Engineering Structures 79 (2014) 169–181

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic characteristics of wind-excited linked twin buildings based on a 3-dimensional analytical model

Jie Song *, K.T. Tse

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China

A R T I C L E I N F O

Article history:
Received 23 January 2014
Revised 4 August 2014
Accepted 7 August 2014
Available online 29 August 2014

Keywords:
Linked building system
3-Dimensional analytical model
Modal property
Wind-induced response
Structural link property

A B S T R A C T

The present work investigates the effects of structural links on the modal properties and wind-induced responses of a linked building system (LBS) by using an advanced three-dimensional analytical model. The LBS in this study refers to a system consisting of twin buildings horizontally connected by structural links such as skybridges and skygardens. The proposed analytical model of the LBS is derived by assembling the structural-property matrices of a rigid floor diaphragm model of the buildings and those of a beam model of each link. The accuracy of the analytical model is then compared with and validated by a detailed finite element method (FEM) model. By employing the analytical model together with the layer-by-layer wind force time histories measured in a wind tunnel, the modal properties and wind-induced dynamic responses are computed for LBSs with different link properties. The results show that the link can substantially alter the modal properties of the system, and hence the structural responses. In some cases, the wind-induced responses of LBSs are reduced in comparison with those of two independent towers (without a link), attributing to the additional link stiffness as mobilizing the stiffness of an individual tower to resist the lateral wind loads. In other cases, the structural responses are increased, due to the extra link mass and the lateral–torsional coupling induced by the link. Therefore, caution should be exercised in the wind-resistant design of a LBS, in particular in regard to the link properties, to avoid undesirable wind-induced responses.

1. Introduction

There is a growing trend to design tall buildings in close proximity to each other as a linked building system (LBS), i.e. a system consisting of several buildings horizontally connected by links such as skybridges, and skygardens [1,2]. The Petronas Twin Towers in Kuala Lumpur, Malaysia and the Marina Bay Sands Hotel in Singapore are two notable examples that illustrate the trend. These LBSs are usually very tall in order to achieve a grand appearance. As such, wind-induced response is one of the primary concerns in structural design practice as wind loads increase significantly with increase of the building height.

Despite the extensive research on the wind-induced responses of a single tall building and the emerging engineering examples of the LBS, only limited studies on the wind-induced responses of the LBS can be found in the open literature due to the great complexity of the problem [1,3–5]. In fact, apart from the aforementioned LBS where adjacent buildings are connected by structural links such as skybridges or skygardens, there are a number of similar coupled building systems that are connected by nonstructural elements. For example, Klein and Healey [6] proposed a cable system to connect two buildings in order to reduce the wind-induced oscillations using the slack and tension of the cable. Another system, which is widely discussed in the seismic field, involves two adjacent buildings connected by control devices, such as passive control devices [7–13], active control devices [14,15], or semiactive control devices[16–22], intended to improve the seismic resistance of adjacent buildings. These studies provide a better understanding of the structural coupling due to these control devices and their capability in response reduction. Meanwhile, some analytical evaluation models for the coupled system have been proposed. For instance, modeling two adjacent buildings as a multiple degree-of-freedom (DOF) system and the connecting damping device as a spring–dashpot system, a matrix-form analytical model was formulated to investigate the seismic behavior of the coupled system [8,9]. Further, Zhu and Iemura [11] simplified each building as a single DOF system and simulated the connecting damping device as a spring–dashpot system in order to examine the dynamic characteristics of the coupled system subjected to stationary white-noise ground excitation. Similar models were also adopted to derive the closed-form equations for solving the

* Corresponding author.

http://dx.doi.org/10.1016/j.engstruct.2014.08.015
0141-0296/

vibration control problem of the coupled system [17,23,24]. In addition, making use of the Galerkin method, Christenson et al. [18,25] presented a simplified analytical model to examine the effects of the connecting control device on the seismic responses.

The aforementioned analytical models successfully addressed the related problems, in particular for the seismic responses of the system. It should be noted, nevertheless, that they cannot be directly applied to estimate the wind-induced responses of the LBS. This is because all the previous analytical models focused solely on the structural motions along the direction of the connecting damping device subject to a seismic excitation in the same direction. Wind forces on tall buildings, however, simultaneously comprise along-wind components and cross-wind components as well as torsional components in the three directions. Moreover, structural motions in these three directions are likely coupled [5,26]. As a result, it is necessary to develop a three-dimensional (3D) analytical model of the LBS, incorporating structural responses in three directions. To this end, Lim's group proposed a simplified six-degree-of-freedom analytical model for twin buildings connected by a skybridge [3,5]. Although this simplified model is three dimensional and addresses wind-induced structural motions in three directions, the model was developed based on assumed structural mode shapes that are independent of the link properties. In other words, the effects of the link on the mode shapes of the LBS were ignored. Whereas mode shapes of a single building are generally simple and can be estimated to a certain degree, the mode shapes of the LBS are difficult to estimate as they can be significantly interrelated with the link properties, resulting in complicated shapes [26]. If the assumed mode shapes deviate considerably from the actual ones, the structural frequencies of the system will be significantly overestimated, according to Rayleigh's method [27]. Unreliable frequency and mode shape will essentially introduce uncertainties in the estimation of the resultant wind-induced responses. Therefore, it is necessary to formulate an analytical evaluation model of the LBS that incorporates the link effects on the structural dynamic properties (i.e. natural frequency and mode shape) and hence can accurately predict the building responses.

