IMPROVING PERFORMANCE OF CONNECTED HIGH-RISE STRUCTURES THROUGH THE USE OF SKYBRIDGES

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Abstract

With recent efforts to increase reliability and enhance the value of emerging high-rise building clusters, skybridges as linking systems are attracting interest by urban designers and could play a key role in the development of our future cities. While the functional and economic benefits of the skybridges are realized, the effects of skybridges on structural systems are not widely understood. Researchers and practitioners in both academia and industry have been investigating the potential of the skybridge to increase the resiliency and sustainability of the connected structures. However, there is a gap between engineering science in academia and engineering practice in industry, which has previously limiting the research outcomes from becoming built realities.

Partnering with an industry expert in high-rise building design, Skidmore, Owings & Merrill LLP, this study seeks to better understand how coupling behaviors between high-rise structures using a skybridge affect various aspects of the individual and the linked structures. In this study, parametric data, including modal information, displacement, shear, and overturning moment are gathered from realistic high-rise structure models to evaluate the structural performance under static and dynamic loading when the skybridge is installed at various locations of the structures.

Keywords: Connected Structures; Skybridge; Seismic Performance

1. Introduction

A skybridge can be viewed as a linking system between high-rise structures that serve many purposes. It can be used to evacuate the occupants in these connected tall structures more efficiently, shelter pedestrians from weather, save floor space, and add space for public zones around the floors where the skybridges are installed [1, 2]. For example, if an event (e.g., the September 11th attacks in 2001) that restricts vertical evacuation occurs, skybridge can be used as horizontal evacuation to a neighboring building. Besides, it can also connect buildings with different service functions (e.g., office building and residential building) to direct the flow of people. Additionally, skybridge can be an architectural attraction. The CCTV Headquarters and The Gate to the East in China, for example, masterfully use skybridges to increase the structural beauty of two high-rise structures.

Although skybridges are used worldwide, their effects on high-rise structures are not widely understood. Typically, skybridges are designed to have as little impact on structures as possible through decoupling the behavior of independent towers [3]. Wood [1] and Wood *et al.* [2] concluded that more considerations must be used when designing such structures, as the effects of coupling tower behavior, especially with wind and seismic reactions, are not well understood. In recent years, researchers have begun to examine the effects of coupling two high-rise structures. Song *et al.* [4] investigated the effects of such structural links on the modal properties and wind-induced responses by using three-dimensional analytical models. In this study, the two linked buildings were modeled identically. The authors investigated the effects of the link parameters, including mass, axial stiffness, bending stiffness, and location on the linked skybridge system. This study focused on how adding a skybridge would affect the wind-induced response of the structures and did not consider the effect of the link on the mode shapes of the system. Christenson *et al.* [5] and Lobo-Aguilar *et al.* [6] evaluated the application of the connected control method to seismically excited adjacent buildings. These studies focused on utilizing the skybridges as a control element and examined the effects of building height and coupling link location on the seismic performance of two linked high-rise structures.

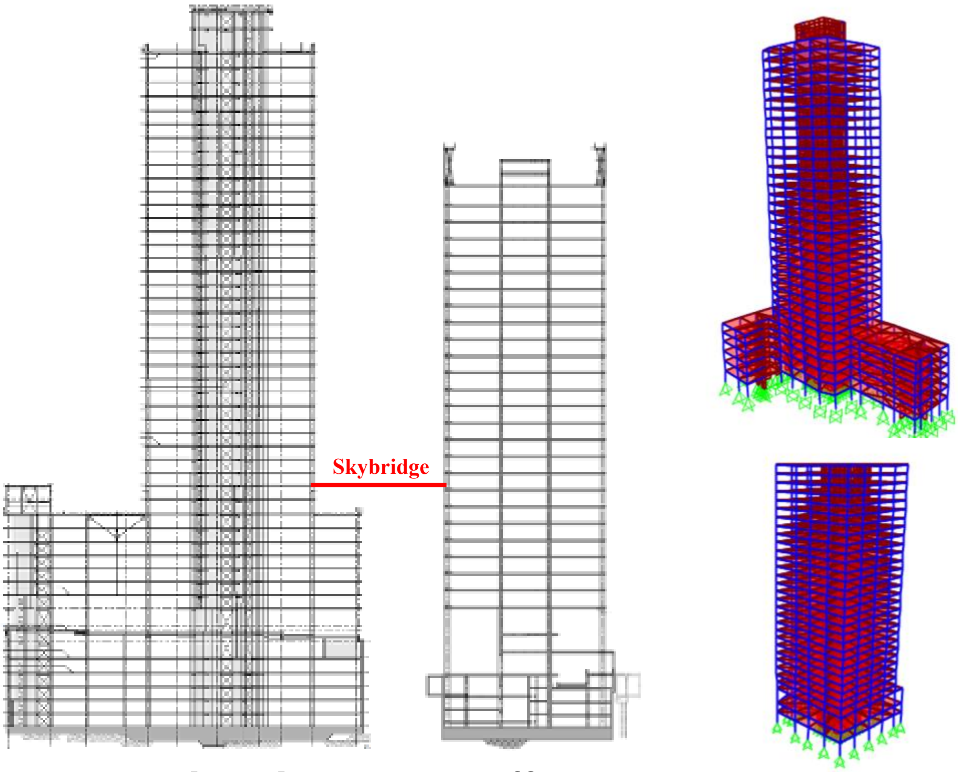
Through a National Science Foundation (NSF) Research Experience for Undergraduates (REU) Site program [7, 8], the study presented in this paper explores how coupling two buildings with a rigid link between them may affect the static and dynamic responses of one or both buildings. Modal, joint displacement, base/story shear, and overturning moment studies are performed on the two standalone buildings with different service functions and linked skybridge system with the skybridge attached at different floors to provide insights on the optimal placement of the skybridge.

