Evaluating the Modal Response of Linked Tall Buildings

Federico Caldi, Graduate Researcher, University of Pisa
Pietro Croce, Professor, Structural Engineering and Bridge Design, University of Pisa
Jenna Wong, PhD, Assistant Professor of Civil Engineering, San Francisco State University
Zhaoshuo Jiang, PhD, Assistant Professor, School of Engineering, San Francisco State University
David Shook, P.E., LEED, Associate Director, Skidmore, Owings & Merrill LLP
Joanna Zhang, S.E., P.E., LEED, Associate Skidmore, Skidmore, Owings & Merrill LLP

Structural Engineering

Finite Element Analysis
Modal Analysis
Seismic
Skybridges
Wind Loads

2020

CTBUH Journal 2020 Issue I

1. Book chapter/Part chapter
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished
Evaluating the Modal Response of Linked Tall Buildings

Introduction

Worldwide, the height of tall buildings is rapidly increasing to address urban densification. This has resulted in architectural, programmatic, and developer concerns about accessibility in tall urban environments. Urban planners are seeking ways to improve not only everyday accessibility, but also community connectivity and emergency egress. To address this concern, connecting tall buildings to each other through skybridges is increasingly being considered (Wood, Safarik 2019). However, such elements introduce complexity to the structural system. To minimize this complexity, the bridges are often structurally “decoupled” from one or both towers using sliding bearings. While mitigating the structural dynamic complexity, this common approach has removed the potential of structural dynamic enhancements between coupled towers.

In a simplified sense, coupled towers (without sliding bearings) tend to either synchronize the movements of the connected towers or transfer loads between the buildings. Therefore, the linked building systems are worth studying to better understand the coupling dynamic behaviors of these systems. Taraldsen (2017) in particular has evaluated the effectiveness of coupling structural behavior through skybridges. In this study, the dynamic behavior of linked twin buildings was investigated by evaluating different skybridge configurations and positions under quasi-static wind loads. This result posed the question of whether this same improvement could be translated to structures under seismic excitations. As will be examined in this paper, when two tall buildings or towers are linked together, they tend to interact with each other by changing their natural frequencies, participating mass ratios and modal shapes, as compared to unconnected towers.

Abstract

Aesthetic characteristics, new materials, structural configurations, and construction technologies are pushing the boundaries of the built environment. At an urban scale, planners are increasingly considering inter-connected tall buildings with skybridges to address a growing need for accessibility between residential and commercial buildings. However, this demand is not only introducing complexities to buildings’ exterior features and height, but also to their structural dynamic behavior, especially when rigidly connected. To date, there is limited work on these inter-connected structures and the effects of their combined behavior. This paper investigates the dynamic response of two prototypical tall building patterns, connected via a skybridge, idealized as a beam having different stiffness. This study uses 3D finite element analysis models to examine the modal shapes and participating mass ratios between individual buildings and the linked building systems.

Keywords: Skybridges, Finite Element Analysis, Modal Analysis, Wind Loads, Seismic Loads

Building Designs

The reinforced-concrete buildings considered in this study are based on the structures in Taraldsen’s study with a number of modifications. Firstly, the central core was enlarged to be more representative of a modern tall building design. Secondly, to understand how the dynamics could be affected at a more general level, the tall buildings considered here are of two different heights. Lastly, to focus the attention on the rigid link, the structural systems are linear and equipped with specific material properties.
Figure 1. Plan, sections and finite element (FE) model of Tower 1 (dimensions in centimeters).

Figure 2. Plan, sections and FE model of Tower 2 (dimensions in centimeters).

Figure 1. Plan, sections and finite element (FE) model of Tower 1 (dimensions in centimeters).

Figure 2. Plan, sections and FE model of Tower 2 (dimensions in centimeters).

(see Table 1). In both structures, each story was loaded with additional weight due to the reinforced-concrete deck of each story (the 3D models consist only of the central core, the columns and the beams). These towers were modeled using SAP 2000 (CSI, 2018).

The taller of the two structures, Tower 1 (T1) is a representative office building with 45 stories and a height of 184 meters (see Figure 1). The framework of such a tower is made up by a rigid core plus moment-resisting frames. Therefore, T1 exhibits a similar distribution of structural elements, with some size variations and a different height from T1 (see Table 1). Here again, the first-floor height was doubled to 8 meters to create a tall lobby, with all other stories remaining at 4 meters’ height.

