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Preliminary Study on Tall Building Coupling Using a Rigid Link

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ABSTRACT

In growing urban cities, there is an evident trend towards vertical expansion with skyscrapers competing to achieve the highest point in the skyline. With this growth, there is an increasing need for interconnected residential and commercial buildings using skybridges to provide more effective movement between the structures. However, this raises questions on how these skybridges influence the structural response. Past studies demonstrated that such connections, if adequately designed, can be advantageous for controlling seismic and wind response. In this preliminary study, the seismic behavior of two skyscrapers is studied considering a rigid link representing the skybridge to understand variations of the base shear between the connected and individual buildings and the impact on story shear. The two buildings are designed to represent typical commercial and residential designs with concrete shear wall cores. This work is carried out through the use of dynamic analyses in SAP2000. The sensitivity of the skybridge placement is also discussed as this is an important factor in understanding how the dynamics of the structures can change with simple movements of the link throughout the building height. This work presents fundamental knowledge on how structural components cannot only enhance community mobility but also control and optimize structural performance .

Keywords: tall building, rigid link, linked buildings system, dynamic response

INTRODUCTION

Today, cities are growing in an unstoppable and unexpected way; they are growing not only thru vertical expansion but also thru horizontal connections. Skybridges at their incredible heights do not only link two buildings but can improve the tall buildings' dynamic features, as past studies have demonstrated. Thus, this article establishes a first approach on the horizontal coupling of two tall buildings or skyscrapers using a rigid link to influence the buildings' dynamic behavior.

To carry out this work the features of the unconnected and connected tall buildings have been analyzed and compared each other, considering multiple link positions; in fact, different locations of the connection show various results since the system can be schematized as two cantilever connected by an infinitely rigid link.

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However, two papers in particular have evaluated the effectiveness of coupling structural behavior through skybridges. The first is Taraldsen [2017] and serves as the main basis for this report's study; in "Linking Skyscrapers", the dynamic behavior of linked twin buildings was investigated by evaluating different skybridge configurations and positions under quasi-static wind loads. Taraldsen observed that by positioning structural links at heights about 0.3 times the total height of the twin towers, the load on one of the towers could be shared equally at the base of both towers. In addition, the displacement at the link was found to vary linearly with height and the magnitude varied with link stiffness. The second is written by the authors of this paper in which the Taraldsen work is taken a step forward with a very simple yet important look at modal response. To further investigate the skybridge influence, a number of areas, including linking buildings of varying heights, the use of modern central core design, modal behavior, and seismic response, are worth looking into.

BUILDING DESIGNS

The Taraldsen Towers were an initial step in examining the response of linked structures. As mentioned above, there are two key structural details that were updated in this study. Firstly, given the current market demand, this study evaluates the connection of a residential and office building of two different heights. Secondly, the original structural system reflected a central core not representative of modern tall building design. The larger core is implemented to limit maximum displacements by increasing the overall building stiffness. As a result, the central cores are the result of a design update based on recommendations from industry experts. Therefore, the two new buildings are completely different from the Taraldsen Towers, because of the modifications to the core dimensions, removal of the internal columns (keeping just the external vertical members), changes of the cross sections, plan; however, as said such paper provided just an initial address. The material properties of the towers are summarized in Table 1 below with the building designs shown in Figure 1.

Table 1. Reinforced concrete properties.

C50/60	
Density	25000 N/m^3
E	37278 Mpa
f_c	50 Mpa

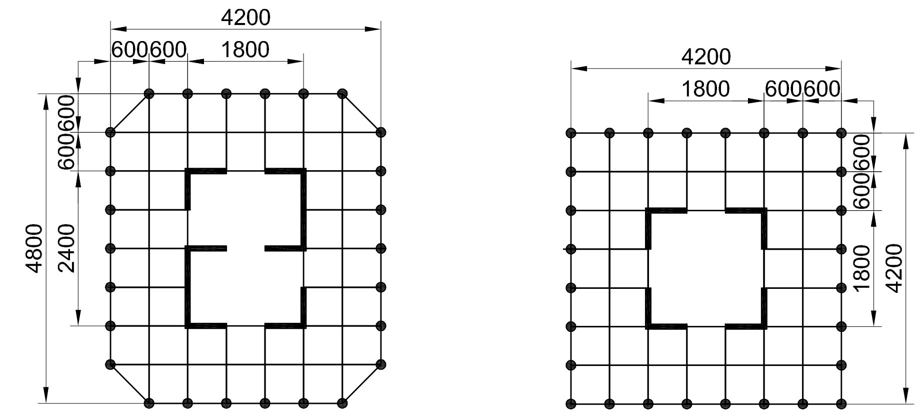


Figure 1. Building Plans: Tower 1 (T1) (a) and Tower 2 (T2) (b); dimensions in centimeters.