2. Building Model

Two skyscrapers, a typical residential and an office structure, were modeled using SAP2000 [9] based on building plans provided by Skidmore, Owings & Merrill LLP (SOM), one of the industry partners of the REU program. The residential building is approximately 400 feet tall with 7-inches concrete floor slabs while the typical office building is approximately 370 feet tall with 11-inches concrete floor slabs. The residential building is the lighter of the two buildings and exhibits more flexible behavior than the office building. A skybridge, represented by a rigid steel beam fixed at both ends, was used to connect the residential and office buildings. The beam's modulus of elasticity was increased by a factor of ten in order to increase its stiffness to allow for the load transfer between the two buildings. The elevation view of the two structures with the link beam is shown in Fig. 1.

Several assumptions were made when modeling the structures. First, a rigid diaphragm was assigned at each floor of both buildings, and the floor slabs were modeled as a membrane. This was to ensure connectivity and lateral load transfer to the concrete core, which was the main lateral support element in both buildings. Besides, cracking factors, in accordance with the Tall Building Initiatives Design Guidelines (v 2.03; [10]), were assigned to the slab, columns, and shear walls. The cracking factors account for the material performance that these structures may experience in a real-world setting. To align the floor of both buildings, the floor heights were slightly modified from the original building designs. This allows this study to understand how a purely horizontal connection affects the structures. From the 5th floor onward in the residential structure, and the 3rd floor onward in the office building, the floor heights were altered to be the same height of 11' 2.5".

Tables 1 and 2 show the first three modes of the two buildings. Comparing to the orginal design, the building models exhibited similar behaviors. The participating mass ratios for both building models (Fig. 2) are also consistent with the evaluation of both physical buildings by SOM.



Residential Office

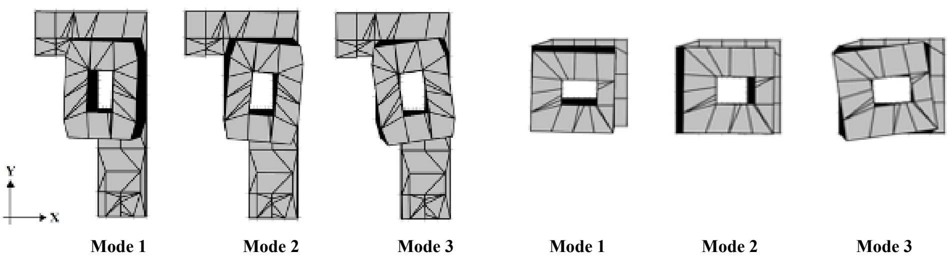
Fig. 1 – Structural Models of Residential and Office Buildings

Table 1: Modal Information – Residential Building

Mode Number	Period (sec)	U_x	U_y	R_z	Description
1	5.45	0.465	0.064	0.0038	Primary X-translational Mode
2	5.04	0.057	0.347	0.107	Primary Y-translational Mode
3	3.51	0.002	0.176	0.228	Primary Z-rotational Mode

Table 2: Modal Information – Office Building

Mode Number	Period (sec)	U_x	U_y	R_z	Description
1	4.82	0.0013	0.599	0.019	Primary Y-translational Mode
2	4.18	0.639	0.0004	0.0025	Primary X-translational Mode
3	3.84	0.0031	0.018	0.682	Primary Z-rotational Mode



Residential Building Office Building

Fig. 2 – Structural Modes of Residential and Office Buildings

3. Analysis Approach

Equipped with realistic building models, this study seeks to understand how changing the location of the skybridge by story would affect the performance of both structures under static and dynamic loadings. Given the large number of possible locations of the skybridge, it is tedious, if even possible, to go through the process of varying the skybridge location and evaluate the structural performance manually. With such, an automated framework was developed to facilitate the process using SAP open application programming (OAPI; [11]) and Microsoft Visual Basic Architecture (VBA; [12]). Scripts were developed to allow for automation of both the skybridge placement and information extraction after running the structural analyses. The automated framework avoided the need to create multiple models with the skybridge attached at different stories and simplified the information extraction process significantly. The flowchart of the developed framework is shown in Fig. 3.

