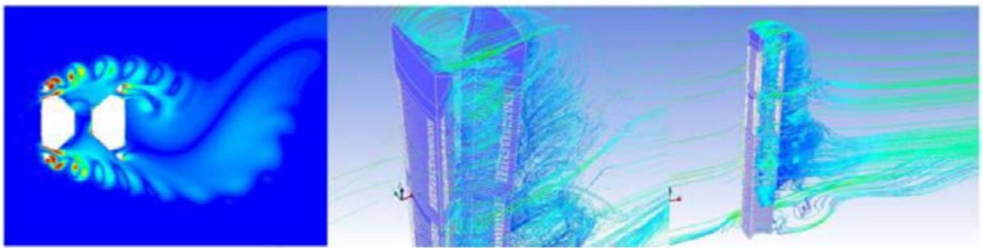

Figure 2 2D-vorticity contours and 3D-velocity streamlines in flow perpendicular to the cross-opening (through the oblique openings) – see also Figure 5 below ; Lim et al, (2013)

3. Serviceability Design

Serviceability is ordinarily considered relative to motion and inter-storey drift, however noise effects are rarely considered. Motion limits were originally controlled through limiting inter-storey drift (effectively displacement) as shown in Table 1 below.

Table 1 Inter-storey Drift Limits – Griffis (2003)

Deformation	Visible Damage	Typical Behaviour
≤ΔH/1000	Not Visible	Cracking of brickwork
ΔH/500	Not Visible	Cracking of partition walls
ΔH/300	Visible	General architectural and structural cosmetic damage etc

With the introduction of ISO 10137 (2007), acceleration limits (peak not RMS) were prescribed based on a 1 year return period. As the building height increases the first mode of vibration decreases. Assuming a floor-floor height of 4m (ΔH) and a first mode shape factor of 2, the average drift in the top 10 storeys of tall (80 storeys), super-tall (160 storeys) and mega-tall (240 storeys) towers is provided in Figure 3 below for different acceleration limits (varying from 5 to 20 milli-g) and first modes of vibration (varying from 0.125 to 0.5Hz). With a drift limit of ΔH/500, the maximum drift limit is 8mm, which is approached or exceeded as the height increases and the frequency of the first mode decreases despite compliance with ISO 10137 comfort criteria (10-20 milli-g depending on the type of occupancy : residential or office).

		Freq (Hz)	0.5			Freq (Hz)	0.25			Freq (Hz)	0.125	
Acc. (milli-g)	**5**	**10**	**15**	**20**	**5**	**10**	**15**	**20**	**5**	**10**	**15**	**20**
Def. (mm)	32	64	95	127	127	255	382	509	127	255	382	509
Storeys	**Drift (mm), top 10 storeys (avg.)**				**Drift (mm), top 10 storeys (avg.)**				**Drift (mm), top 10 storeys (avg.)**			
80	0.7	1.5	2.2	3.0	3.0	6.0	9.0	12	12	24	36	48
160	0.4	0.8	1.2	1.5	1.5	3.1	4.6	6.2	6.2	12	19	25
240	0.3	0.5	0.8	1.0	1.0	2.1	3.1	4.2	4.2	8.3	12	17

Figure 3 Maximum acceleration, deflection and inter-storey drift estimates

The aerodynamic form of the building can be modified to reduce structural loads as noted above, however this does not necessarily mean significant reductions in motion given the normalised frequency (fB/U_H) is less for an 500 year return period wind speed (used for structural loads) relative to an annual return period wind speed (for serviceability). This is shown below in Figure 4 (H90 limit prescribed in AIJ is practically equivalent to the residential limit in ISO 10137).