Tower 1 (T1) is the taller of the two structures standing at 184 meters high or about 604 feet (45 stories). This structure is designed to be a representative office building that has a fixed release with the ground. The square cross sections of every column changes with the tower's height of the story from the ground with the largest cross sections (1.80x1.80 meters) at the bottom and decreasing to the smallest cross sections (0.70x0.70 meters) at the top .The moment frame core dual system are 1.80 meters in thickness on the base and 0.40 meters on the top . The beam cross sections are two types, 0.60x0.90 meters for the lower stories and 0.50x0.70 meters for the upper stories. In this way, the tower design follows the rules of capacity design, strong column and weak beam. These choices are in line with the structural system of modern buildings. Furthermore, the first story height was doubled to 8 meters to create a main hall. The remaining stories are 4 meters high. Tower 2 (T2) is smaller at 124 meters high or about 407 feet (30 stories). This tower is a representative residential building that has a fixed release with the ground. The column cross section variation is similar to Tower 1 with the largest square columns at the bottom (1.80x1.80 meters) and the smallest cross section at the top (0.70x0.70 meters). The cores follow the same rule (1.50 meters in thickness on the base and 0.70 meters on the top). The structure has one consistent beam cross section of 0.50x0.80 meters. Again, this tower design follows the rules of the capacity design. Similar to Tower 1, the first story height was doubled to 8 meters height to create a main hall.

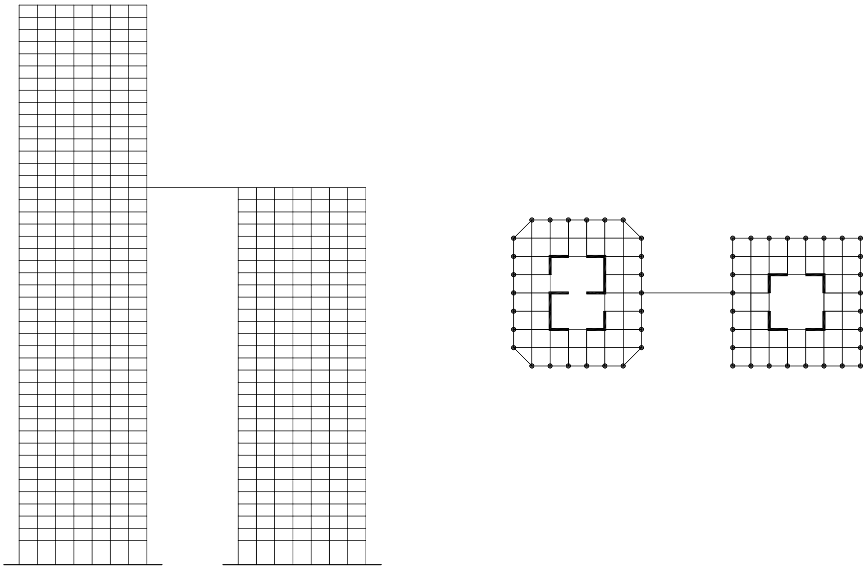


Figure 2. LBS overview (frontal view on the left side and plan on the other one).

Once the two towers were designed, a 30 meter long rigid link was placed between them as shown in Figure 2. Such length is based on the average distance between two skyscrapers located on the opposite side of downtown streets. The skybridge was designed as a single beam linking the two towers frames to each other at the same height. The structural systems were designed such that the floor levels would align. In reality, there may be an offset especially if the link is added later in the structural life of the Towers. A height offset is an additional feature to study in the future. The diaphragm constraint was applied to the beam points (two for each tower). By doing this, the deck of the bridge was hypothesized as infinitely stiff. Figure 2 shows an overview of the Linked Buildings System (LBS).