Tower 2 (T2) is a representative residential building, which has 30 stories and a height of 124 meters (see Figure 2). The framework of this tower is the same as that of Tower 1, i.e., it is made up by a rigid core plus moment-resisting frames. Therefore, T2 exhibits a similar distribution of structural elements, with some size variations and a different height from T1 (see Table 1). Here again, the first-floor height was doubled to 8 meters to create a tall lobby, with all other stories being 4 meters high (see Figure 2).

Lastly, the linkage is modeled using a beam 30 meters long, which is representative of a coupled connection between buildings on opposite sides of a street. In the first case, the link is placed between two identical* Tower 2’s (see Figure 3); whereas in the second case, it connects Tower 1 to Tower 2 (see Figure 4). These patterns produce two situations that might occur when buildings are connected. The twin-tower system (TTS) describes a well-ordered scenario, in which the link can be realized in a symmetric position and the buildings have almost the same masses, heights and footprints. However, these conditions are not always a given; therefore, any change to the model increases the computation time needed to process any variations. In the second case, which is, in fact, representative of such a disorder, two completely different towers are linked together in an asymmetric configuration. This second building system, the twin-tower/asymmetric (TTA) system, is doubtless more realistic than the first one, but in order to better understand how the behavior of such structures changes, it is fundamental to compare a simple pattern to one that is more complex.
Link rigidity was also examined in the study. Two different links have been used. The first is infinitely rigid, and therefore, floors that it connects between two buildings and across the link behave as one single stiff slab. The second type of linkage has been designed to act as a flexible element instead. Although the floors it connects do not work as one stiff element, there are some interactions, due to the fact that the link behaves as an unloaded tie bar (that is, one building might drag the other). Both links have a weight equal to 0 and infinite resistance (they cannot collapse or be damaged).

Modal Analysis

For this study, response-spectrum (modal) analysis is used. Regarding to the modal mass evaluation the section “Seismic Design Requirements for Building Structures” of ASCE 7-10 (American Society of Civil Engineers, 2010) is followed. First, unconnected towers are evaluated. Then, the coupled condition is evaluated. The size and design of the towers are not varied between the two experiments. Instead, the rigidity of the link varies from infinitely stiff to infinitely flexible. Additionally, the floor-by-floor location of the connection is changed.

Individual Towers

To create a baseline of behavior, 3D models of the individual towers were studied. Modes 1 and 2 (see Figure 5) are the most important modes, with translational movement in the x and y directions, exciting about half of T1’s modal mass. T1 excites 75 percent of the total seismic mass through the first six modes in both directions (see Table 2). Also, as expected, there are no torsional effects in the modal results of the first two modes, due to the symmetry of the structure’s plan and the coincidental location of the mass and stiffness centers.

Modes 1 and 2 of T2 (see Figure 6) have the largest mass participating factors along the x and y directions, similar to T1. However, T2 shows slightly different behavior from T1 (see Table 2). Here, 80 percent of the total mass participation is achieved in the first six modes. Additionally, this structure has a lower fundamental period of 2.7 seconds, compared to T1’s 3.7-second period, which is consistent with the difference in structural height. Similar to T1, T2 has only translational motion in the first and second modes. Notably, both buildings require approximately 12 modes to reach 85 percent mass participation in each direction. The majority of mass participation (about 75 percent) in both towers occurs in the first six modes, underlining the higher modes’ influence. The influence of higher modes is very significant for tall buildings, and perhaps an issue that coupled towers could address.

Overall, the modal analysis of the individual towers presented several key observations. Firstly, the difference in the natural periods is 1 second. However, because of their plan configurations, both towers have two main translational modal shapes and one torsional shape, with no coupling of the responses.

Linked Buildings System

For this portion of the study, the two links were iteratively repositioned throughout the heights of the structures to evaluate the influence of their positions on the structural responses.