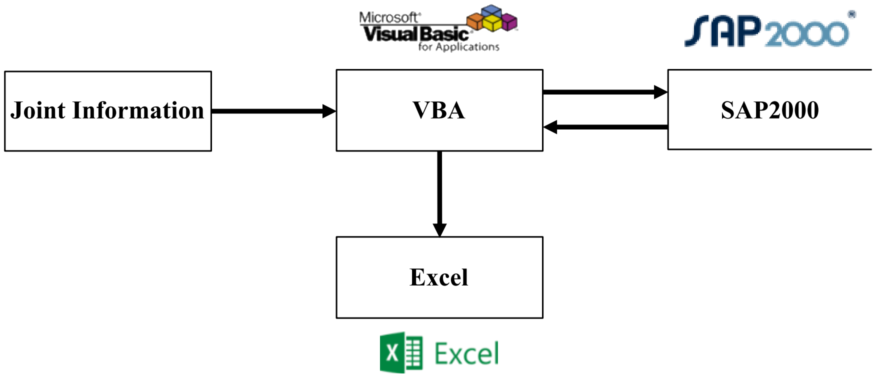


Fig. 3 – Automated System Flowchart.

In this framework, a VBA script was first written to draw a skybridge element in SAP2000 between the building models at the joints of the lowest floor of interest. The same process was then iterated to delete the previously drawn skybridge and place a new skybridge one floor higher. Between iterations, analysis in SAP2000 was also be commanded to run through the Microsoft VBA script, allowing for the automation of the analysis. Once the analysis was done, results (i.e., modal, joint displacement, shear, and overturning moment information) were extracted and exported to Excel for postprocessing. Thirty different skybridge locations were analyzed without the need of user input, ranging from the 5th floor in the residential building (3rd floor in the office building), to the 33rd floor (31st floor in the office building).

4. Results

4.1 Modal analysis

A modal study was performed to determine how adding a rigid link between the two structures would affect the modal periods and mass participation ratios of the buildings. Table 3 shows a typical modal analysis result when the skybridge connected at the 33rd story of the residential building. The corresponding vibrating mode shapes are shown in Fig. 3. It can be observed that when a skybridge is added between the structures, the modal periods are no longer the periods of the individual buildings, but rather a combination of the two. This demonstrates that the rigid link couples the buildings and will, therefore, alter the static and dynamic responses of the two buildings.

Table 3: Modal Information – Connected Building with Skybridge at 33rd Story

Mode Number	Period (sec)	U_x	U_y	R_z	Description
1	4.93	0.007	0.379	0.028	Primary Y-translational Mode
2	4.79	0.006	0.145	0.364	Primary Z-rotational Mode
3	4.62	0.568	0.004	0.009	Primary X-translational Mode

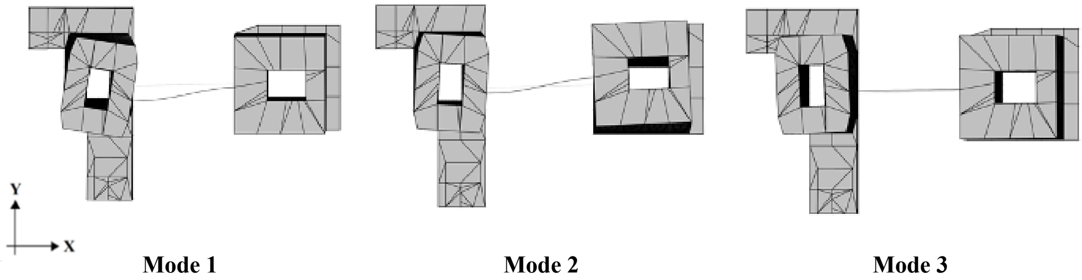


Fig. 3 – Structural Modes of Connected Buildings with Skybridge at 33rd Story

To demonstrate the effects of the skybridge on the mass participation ratios (MPR) in the x, y, and rotational z-directions, the first ten modes were gathered for the two individual buildings and the coupled structures with the skybridge connecting the structures at thirty different story heights (see Figs. 4-6). The red bars represent the residential building and the green bars the office building. The mass participation ratios of the individual buildings were normalized in these figures to consider the mass of both structures as opposed to just the individual structure. This allows the visualization of how connecting the structures with a skybridge changes the MPR in all three directions. It also shows how adding the skybridge at certain stories changes the MPR more than when it links the buildings at other stories. In these figures, the blue gradient describes the mass participation ratio in the x-direction with the skybridge connecting the buildings at various stories. Similarly, the yellow gradient depicts the mass participation ratio in the y-direction, and the gray gradient depicts the mass participation ratio in the rotational z-direction. The darkest color in each gradient represents when the skybridge is at the lowest story (5th story of the residential building and 3rd story of the office building), and the lightest color represents when the skybridge is at the highest story (33rd story of the residential building and 31st story of the office building).