MODAL RESPONSE

Time-history analysis provides an evaluation of dynamic structural response under loading which may vary according to a specified time function. However, it is the natural dynamic behavior or modal response of structures that will influence the overall seismic response which accounts for its unique properties (mass, stiffness, shapes, structural material). As a result, it is imperative to understand how a link between structures with different dynamic behaviors can influence and change the overall dynamic behavior. Caldi [2019] studied the modal behavior of these towers in-depth and showed that rigid connections change the towers dynamic response. Since the link synchronizes the motions of the tall buildings, the LBS natural higher periods are closer to the taller tower. With the height of the link, which is placed parallel to the X-axis, the smaller tower increases its stiff power altering the higher periods of the LBS (linked buildings system). (Because of the variables involved (different heights, masses, and plan shapes), LBS modal shapes have mixed modal shapes (i.e. Y-translational-torsional modes). Along the X-direction the connection mainly increases the stiffness of the system while that in the Y-direction does not notably influenced by. Therefore, the modal motions of the system, once the rigid link is placed, are a compound of translational and torsional shapes that depends from the location of the connection. Considering the influence at the modal level, the next step is to understand how this translates to dynamic analysis.

TIME HISTORY ANALYSIS

Time history analysis is used when the variation of each load with time is explicitly known, and the goal is to study the response of the structure as a function of time. After running the study, displacements, stresses, strains, reaction forces, etc. at different time steps can be observed. However, before exploring a fully nonlinear model, it is important to understand the dynamic response at a linear level; this because the LBS is complex with multiple components including the two individual towers and the rigid link. As a result, For the time history analysis, the simulations were conducted in SAP2000 [Computers and Structures Inc.]. In this software, there are two options for analysis: modal and direct integration. With the goal being a linear response, modal analysis was selected.

Ground motions functions

To investigate the dynamic response of the LBS, two different ground motions were used. The motions included: Imperial Valley, El Centro (1979) and Loma Prieta Hollister City Hall (1989). They have been applied on the system considering just one direction at a time. Therefore, the excitations about the two axes have been considered uncoupled. The next Figure 3 shows the ground motion response spectra (spectral acceleration-natural period) and it gives a comparison with the main natural periods of the single towers.

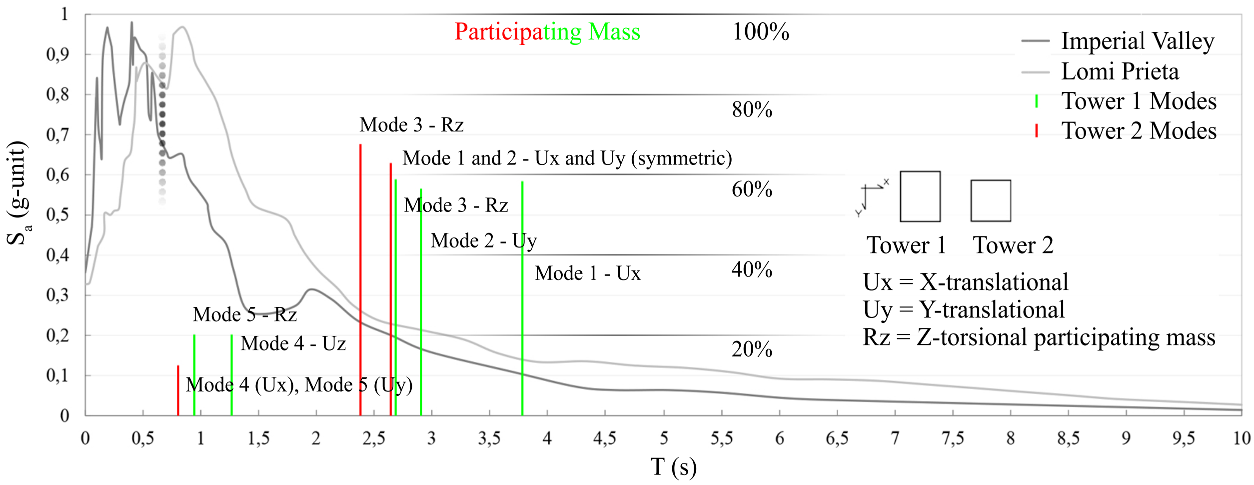


Figure 3. Comparison between ground motions response spectra the and single towers main natural periods (dots line distinguishes the higher periods from the lower and the peak zones of the two functions).