In addition, the mass of the link, for instance the masses of the vibration control devices [8,18,23,25] and the mass of the skybridge [5], was usually neglected in previous studies. This might be appropriate for seismic response estimation because of the relatively light weight of the damping devices. However, the mass of structural links, such as a skybridge or a skygarden, in the LBS is relatively large, especially when the link span is large. In this case, the additional link mass can be one of the key parameters in the wind-induced responses. Therefore, when developing an analytical model, it is necessary to take the link mass into account in order to more accurately predict wind-induced responses of the LBS.

In spite of the extensive research on the coupled building system connected by control devices and a few preliminary studies on the dynamic properties of the LBS, there is still a need to research comprehensively the effects of the link mass and stiffness as well as its location, through deriving a more accurate 3D analytical model. It should be noted that, in addition to the effects of the link on the structural properties of the system, the wind loads on the system can be significantly modified due to the aerodynamic interference effect of adjacent buildings [28–31]. Since the aerodynamic interference effect of adjacent buildings has been investigated extensively, the present study focuses on the effects of link on the modal properties and the wind-excited structural responses of the LBS. Firstly, a 3D analytical evaluation model for two adjacent buildings connected by several structural links was formulated in a matrix-form. After validating the accuracy of the analytical model, the effects of the link properties, namely mass, stiffness and location, on the modal properties of the system were examined. Subsequently, the responses of the LBS subjected to wind forces measured in wind tunnel tests were calculated by means of modal superposition. The variations of the responses with the link properties were also examined in terms of both modal and total building responses for two representative wind directions. The main findings and suggestions are summarized in the conclusions.

2. Analytical model of linked twin buildings

2.1. Assumptions and limitations

In order to highlight the structural coupling due to the link and to properly definite a meaningful and yet manageable problem, some necessary assumptions are given and discussed in the following section.

The floor elevations of the two adjacent buildings are assumed to be identical so that two neighboring floors at the same elevation can be notionally connected by an inter-building link, as shown in Fig. 1. For simplicity of illustration, the two adjacent buildings in the LBS under consideration are assumed to be identical, analogous to the Great Arch de la Defense in Paris, France and the Petronas Twin Towers in Kuala Lumpur, Malaysia. The proposed analytical model, however, can be directly extended to an LBS connecting two different buildings. It should be mentioned that two different buildings were commonly employed in previous studies on the seismic responses of coupled building systems [13,25]. This is because the wave effect of the seismic excitation is usually neglected in these studies and thus, for two identical buildings subjected to the same ground excitation, the link connecting two buildings synchronously sways with the buildings and has no effect on the seismic responses of the system [25]. On the contrary, fluctuating wind pressures on building surfaces are not perfectly and spatiotemporally correlated [32]. Therefore, the wind-induced responses of adjacent twin buildings are not synchronous, and thus the link plays a key role in the resultant wind-induced responses of the LBS with twin buildings.

To clearly show the inter-building structural coupling induced by the links, the internal structural coupling within each building caused by eccentricities is eliminated by assuming that the mass center of each tower floor coincides with the stiffness center of the same floor. Each individual building is modeled as a linear multiple DOF system, where the lumped mass of each floor has three degrees of freedom, i.e. two horizontal translations and one rotation about the vertical axis [33]. The in-plane deformations of the tower floor systems and the vertical deformations of the tower

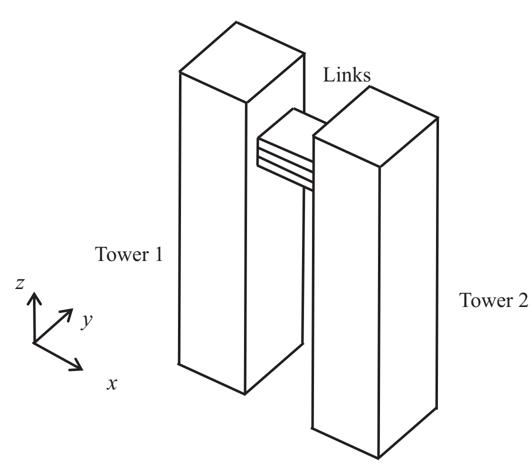

Fig. 1. Schematic of a linked building system (LBS).