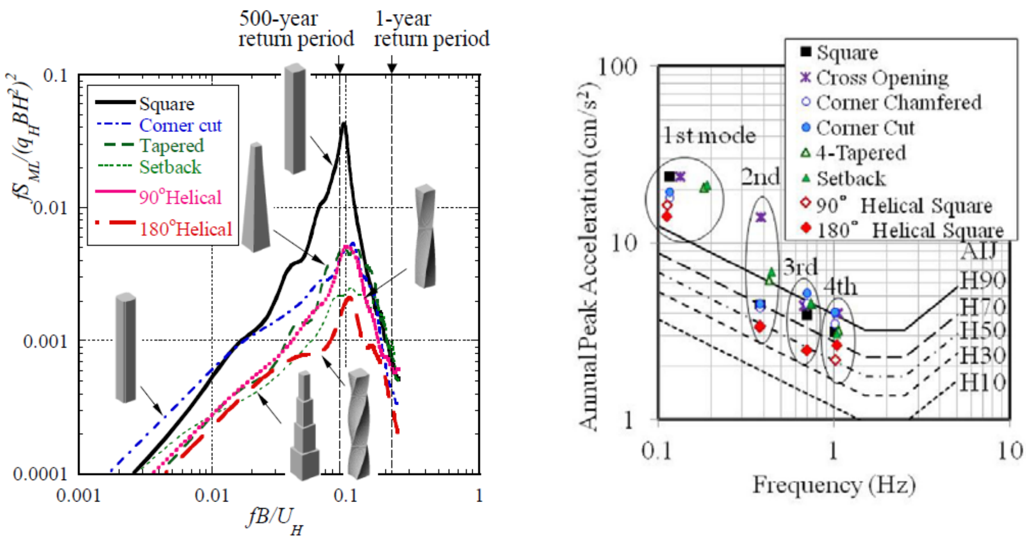

Figure 4 Power spectral density relative to normalised frequency, and Annual peak acceleration relative to frequency for differing aerodynamic forms. Tanaka et al (2013).

4. Aerodynamic Noise Generation

Introducing cross or oblique openings through the façade has the potential to generate noise through flow interaction with bluff bodies through incorporation of louvered elements on the façade as shown below for Incheon tower in Figure 5. Wind induced noise can also be generated through creaking of building elements within the tower, however this is not considered herein.

Blake (1986) derived a simple relationship for calculating the sound pressure level produced by a rigid cylinder (of arbitrary cross section) submersed in cross flow, with the RMS (root mean square) pressure given by $\overline{p^2(r)}$ is:

$$\overline{p^2(r)} \propto \overline{C_L^2} U^6 St^2 \left(\frac{2\Lambda}{L}\right) \quad (1)$$

Where $\overline{C_L^2}$ is the RMS lift coefficient and Λ is the span-wise correlation coefficient, Strouhal number $\mathrm{St} = fD/U$, with f the frequency of vortex shedding, D is the cross-wind dimension of the bluff body and U is the wind stream flow velocity approaching the section. It can be seen that the sound intensity can be reduced by primarily reducing the Strouhal number and fluctuating lift coefficient (eg. Introducing curvature to the bluff body), and reducing the correlation length (eg. Through disrupting vortex shedding along the length).

Figure 5 Incheon tower with side louvres shown on architectural and wind tunnel models – RWDI/Samsung

Typical return period 10 minute mean wind speeds vary with height and are given below in Table 2. A doubling of the wind speed at 600m and above (within the region of super-tall and mega-tall structures) results in almost a 20dB increase in noise level (4 fold increase in subjective loudness), and depending on the occurrence interval (weekly to annual), this could be a tripling of the mean wind speed (30dB increase). Wind induced noise is therefore a critical design consideration.

To understand likely variations in the Strouhal number and RMS lift coefficient, reference is made to Carassale (2012), who studied the aerodynamic behavior of square cylinders with rounded corners, in the Reynolds number range of 2.5×10^4 and 1.8×10^5 and turbulence intensity up to 6%. With rounded corners, the Strouhal number increases by about 20% (less than 3dB increase in noise level which is barely perceptible), while the RMS lift coefficient decreases with increasing radius of the rounded corner (about a 20% reduction with a radius of about 10% of the breadth of the cylinder, which counteracts the increase in noise level), as shown below in Figure 6.

Table 2 provides the vortex shedding frequencies for bluff bodies with differing width and Strouhal numbers (0.15 to 0.25). As noted, while changes in the Strouhal number (through curvature of a bluff body) has been shown to have limited effect on the intensity of noise, it does increase the frequency of the tone and therefore increases the subjective impression of loudness (and the overall A-Weighted noise level). However this can be counteracted by increasing the width of the bluff body to reduce the frequency, with a reduction from 125Hz to 63Hz resulting in a 10dB reduction in loudness (perceived as half as loud).

