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Along-wind response of super tall towers equipped with external cable bracing system: preliminary model

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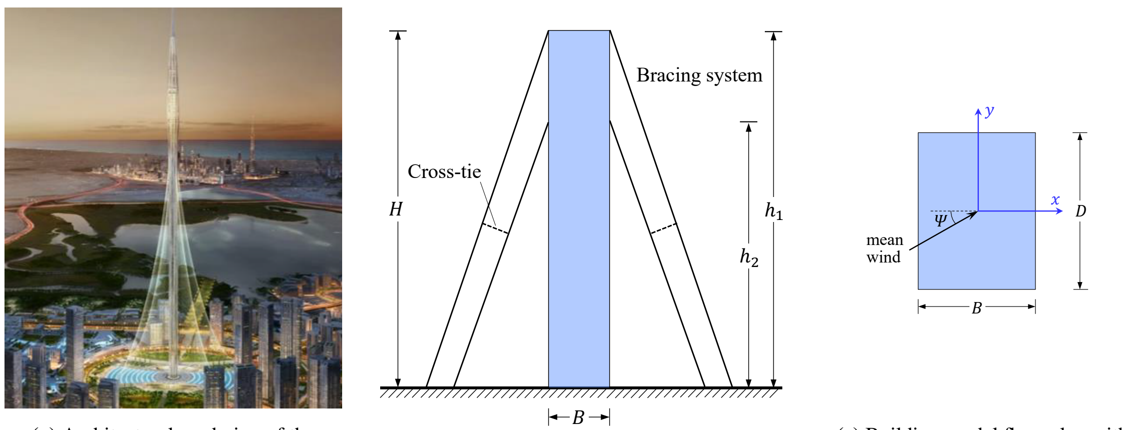
SUMMARY:
A state-of-the-practice three-dimensional cable-cross-tie bracing system, devised for the Dubai Creek Tower, currently under construction, presents an extraordinary opportunity to study the dynamic interaction of a slender *cable-building system* under random wind load excitation. Hence, this preliminary study examines wind-induced vibrations of super-tall buildings equipped with external cable bracing systems. The cable-stays of the bracing system may reach unprecedented lengths and, thus, may be prone to aeroelastic stay-cable vibration. In this preliminary study, transverse cross-ties, which have been proposed to mitigate vibrations of the bracing system by connecting two neighboring cables, are not yet included. The cable bracing system, composed of two sets of inclined stays symmetrically installed in the *x-z* plane of the building, are installed to control along-wind vibration. Data sets from the benchmark CAARC building are adapted to derive a reduced-order model of the building's buffering response. This preliminary investigation investigates the along-wind response, accounting for nonlinear mode shape corrections of HFFB (high-frequency force balance) experimental, generalized load spectra. Future studies are planned to consider across-wind and torsional oscillations.

Keywords: tall building, cable bracing system, aerodynamic response

1. INTRODUCTION

Performance-based wind engineering (PBWE, Ciampoli et al. (2011)) has received considerable attention in recent years, owing to the growing need to design taller and slender structures. The extreme slenderness of this type of structures, however, is prone to considerable global, lateral or torsional deformations under the excitation by wind forces; deformations and accelerations may affect occupants' comfort and well being after prolonged exposure to vibrations (Kwok et al., 2009). To address the problem, external bracing systems of various shapes and geometry may be designed and installed onto to tall buildings; these systems provide desirable stiffness properties against global lateral deflections and drift.

For super-tall tower structures, a state-of-the-practice three-dimensional bracing system of stays has been proposed for the Dubai Creek Tower project (Fig. 1a), the world's tallest observation tower with an anticipated above-ground height of 928 m. The stays, in particular, can be very long and are sensitive to aeroelastic vibrations. Therefore, one proposed solution is to consider installation of cross-ties, strategically positioned, to reduce the vibrations. The coupled response of the resulting *cable-building system* is a challenging wind engineering analysis task. Several studies (Gattulli et al., 2002; Xia and Fujino, 2006) have successfully tackled the problem of cable-beam analysis under random excitation, primarily for an application to deck-stay dynamic in cable-stayed bridges. However, very few models are available on the dynamic responses of super-tall buildings equipped with braced, restraining cables and cross-ties, and excited by turbulent wind loads. Hence, this study introduces a novel, reduced-order model for the evaluation of wind-induced vibrations of the cable-building system.



(a) Architectural rendering of the Dubai Creek Tower (reproduced from *Google search*)

(b) Building model geometry (elevation and cable bracing configuration)

(c) Building model floor plan with indication of wind direction (bracing not shown)

Figure 1. Schematics of the cable-building system.

2. ALONG-WIND ANALYSIS

The standard aerodynamic and random vibration theories, implemented in the frequency domain, are used in wind engineering for the evaluation of wind loads, wind-induced response and serviceability limit states of slender structures (Davenport, 1961). Using the generalized formulation proposed by Cui and Caracoglia (2018), a three-dimensional theory for multi-directional wind response is employed, accounting for aerodynamic damping and stiffness effects as well as inter-modal coupling. In this preliminary application, however, along-wind analysis is examined; across-wind and torsional vibrations will be readily considered in future implementations. The theory is briefly described below. The power spectral density (PSD) of the generalized buffeting forces can be estimated by Eq. (1), while the PSD of the generalized dimensionless vibration response is given by Eq. (2).

$$\mathbf{S_{QQ}}(n) = \iint_0^h \frac{\rho^2 D^2}{4} \bar{U}(z_1)\bar{U}(z_2)\mathbf{\Phi}^T \mathbf{C}^* \begin{bmatrix} S_{\mathrm{uu}}(n,z_1,z_2) & 0 \\ 0 & S_{\mathrm{vv}}(n,z_1,z_2) \end{bmatrix} \mathbf{C}^{*,T} \mathbf{\Phi}\, \mathrm{d}z_1\, \mathrm{d}z_2 \tag{1}$$

$$\mathbf{S_{XX}} = \mathbf{H}\mathbf{S_{QQ}}\mathbf{H}^{*,T} \tag{2}$$

In the previous equations, $\mathbf{S_{QQ}}$ and $\mathbf{S_{XX}}$ are the PSD matrix of the generalized buffeting forces and the generalized buidling response, respectively; $\bar{U}(z)$ is the mean wind speed at elevation z; $\mathbf{\Phi}$ is the mode shape matrix incorporating inter-modal coupling due to non-uniplanar, complex structural mode shapes. In this study, wind direction is $\Psi = 0$ (Fig. 1c).