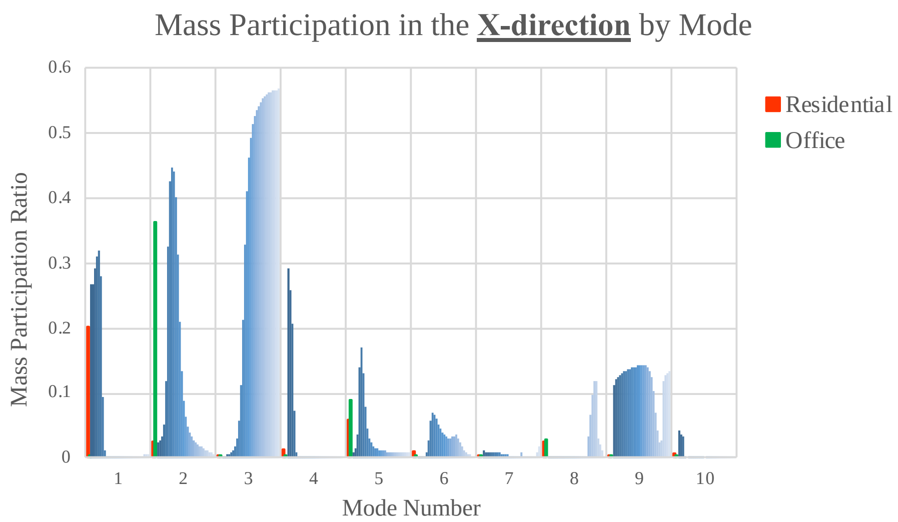


Fig. 4 – MPR in the X-direction by Mode

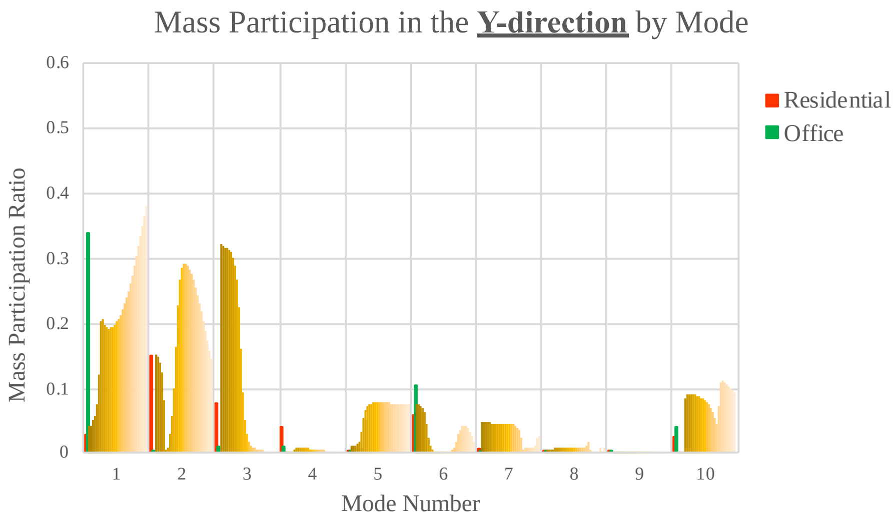


Fig. 5 – MPR in the Y-direction by Mode

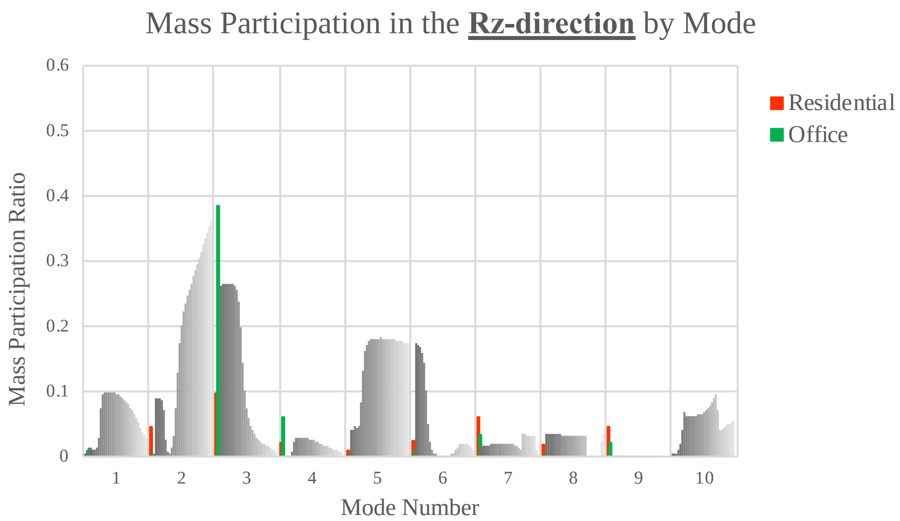


Fig. 6 – MPR in the Rz-direction by Mode

This modal study allowed for observations on how coupling the buildings with a rigid link affected the modal properties of the connected structures. By linking the two structures, the mass participation appears to redistribute with the skybridge located at a different height. For example, it can be observed that the mass participation ratio in the x-direction decreases in the first mode when the skybridge links the structures at the higher stories. It was discovered that in the higher modes, the mode of the linked structure is neither dominated by the residential or office buildings. Instead, the linked structure produces modes independent of the individual structures.

4.2 Joint displacement analysis

To determine how the joint displacement of the individual structures changed when the skybridge was added to connect the buildings at various story heights, the point of maximum displacement on the top floor of each building was analyzed. Joint displacement data was gathered from the performance of the structures under response spectrum in both x and y directions as well as the time histories of four earthquakes: (1) Kobe, (2) Imperial Valley, (3) Northridge, and (4) Loma Prieta. Given the space limitation, only response spectrum analysis results are shown here as examples.