Table 2 10 minute mean wind speed at 10m and 600m height (for different return periods), and vortex shedding frequency at 600m height (differing width and Strouhal number)

Return period (years)	10 minute mean wind speed (m/s)		Vortex shedding frequency at 600m (Hz)			
	10m	600m	D=40mm St=0.15	D=40mm St=0.25	D=80mm St=0.15	D=80mm St=0.25
0.02 (weekly)	~7.5	~15	56	94	28	47
0.1 (monthly)	~10	~20	75	125	38	63
0.5 (1/2 yearly)	~12.5	~25	94	156	47	78
1	~15	~30	113	188	56	94

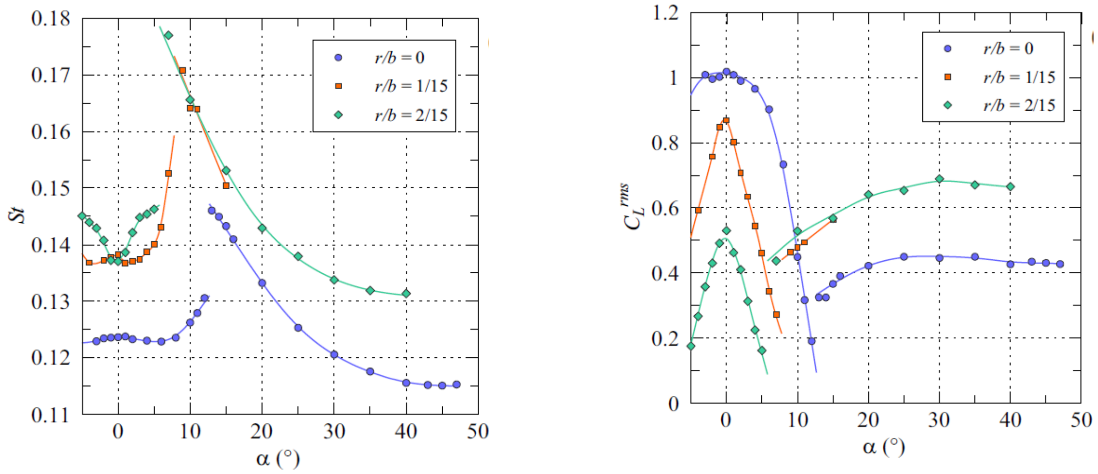

Figure 6 Strouhal number, St, and RMS lift coefficient, C_L^{RMS}, in smooth flow at angle of incidence, α, to a square cylinder (corner radius, r, breadth, b) ; Carassale et al (2012)

Mittal and Raghuvanshi (2001) carried out numerical simulations confirming experimental research by Strykowski and Sreenivasan (1990) that vortex shedding past a cylinder can be controlled (and potentially completely suppressed) by proper placement of a much smaller control cylinder close to the main cylinder. It was observed that the control cylinder provides a local favorable pressure gradient in the wake region stabilizing the shear layer of the main cylinder. This therefore suggests that a wire mesh located in the immediate wake of bluff bodies could have a similar effect.

Wind generated noise from louvered elements of a super/mega-tall building were assessed with trapezoidal louvres fabricated from an aluminium RHS section clad in "plastic wood" to enable the trapezoidal form of the extrusion to be formed. The louvres were fixed to timber battens to enable the set to be removed and installed on horizontal and vertical frames, mounted on a turntable, as shown below on Figure 4. The support frame, frame with louvres, and with backing mesh were each tested at differing wind speeds and angles. The test panel (about 1.0m^2) was mounted at about 400mm above the floor to ensure a uniform wind speed profile across the panel. Background noise was measured with and without the frame prior to installing the louvres and mesh, with sound pressure levels measured at a given distance from the panel.

Results are shown below in Figure 8, with fine mesh (1mm diameter, 25mm grid) initially having no effect on tonal noise which was at such an intensity as to exceed environmental noise criteria at considerable distances (~1km) from the tower and internal noise levels within the tower (transmitted through the façade). The intensity of the tone reduced significantly (unexpectedly), and the frequency increased (as expected) with the introduction of rounded corners on the louvres. Inclusion of mesh of sufficient diameter (10% of the breadth of the louvres) completely suppressed vortex shedding. Similar results were found with a louvre of twice the width, with the vortex shedding frequency reducing as expected, but also the sound intensity of the tone.