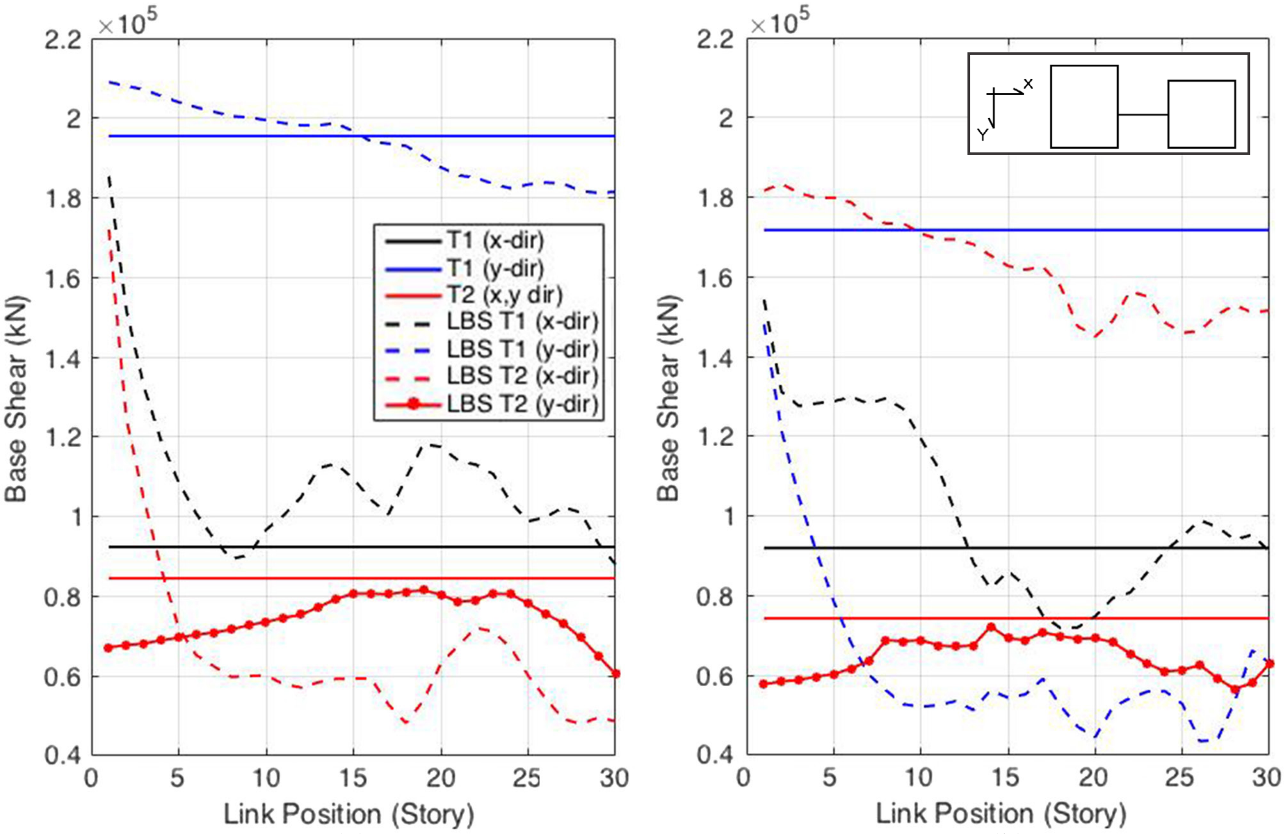
From the graph above, it can be observed which Lomi Prieta has the highest response for first natural periods of both towers (Modes 1,2 and 3). On the other side, Imperial Valley shows the greater response in proximity of the vertical axis. In addition, the series of black and gray dots divides the graph in two parts; where El Centro has an higher spectrum (left side) and where the other function have an higher response (right side). To better understand the tower dynamic sensitivity under these seismic excitations, on the bottom of the graph the participating mass of the single towers is depicted; it has smaller values when it is on the the left portion (lower modes) while on the right side the participating mass owns larger values (main vibrating modes). Because of as said so far it can be deduced which Lomi Prieta has its maximum peak in the part of the graph where most important natural periods occur. In that, the first 5 modes both single towers reach a total participating mass (in the X and Y directions) of about 75%. After the 5th, each mode has no more than a 6% participating mass ratio in the X and Y directions (fort this reason they were not depicted). The requested participating mass ratio of 85% (by most of the buildings code) is reached after mode 15.

SHEAR SENSITIVITY

The variation of structural shear is an important factor especially when the covered topics are tall slender structures experiencing earthquake excitations. When an earthquake occurs, shear stress and bending moment is produced in the structural members. Unlike bending moments, when structural member experiences failure by shear, it can be an unexpected and extremely dangerous situation. Tall buildings experience significant shear stress due to their height, so they must be designed to provide resistance to shear forces. As observed in Caldi [2019], the placement of a rigid link is crucial as it can increase the stiffness of these buildings. However, this shear sensitivity can vary depending on the location of the rigid link. As a result, this dynamic study evaluates the placement of the rigid link at all locations throughout the height of the tower to observe the variations in shear of the individual towers and the LBS.