In order to further study how linking the two structures with a rigid skybridge affects the joint displacement at the top floor of each building, the relative joint displacements of both the residential and office buildings are overlaid. The joint displacements are normalized by dividing the top floor joint displacements of the linked skybridge systems by the top floor joint displacement of the individual buildings. Therefore, if the relative maximum joint displacement is greater than one, there is an increase in the top floor joint displacement when the skybridge is added. If the relative maximum joint displacement is less than one, on the other hand, the top floor joint displacement decreases when the skybridge is added.

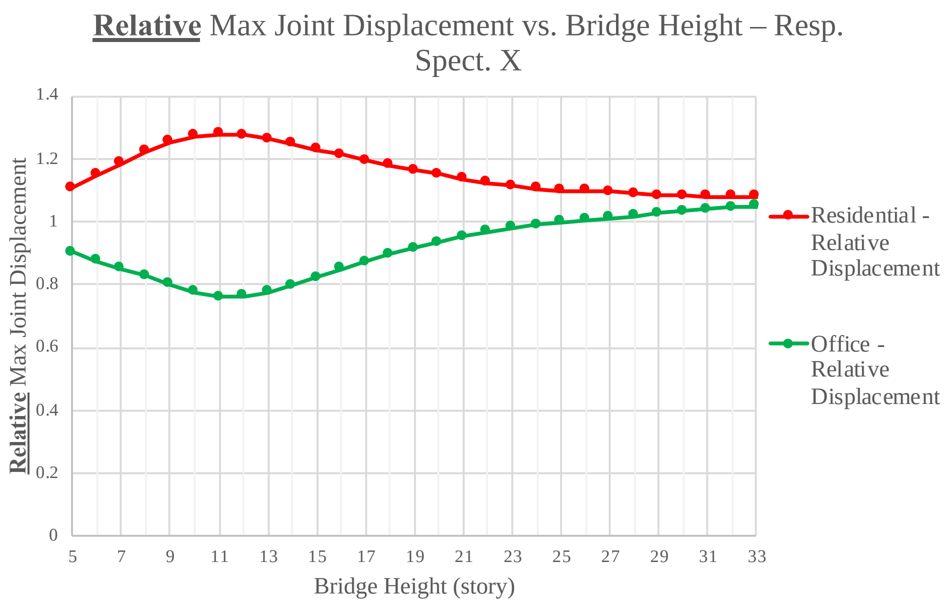


Fig. 7 – Relative Max Joint Displacement vs. Skybridge Height

Fig. 7 plots the response spectrum in the x-direction. When a rigid link is added, the top floor joint displacement of the residential building tends to increase, and the top floor joint displacement of the office building tends to decrease. When the skybridge is at the higher stories, however, the top floor joint displacement of both the residential and office buildings increases.

4.3 Shear and overturning moment analysis

For dynamic responses, base shear, story shear, and overturning moment data were exported to Excel automatically after performing the analyses. This data was then plotted in order to visualize how these values changed for both buildings as the link skybridge was installed up the buildings. Figs. 8 and 9 are used as examples to demonstrate how the maximum base shear in each building changes as the skybridge is installed at different locations up the buildings. The control cases, as in the buildings with no skybridge, are displayed for reference using dashed lines. It should be noted that all dynamic responses and measurements were taken in the global x-direction, and skybridge height is taken with respect to the residential building.