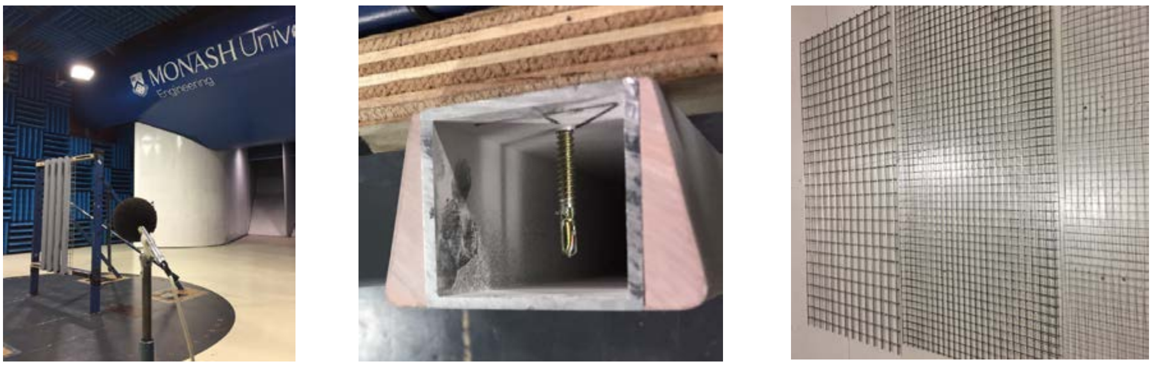

Figure 7 Wind tunnel setup, louvre section and mesh types tested

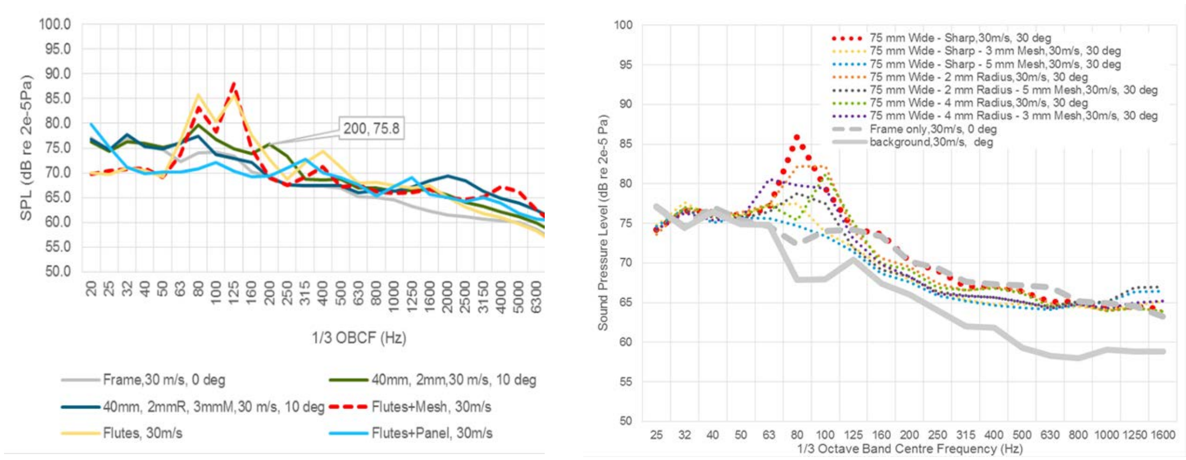

Figure 8 Wind tunnel tests of noise from louvres (LEFT, 40mm, RIGHT, 75mm)

4. Conclusions

Aerodynamic modifications to the form of super and mega tall towers can significantly reduce structural loads and potentially some serviceability conditions (motions), but they can also exacerbate other serviceability conditions (noise). This paper has outlined the potential significance of tonal noise generated by wind passing through cross and oblique openings where noise can be generated from bluff bodies shielding or exposed within such openings. Mitigation measures have also been nominated and shown to effectively suppress vortex shedding from such bluff bodies.

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