Influence of Symmetric Placement of Link

The first results examine how the position of the link in the TTS versus TTA influences the modal response. For TTS, the mode shapes are purely translational, with no torsional response (see Figure 7). However, if a slight asymmetry is introduced as in TTA, the second mode shape starts to assume torsional nuances (see Figure 8). The wider
the asymmetry in the plan of the buildings, the clearer and more significant is their torsional nature. Mode 1 does not see any change in the modal response between TTS and TTA, as it remains translational. Mode 2 goes from being purely translational to being either translational or torsional (depending on link position through height) in the TTA scenario. In fact, for higher link placements, the shape of mode 2 is driven by the y-translation of T1, while T2 acts solely as a restraint of such movement. This constraining effect of T2 decreases the closer the link is to the ground. The final result is a mixed y-translational and torsional mode form. This is because modal motions of a system are led by the “main” modal movement, which occurs under a specific natural period. The modal motions of linked-building systems are often made up by the principal movement of one tower plus the accompanying movement of the other.

**Influence of Link Rigidity**

The next set of results examines how the link’s rigidity influences the modal response for the TTS system. Overall, regardless of its placement height, a stiff link synchronizes and affects the motions of the buildings (TTS and TTA). However, by decreasing link rigidity, synchronous motion between the towers dissipates. For instance, a mid-height placement of a flexible connection linking twin towers does not provide enough stiffness to the system, and because of that, the towers move in different directions (see Figure 7).
Figure 9. When a very stiff link is added, it synchronizes and affects the motions of the buildings, regardless of where it is placed. This is particularly evident in linked buildings that have different features like height, material or weight.

Next, a comparison of modal periods of the individual towers against six different TTS scenarios (three considering the stiff link, and three the flexible link) was performed. The link was placed at the second, 16th and 30th stories of the connected buildings. Some observations can be deduced from this analysis. Almost the same periods can be noticed when TTS are compared to the individual T2 natural periods. Surprisingly, rigid link placements far from the base induce natural periods closer to those of the single T2. On the other side, flexible links show an increase of the TTS' periods (see Figure 10).

This could be deceiving, since towers (as for instance, in the TTA) connected through flexible links should behave as uncoupled. However, when twin buildings are connected, some side effects are produced. To be understood, they must be discussed in conjunction with the participating mass ratio.

Influence of Link Rigidity and Placement
Here TTA was used to study how this asymmetry, when coupled with the rigid and flexible links, will influence the response. Often in these systems, there is one building that is heavier and more deformable; it literally drags the other along the direction where the link is more effective. This effect is marked in the first modes and changes with the link position. One interesting aspect is that torsional modes, which are greater in number in TTA systems than in the corresponding individual towers, does not change with the connection height. Since the link is flexible, it is in fact impossible that such a case occurs. The scenario mainly affected by the link introduction is that with different towers connected by rigid link. The influence of the connection is greater in these systems because the stiff link restrains the modal shapes that otherwise would be produced by the individual towers.

Additionally, an extremely rigid link tends to decrease the natural period as connection height increases (see Figure 11). This is reasonable, since T1 has a higher fundamental period than T2. Therefore, the stiffer and shorter T2 acts as a restraint of the
main modal shapes of the higher and heavier tower. This restraint effect clearly increases with connection height, since greater modal displacements occur near the top of T1. On the other hand, flexible links do not affect the higher TTA’s natural periods, as those were the same as the periods recorded when T1 was uncoupled. In this case, in fact, the connection has a limited influence on the stiffer building. It is interesting to note that, when using flexible links, the natural periods of the system are similar to the individual tower periods. This is also true for rigid links located near the base, as this produces an uncoupled response between the towers. Overall, the behavior tends to the modal response of T1. That is, the taller tower leads the system’s modal motions, especially in the first, most important modes, while the smaller one acts as a restraint.

Next, the variation in participating mass for the individual TTS and TTA systems across the first eight modes is discussed. When twin buildings are connected through a rigid link, the participating mass does not change with the position of the connection (see Figure 12). In addition, the participating mass of the system follows that of the individual T2. Therefore, the modal shapes of the first two modes are translational and the third torsional. However, in this torsional mode, towers tend to rotate around the middle of the rigid link, since the connection changes the position of the center of stiffness of the individual towers (see Figure 13).

If the rigid link is replaced with a flexible one, the participation of the mass appears to fluctuate (see Figure 14). This type of link, combined with the fact that the towers are identical, produces an interesting situation. In fact, looking at the trend of the participating mass along X and Rz (Y does not considerably change), it seems that for some link position the second and third modes are translational, while for others, the result is torsional. However, this is not true; a flexible link has to let the towers move independently relative to each other; therefore, it is not possible to have a torsional mode. The reason the software recognizes
this mode as “torsional” is that the two towers move in opposite directions (as previously seen in Figure 9). Actually, the first real torsional movements present in the sixth mode (see Figure 15), a situation that is more plausible in this kind of system.