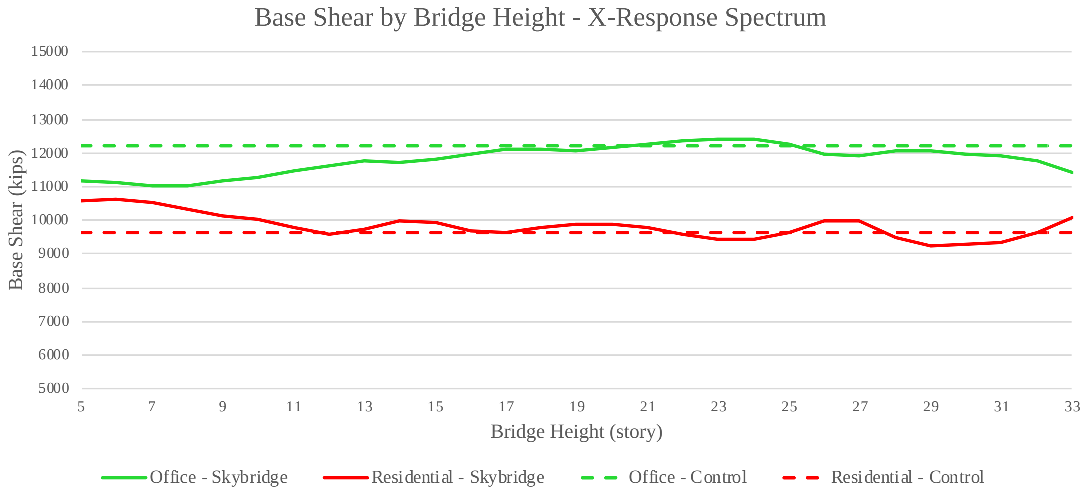


Fig. 8 – Base Shear vs. Skybridge Height – X Direction Response Spectrum

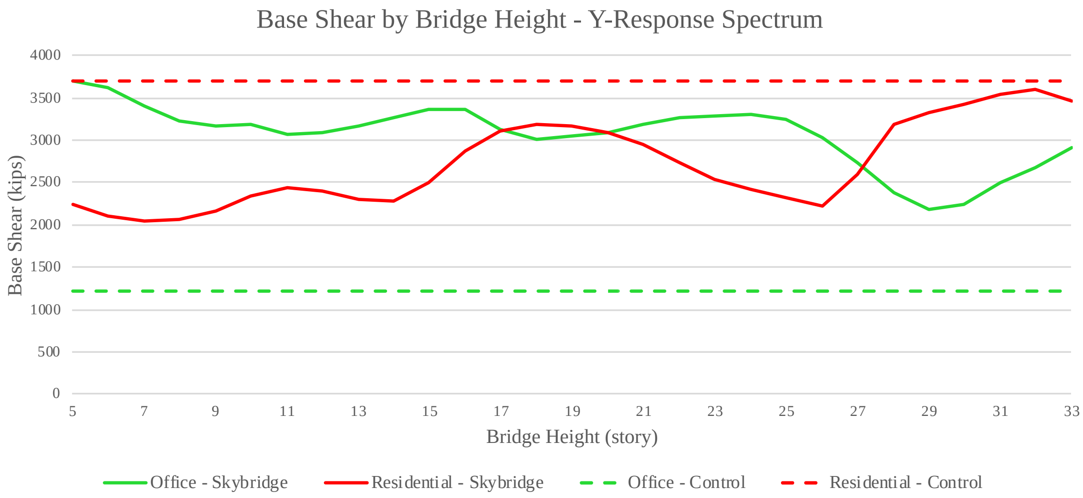


Fig. 9 – Base Shear vs. Skybridge Height – Y Direction Response Spectrum

Here a “mirrored” behavior is observed. For example, in Fig. 8, when the office building’s base shear increases, the residential building’s base shear usually decreases, and vice versa. It is also interesting to see that the office building has lower base shear when the skybridge is at the lower stories, and the residential building has an increased base shear at these scenarios. This can also be observed when the skybridge is placed at story 32 and 33.

A similar sensitivity can be observed in the story shear. Figs. 10 and 11 show the story shear in both buildings as the skybridge moved up the building for both buildings at selected floors. The control cases are once again displayed for comparison.