Base Shear

Figures 4 below give a first overview of the base shear response. In these plots, the horizontal lines represent the base shear of the individual, unlinked towers against the lines presenting the shear based on link position. The LBS shears have been separated to present the shear in each linked building. This procedure have been carried out through the use of the section cut command. In fact, Two different planes have been designed on the base of both towers in order to capture the different amounts of shear that characterized themselves.



(a) (b)

Figure 4. Base shear as a function of link position; (a) Lomi Prieta and (b) El Centro.

There are several observations to be noted from these figures. When the link is placed in the bottom 5-6 stories, the base shear of the LBS is significantly larger than the individual towers except for T2 in the y-direction. In this portion, the greatest difference occurs in the x-direction or direction of excitation with an increase of nearly 200% for T2 (when the link is located on the first floor); also, in the Y-direction the link acts balancing the base shear of the two buildings (while the LBS T2 Y is growing up the LBS TY Y is decreasing). At some point when the link reached a position pretty high (between the 10 and 15 stories), in the X-direction the T1 base shear of the connected and unconnected towers assume the same value, while in the Y-direction the shear keeps interchanging itself between the buildings; in this scenario it can be noticed an improving of the T2 base conditions in both directions. Keep increasing the connection height, between the 16th and 17th story, LBS T1 X reached its minimum that is absolute under El Centro excitation while it's a considerable local minimum under Lomi Prieta excitation; this point even represents a local minimum for LBS T2 X. In the other direction the two graphs show in contrast trends: in Lomi Prieta the LBS T1 Y is up to the T1 Y while in El Centro is the opposite. This is probably due at the different spectra of the functions. In the next zone between the 19th and 23th story it is interesting to notice an increasing of LBS T2 X base shear; at this follows two opposite reactions of LBS T1 Y, depending from the earthquake function. To conclude, when the link is located in the last upper floors, both of the LBS T2 base shear tend to be the same while the LBS T1 Y base shear assumes about the value of the T1 unconnected tower. These two charts underline how different earthquake functions affect two towers when they are linked together through a rigid link. Comparing these curves, it can be noticed common trends of both but Lomi Prieta provides a better case to discuss because the shear assumes higher values and also, along the X-direction T1 shows the worst conditions (T1 LBS X curve is basically always up to the T1 X curve). Thus, once base shear sensitivity of the system has been completely examined, the variation of the floors shear has been analyzed. The base shears variation provided a first overview on the problem. In fact, more than in the top elements, the base columns of a building need to be carefully designed in order to avoid the soft story phenomenon which brings the structure to the collapse of itself. However, to study in deep these linked buildings system it is important to understand the distribution of the shear in all of the building floors under different rigid link positions.

Floors shear

In the next step, through the analysis of four cases, the LBS floors shear have been studied and compared to the individual buildings. To do that, two groups of section cuts have been created. The first cut each LBS T1 story while the others cut LBS T2 floors. The same has been made to the single buildings models in order to compare the unconnected and the linked towers outcomes. The four floors where the link has been placed are based on the base shear investigation, and they are 5th, 13th, 21st and 30th story respectively. These 4 positions were discussed under Lomi Prieta spectrum, and they own singular features (based on Figure 4). In the first case, where the link is located on the 5th story, the shears in the LBS T2 assume the same value in both direction; since the individual T2 owns a square plan and so same base shear values along both the axes. The link placed on the 13th floors produces on the base of LBS T1 about the same value of the T1 single building. In the third case, where the link is located on the 21th story, the LBS T2 X base shear assumes its minimum while the LBS T1 Y is starting to decrease (Lomi Prieta). FInally, the last connection position instead represents the best solution for both Towers considering the two directions. In fact, all of the LBS curves are down to the base shear of the individual towers respectively. However, through this investigation it will be shown the local effect due to the connection since the base shear provided a global trend of the shear near the bottom of the buildings.

The x-direction results shown in Figure 5 are discussed based on dynamic analysis using the Loma Prieta ground motion.