When TTA is used instead of TTS, the participation mass fluctuation becomes more marked. A first step of this variation is noticed when a flexible link is used. Along the direction of the link, the participating mass ratio is in fact being affected by the connection height (see Figure 16). Having different high natural periods, the TTA towers affect each other more than do the TTS towers. In the rigidly coupled system, the participating mass variation can be subdivided into zones based on the level of sensitivity due to the link placement: the Zone 1 link affects only the participating mass factor, and the Zone 2 link affects either the participating mass or mode shape (see Figure 17). In Zone 1, the modal shapes are uniquely defined under every possible link position, falling into the group of the first three modes. The second and third modes are always y-translational and torsional while presenting an almost steady trend of participating mass. In Zone 2, different modal shapes can occur inside of the same mode, because of the diverse link height. Unlike the first three modes, the fourth mode’s participating mass factor and modal shape are affected by the link position. For this mode, higher link positions produce translational shapes along the x direction, while lower and middle link positions produce mixed torsional and y-translational shapes (indeed, they produce sharply y-translational forms for bottom link placements). This modal behavior is in line with expectations, since connections will lead to an uncoupled situation (T1 does not affect T2, and vice versa).

In principle, lower link positions decrease the participation factor of modal mass, mostly along the link direction; this is reasonable, as the tower motion can be considered basically uncoupled and the system is able
to excite less mass per mode. Furthermore, when the link is placed near the bottom of the TTA system, it is interesting to observe which modal shapes maintain a certain recognizability (i.e., the system modal motions present only a predominant displacement or rotation, without showing small modal movements in any other direction or rotation). On the other hand, a link placed close to T2’s top increases the influence of T1’s modal motions on T2 and vice versa, increasing the participating mass per mode.

Lastly, it is important to note these graphs do not consider the modal mass of single towers when they are linked together; they refer to a sum (T1’s excited mass plus T2’s excited mass). Therefore, it is not possible to capture the amount of modal mass excited by one tower singularly. For instance, a connection placed at the top of T2 produces, in the first mode, a total participating factor of 55 percent, but it does not provide any information about the amount of mass T1 and T2 excited in the x-direction singularly.

Concluding Remarks

Horizontal coupling in tall buildings is an important practice that needs to be carefully studied. As is shown in this preliminary study, these connections change the modal dynamic behavior of tall buildings with the increasing of link stiffness. Since the rigid link synchronizes the motions of tall buildings, the naturally higher periods are closer to the taller single tower, or they do not change at all, in the case of twin towers. Although the variation in period does not change much in the first four modes, there is an increasing difference in the higher modes. Meanwhile, there is no variation in TTS. In TTA systems, when the link is rigid, the smaller building acts as a stiffener, altering the natural vibrating modes (this is considerable for lower periods).

This does not occur in twin-tower systems, because of the modal similarities that exist in both towers. Because of the different heights, masses and plan shapes, rigidly connected TTA systems have modal shapes that do not operate in a predominant direction, especially during the first modes, but they have mixed modal shapes (y-translational and torsional modes). In TTAs, the stiff link placed along the x-direction mainly increases the stiffness of the system in that direction; also, modal shapes along this direction are not coupled with any y-translational or torsional shapes. Unlike the x-direction, the y-translational or torsional mode forms can present mixed shapes. On the other side, flexible links increase the “individuality” of towers that, however, remain still affected by some “coupling effects” along the link direction.

This study provides an exploratory investigation of coupled towers by way of rigid and flexible links, providing some important outcomes that underline the modal features of rigidly- and loosely-linked building systems, and how these connections affect coupled towers. Although, rigid and flexible connections are idealized situations, in which the motions of two tall buildings are restrained, these stiffness variations allow definition of the contours of all modal changes. In fact, in all probability, having a defined stiffness, a realistic skybridge will induce changes in the system that would register at the midpoint between those produced by the rigid and flexible links, respectively.

Unless otherwise noted, all photography credits in this paper are to the authors.

Further Reading


Editor’s Note: See more on CTBUH skybridge-related research at bit.ly/38Is1Kt

References

American Society Of Civil Engineers (ASCE). (2010). Section 12.7.2,“Seismic Design Requirements for Building Structures” ASCE 7-10.