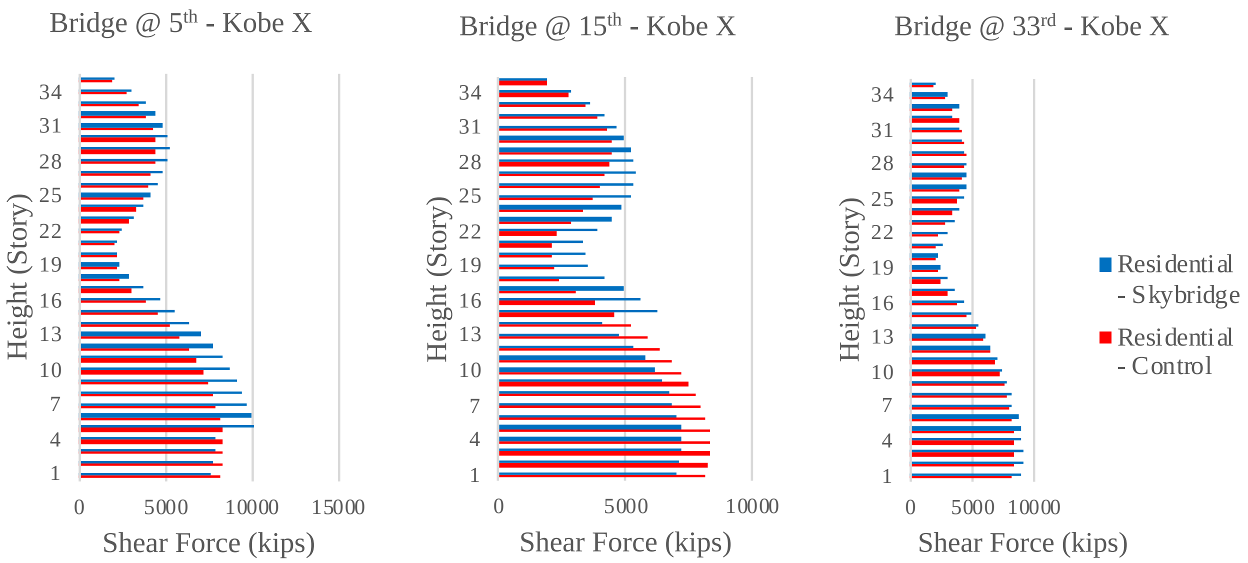


Fig. 10 – Residential Building Story Shear vs. Skybridge Height

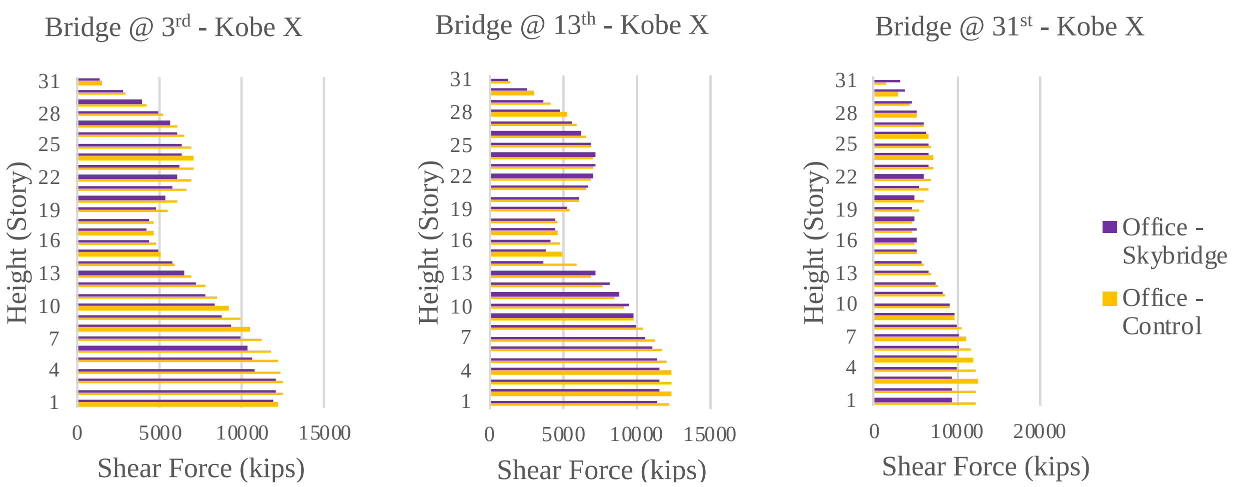


Fig. 11 – Office Building Story Shear vs. Skybridge Height

From these graphs, it is clear that the shear behavior changes at the floor where the skybridge is installed on, where an increase can usually be seen in the shear. The shear in the floors above and below the skybridge typically change too. In fact, the base shears for most dynamic responses decrease in the office building when the skybridge is installed at the highest floors. The increase in the shear at the higher stories for this case is not of large concern either, considering that the higher floors of the building are often over-designed to account for elevators and link beam width. As a general trend, the shear performance in the office buildings is usually improved, while the residential building is worsened. However, the changes in performance are relatively small in most cases.

Lastly, the overturning moment around the global y-axis was also recorded. This base reaction is the moment that attempts to tip the structure over. Figs. 12 and 13 show the overturning moments similar in behavior to the story shear in format, and in behavior.

