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Performance of wind-excited linked building systems considering the link-induced structural coupling

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ABSTRACT

This study investigates the performance of wind-excited linked building systems (LBSs) considering the structural coupling caused by horizontal links that connect two adjacent buildings. An analytical evaluation model of the LBS and wind force data acquired from wind tunnel tests were used to calculate the wind-induced response, to assess the performance. After determining the critical wind directions, the effects of link properties (e.g., mass, stiffness, and location) on the acceleration response of LBSs were comprehensively examined for these wind directions. Results show that the extra link mass tends to decrease the acceleration response, although it usually increases the displacement response. The translational acceleration responses of the LBS decrease with increasing link stiffness and location, whereas the torsional acceleration response of the LBS is usually larger than that in the associated unlinked case. As a result, in some cases the resultant acceleration of the LBS exceeds that of the associated unlinked case, although in many other cases the resultant acceleration is decreased in LBSs. Therefore, researchers and practicing engineers should exercise caution when designing LBSs to avoid unfavorable acceleration responses.

1. Introduction

In recent decades, high-rise buildings in metropolises have often been built near each other because of limited available land. In turn, these high-rise buildings are increasingly being designed as linked building systems (LBSs), i.e., systems comprising several buildings connected by horizontal links such as skybridges, skypools and skygardens. They are usually built to great heights in order to achieve a grand appearance, so wind-resistance is one of primary concerns in design practice, especially in typhoon-prone cities such as Hong Kong and Tokyo.

Compared to a single isolated building, wind-resistant design for an LBS is relatively complicated because of the interference of effect on wind buildings in close proximity and the existence of the link that connects adjacent buildings. The interference effect will distort wind forces on building surfaces [1,2] and hence the commonly-used wind force model in the codes of practice may not applicable for LBSs. The link can provides an additional passage and an evacuation route in the event of a fire or other emergencies [3]. Furthermore, from a structural point of view, the link can introduce inter-building structural coupling for vibrations in the linked buildings [4,5] and hence affect the modal properties and wind-induced responses of the LBS [6,7]. Because of this complexity, only a limited amount of literature can be found on the performance of wind-excited LBSs [4,8–10].

Apart from the aforementioned LBSs where adjacent buildings are connected by structural links such as skybridges, skypools and skygardens, there are a number of other coupled building systems that are connected by nonstructural elements. These building systems share considerable similarities to LBSs, so it is worth reviewing studies on coupled building systems. For example, Klein and Healey [11], initially, proposed a cable system to connect two buildings in order to reduce wind-induced oscillations of the two buildings. Another type of the coupled building systems consisting of two adjacent buildings connected by control devices was widely discussed in the field of seismic design of tall buildings. These discussions proposed using passive control devices [12–17], active control devices [18,19], or semi-active control devices [20–22] to connect two adjacent buildings in order to improve seismic resistance. These studies provided an adequate understanding of structural coupling due to such control devices and their effects on the structural performance. It should be mentioned, however, that most of the above studies focus on seismic responses and performance of the coupled building system. Results and conclusions

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from the above studies about seismic response and performance of coupled building systems cannot be directly applied to assessing the performance of wind-excited LBSs. This is because one-dimensional seismic excitation was adopted in these studies, whereas one distinct characteristic of wind forces on tall buildings is that there simultaneously exists along-wind, cross-wind, and torsional force components. Moreover, wind forces vary along the structural height, rather than external loads merely at the structural base.

To evaluate the performance of wind-excited LBSs, Lim's group [8,9] proposed a simplified 3D evaluation model with six degrees of freedom for twin buildings connected by a skybridge. Similar to the derivation given by Christenson et al. [23], this model was created based on assumed structural mode shapes (or trial functions). The wind-induced responses of the LBSs can then be easily calculated using the traditional HFBB based approach requiring mode shape correction. Their studies have offered a simple and useful formulation of wind-exited LBSs. However, whereas the (first) mode shape of an isolated building is generally simple and can be estimated to a certain degree, the mode shape of an LBS is usually difficult to estimate as they can be significantly interrelated with various link properties, resulting in complicated shapes [6,7]. As a result, the inherent assumption about mode shapes and the use of mode shape correction factors may introduce uncertainties for the predicted generalized forces and structural responses [24–29]. Recently, Song's group developed a 3D analytical evaluation model that did not require any assumptions of mode shapes [6] and can allow for the effects of all link properties (i.e., the mass, location, and stiffness). The effects of the link properties on the modal properties such as frequencies and mode shapes were comprehensively examined using this model to shed light on the effect of the link-induced structural coupling.

Compared to modal properties, the wind-induced responses (e.g., displacement, acceleration, base moment, stress in an element, etc.) are clearer and more straightforward in illustrating the performance of tall buildings subjected to severe wind excitations and hence are of great importance and practical concern for structural engineers. Although a simple case study was conducted in [6] to show the effects of a link on the wind-induced response of LBSs, the full effects have not yet been examined comprehensively. Therefore, this paper extends previous research in the analytical model to examine the effects of link properties on the performance of wind-excited LBSs due to differences in the link's mass, axial stiffness, bending stiffness, and location.

In this study, the 3D analytical model and a pressure measurement wind tunnel test were briefly described first. After examining the key characteristics of wind pressure on the LBSs, the performance of wind-excited LBSs was then assessed in terms of the acceleration response. The effects of link properties, including the mass, axial stiffness, bending stiffness, and location, on the acceleration response were investigated comprehensively, to provide guidance for initial design of LBSs. A simple example was presented to show the application of the results. The main findings were summarized in the concluding section.