3. BUILDING MODELS

The models used in this study are adapted from the benchmark tall building of the Commonwealth Advisory Aeronautical Research Council (CAARC). The prismatic CAARC building, standing at $H = 183$ m above ground, has a rectangular floor plan of dimensions $D = 45.7$ m $\times$ $B = 30.5$ m. The slenderness ratio of the original CAARC (OC) building is $H/D = 4.0$. Two super-tall variants of the CAARC building, the "stiff" super-tall model (ST1) and the "slender" super-tall model (ST2), achieving different slenderness ratios, are adapted from the OC building. Both ST1 and ST2 are equipped with two sets of inclined stay-cables, and are designed for preliminary examination of cable-building coupled vibrations. Properties are summarized in Table 1. The two sets of cables, are installed symmetrically along the external surface of the ST1 and ST2 models in the z-x plane; the upper anchorages are fixed at height $h_1 = 600$ m and $h_2 = 450$ m, respectively; their geometry is schematically illustrated in Fig. 1b. Cross-ties are also shown in Fig. 1b for the sake of completeness even though they are not included in this communication. The buildings are analyzed by finite elements (via equivalent, cantilever "stick-beam" model). The reduced-order model is based on the first fundamental lateral bending mode (matrix $\boldsymbol{H}$); therefore, the properties of the three structural systems are tuned to achieve a fundamental, along-wind lateral mode with natural frequency $n_{0,x} = 0.2$ Hz; the structural modal damping is set to $\xi_{0,x} = 0.01$. The fundamental mode shape of ST1 and ST2 is presented in Fig. 2. We note that the maximum lateral drift for model ST2 occurs at $z = 233$ m and that the mode shape is greatly influenced by the presence of the bracing system.

Table 1. Parameters of the analyzed CAARC building models.

Parameter	Original CAARC (OC)	"Stiff" super-tall CAARC (ST1)	"Slender" super-tall CAARC (ST2)
Height H [m]	183.0	600.0	600.0
Floor-plan depth D [m]	45.7	149.8	45.7
Floor-plan width B [m]	30.5	100.0	30.5
Slenderness ratio H/D	4.0	4.0	13.1
Distributed mass $\bar{m}$ [kg/m]	2.23×10^5	2.19×10^6	2.23×10^5

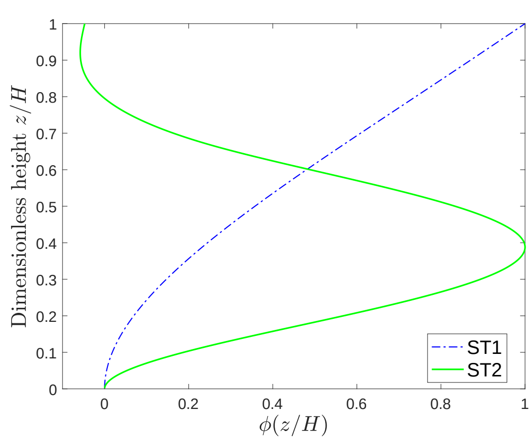


Figure 2. Fundamental, lateral bending mode shapes of ST1 and ST2 building models.

4. NUMERICAL RESULTS

4.1. Along-wind Response

The along-wind response of the three buildings, using available information from HFFB measurements (Cui and Caracoglia, 2018), is presented in Table 2; the reference mean wind speed at the top of OC building is $U_H = 50$ m/s; the roughness length of the boundary layer of OC, ST1 and ST2 is $z_0 = 0.5$ m. We note that the rigid model used in the wind tunnel (Cui and Caracoglia, 2018) is a scale model of the original CAARC building, and hence the HFFB measurements are meaningful for OC and ST1 only. The same HFFB data sets are preliminarily used for the estimation of aerodynamic response of the model ST2; future experimental studies are planned to derive HFFB measurements compatible with the geometry of model ST2. It is also worth noting the non-linear and non-monotonic function in the fundamental mode shapes of ST1 and ST2 buildings, clearly affected by the interaction with the external restraining cables. The HFFB data sets of ST1 and ST2 are aptly adapted through application of mode-shape correction factors, following the approach by Holmes (1987).

Table 2. Along-wind lateral response at various elevations for OC, ST1 and ST2.

Lateral response parameter	Elevation z [m]	OC	ST1	ST2
Static: mean value [m]	183	1.105	0.155	0.768
	600	-	1.023	0.040
Dynamic: standard deviation [m]	183	0.584	0.077	0.457
	600	-	0.507	0.024

5. CONCLUSIONS AND OUTLOOK

Super-tall building along-wind response, using a multi-directional generalized aerodynamic formulation, is estimated. The cross-ties, functioning as a mitigation device for the external cable bracing system, will be modeled and included in the final presentation. Additional wind tunnel tests are needed for accurate estimation of the generalized aerodynamic loads on model ST2.

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