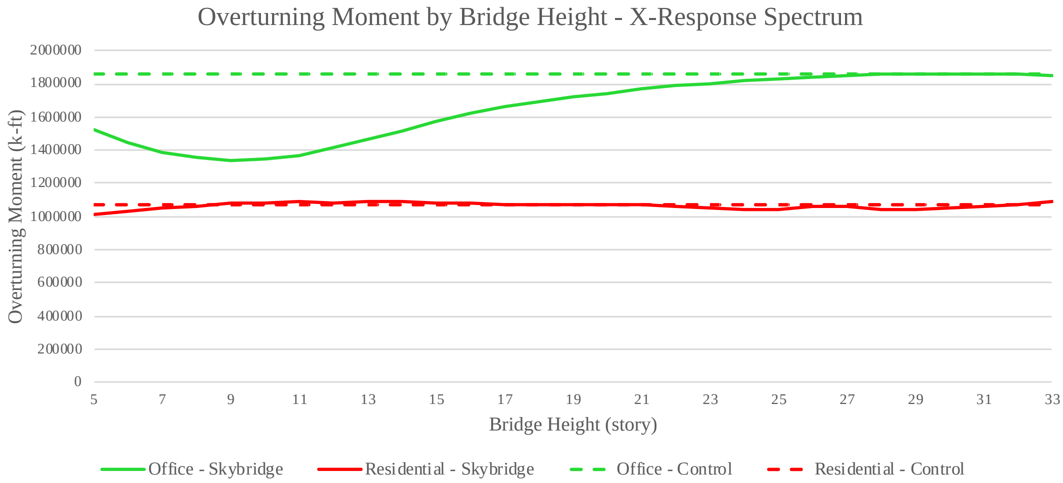


Fig. 12 – Overturning Moment vs. Skybridge Height – X Direction Response Spectrum

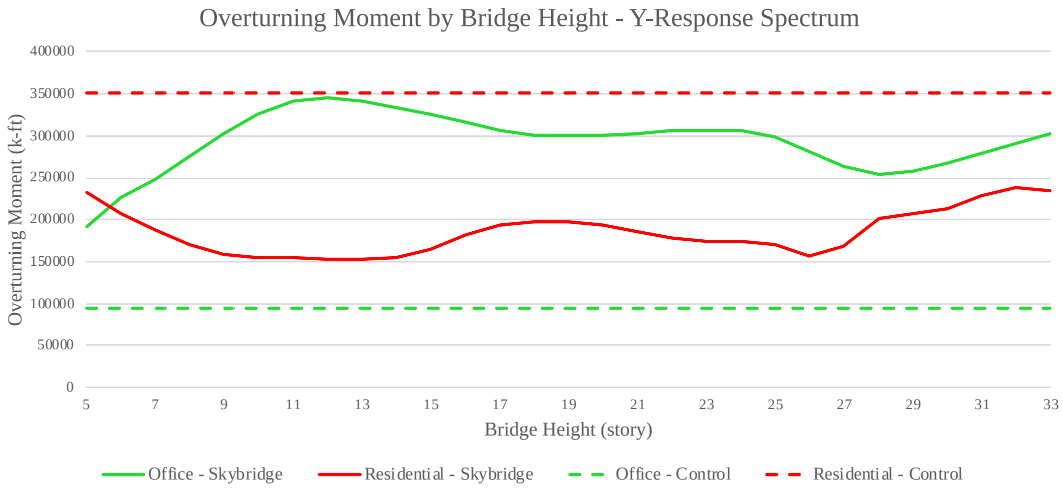


Fig. 13 – Overturning Moment vs. Skybridge Height – X Direction Response Spectrum

5. Conclusions

In recent years, aesthetic attraction, advancement of materials, and innovation on structural design and construction techniques are pushing the boundaries of high-rises. Connecting such structures with skybridges is increasingly being considered as a way to address the need for accessibility. By using two realistic models of residential and office buildings, this study intends to provide insights on the behaviors of these structures with a skybridge connecting between them. As a preliminary study, the skybridge is assumed to be rigid so that the loads can be transferred between the two structures through the rigid diaphragm. Thirty different skybridge locations were analyzed using an automated framework to investigate the effects on static and dynamic responses of the connected structures.

From the modal study results, it was evident that by coupling the behavior of two buildings, one could potentially significantly strengthen the weak modes a structure through the clever placement of a skybridge. Looking at the displacement, the skybridge had a small but noticeable effect. Future studies on movement perception or displacement performance criteria could provide better insights into the optimal placement of skybridge in terms of displacement reduction. The results from the shear and overturning moment study, base shear could potentially be improved. Shear performance could be improved at lower floors, at the cost of increasing the shear on higher floors. This could be beneficial, considering the over-design of most lateral systems at the higher floors of skyscrapers. Overall, this study highlighted the variability in the structural performance of skybridge systems with varying the skybridge location, which provides a preliminary understanding of what parameters could potentially be examined in order to find an optimal location. It shows that skybridges also potentially offer structural benefits, and at the very least, highlights potential to change the performance of structural systems through the placement of such a link. In the future study, observations of other structural characteristics could be varied to give an even better understanding and lead to the more informed design of such systems. In addition, modifications to the skybridge system, such as varying the connection angles, including damping or changing connection types, would also be interesting to investigate.

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