2. Analytical model of wind-excited linked building system

Two adjacent tall buildings are horizontally connected by structural links to form an LBS, as shown in Fig. 1. A 3D analytical model in matrix form is developed to reproduce the salient features of the LBS. This section, summarized from [6], briefly explains the formation of the analytical model of the LBS.

2.1. Assumptions of 3D analytical model

The LBS consists of two identical buildings (with given structural properties such as height, mass, stiffness, and damping properties) connected by several horizontal links. To highlight the link-induced structural coupling, the internal structural coupling of each building caused by the eccentricities between the mass and stiffness centers is eliminated by assuming that the mass center of each tower floor coincides with the associated stiffness center. Each individual building in the LBS is modeled as a linear multiple DOF system, in which each floor has three degrees of freedom, i.e., two horizontal translations and one rotation about the vertical axis [30], as shown in Fig. 1. Each link is regarded as a beam rigidly connected to the twin towers, although other types of connection, such as semi-rigid and hinged connections, are possible [31]. Compared to the structural damping of each building, link damping is usually insignificant. In addition, the rigid connection will not provide considerable damping for the system. Therefore, the damping of the rigidly-connected link is ignored in this study. The case with significant link damping is out the scope of this study, as in this case the LBS is not a classical damping system.

2.2. Formation of the analytical model

Each building in the LBS has m floors and the two buildings are interconnected by n ($n \leqslant m$) links at n arbitrary floors. The LBS can be regarded as a $6m$ degrees of freedom system and the equations of motion for the LBS when subjected to external wind loads can be written as

$$[\mathbf{M}+\mathbf{M_L}]\ddot{\mathbf{D}}+\mathbf{C}\dot{\mathbf{D}}+[\mathbf{K}+\mathbf{K_L}]\mathbf{D}=\mathbf{F} \tag{1}$$

where **M**, **C**, and **K** are the mass, damping, and stiffness matrices of the twin buildings, respectively; $\mathbf{M_L}$ and $\mathbf{K_L}$ are additional mass and stiffness matrices due to the link; $\mathbf{F} = \{F_{1x}, F_{1y}, F_{1\theta}, F_{2x}, F_{2y}, F_{2\theta}\}^{\mathrm{T}}$ is the external wind force vector, in which F_{gs} ($g = 1, 2$; $s = x, y$ or θ) is the wind force acting on tower g in the s direction; $\mathbf{D} = \{D_{1x}, D_{1y}, D_{1\theta}, D_{2x}, D_{2y}, D_{2\theta}\}^{\mathrm{T}}$ is the displacement response vector of the LBS, in which D_{gs} is the displacement vector of tower g in the s direction. The details of each matrix are listed as follows:

$$\mathbf{M}=\begin{bmatrix}\mathbf{M}_1 & \mathbf{0}\\ \mathbf{0} & \mathbf{M}_2\end{bmatrix}_{6m\times 6m}\quad \mathbf{C}=\begin{bmatrix}\mathbf{C}_1 & \mathbf{0}\\ \mathbf{0} & \mathbf{C}_2\end{bmatrix}_{6m\times 6m}\quad \mathbf{K}=\begin{bmatrix}\mathbf{K}_1 & \mathbf{0}\\ \mathbf{0} & \mathbf{K}_2\end{bmatrix}_{6m\times 6m} \tag{2}$$

$$\mathbf{M}_1=\mathbf{M}_2=\begin{bmatrix}\mathbf{M}_x & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{M}_y & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{J}\end{bmatrix}_{3m\times 3m}\qquad \mathbf{K}_1=\mathbf{K}_2=\begin{bmatrix}\mathbf{K}_{xx} & \mathbf{0} & \mathbf{K}_{x\theta}\\ \mathbf{0} & \mathbf{K}_{yy} & \mathbf{K}_{y\theta}\\ \mathbf{K}_{\theta x} & \mathbf{K}_{\theta y} & \mathbf{K}_{\theta\theta}\end{bmatrix}_{3m\times 3m} \tag{3}$$

where $\mathbf{M}_g$, $\mathbf{C}_g$, and $\mathbf{K}_g$ are the mass, damping, and stiffness matrices of tower g, respectively; $\mathbf{M}_x$, $\mathbf{M}_y$, and **J** are the mass and mass moment of the inertia sub-matrices of each tower; $\mathbf{K}_{rs}$ (r, $s = x$, y or θ) is the stiffness sub-matrix of each tower.

Matrices $\mathbf{M_L}$ and $\mathbf{K_L}$ in Eq. (1) are the products of the links and can be derived from the associated structural-property matrices of each link. The stiffness matrix of each link against the deformations at the two link ends (i.e., $d_{L1x,p}$, $d_{L1y,p}$, $d_{L1\theta,p}$, $d_{L2x,p}$, $d_{L2y,p}$, and $d_{L2\theta,p}$ shown in Fig. 1) can be expressed as [9,32]

$$\mathbf{K}'_l=\begin{bmatrix} k_a & 0 & 0 & -k_a & 0 & 0\\ 0 & 12k_b/l^2 & 6k_b/l & 0 & -12k_b/l^2 & 6k_b/l\\ 0 & 6k_b/l & (4+\beta)k_b & 0 & -6k_b/l & (2-\beta)k_b\\ -k_a & 0 & 0 & k_a & 0 & 0\\ 0 & -12k_b/l^2 & -6k_b/l & 0 & 12k_b/l^2 & -6k_b/l\\ 0 & 6k_b/l & (2-\beta)k_b & 0 & -6k_b/l & (4+\beta)k_b \end{bmatrix} \tag{4}$$