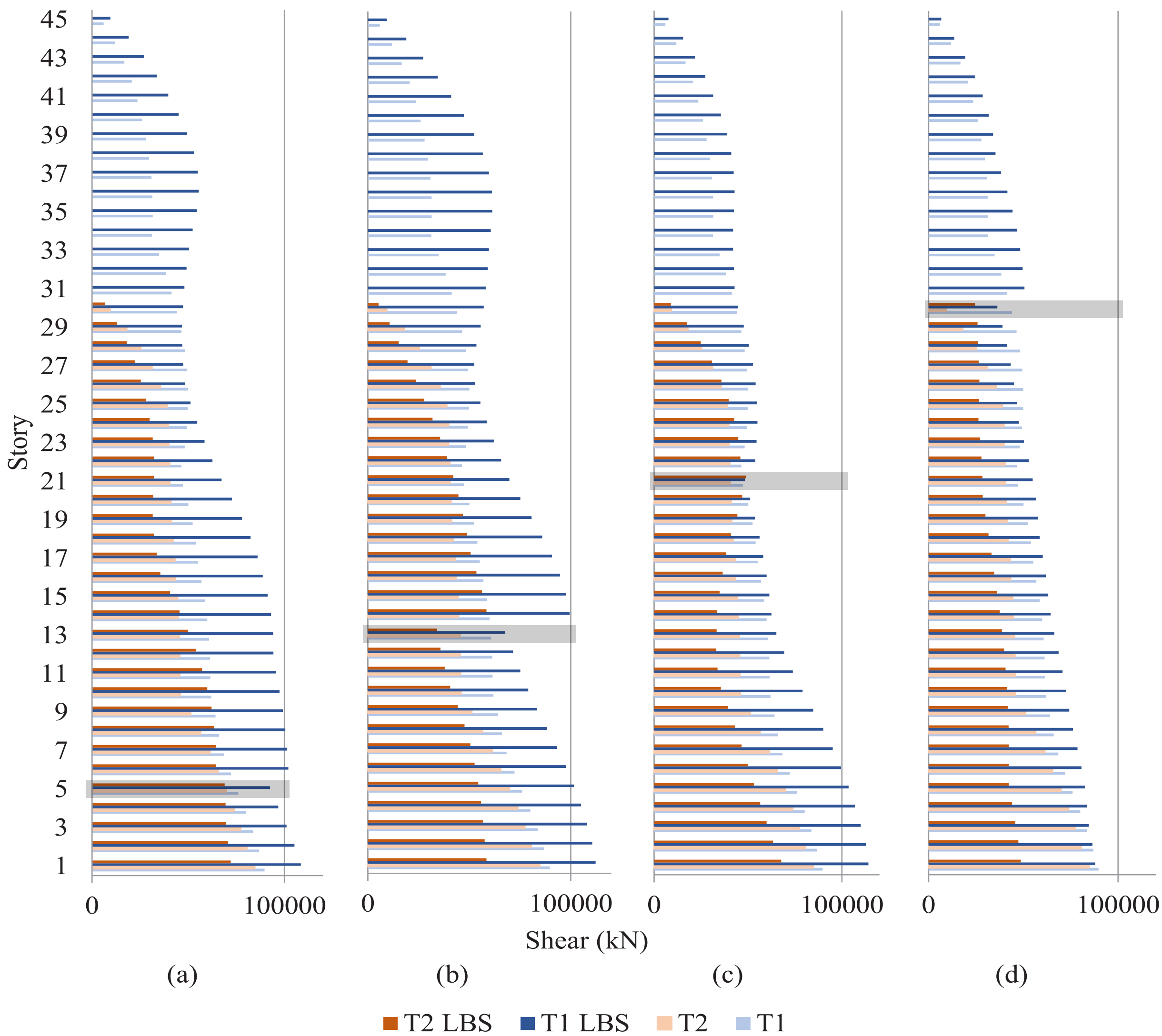


Figure 5. Floors shears of the individual and LBS buildings in the x-direction with a link placed at the (a) 5th, (b) 13th, (c) 21st, and (d) 30th story. Gray bar highlights the location of the link in each plot.

Findings

Several observations can be made from the plots in Figure 5. When the rigid link is located near the base the Tower 1 stories are subjected to a huge increasing of the shear (of about 30%) which is spread in almost all of the T1 LBS floors. On the other side, most of the T1 LBS stories are slightly subjected to a shear decreasing; just few floors uppers to the rigid connection show a negative reaction. With the growing of the link height, the total amount of the T1 LBS shear tends to decrease, assuming almost the same value of the same unconnected building. However, if it compared to the others, the case b (link on the 13th story) shows an inversion of as said so far; in fact, both the towers shear increase (in the higher tower this variation is more pronounced, mostly near the connection). The T2 LBS stories are subjected to an increasing of th shear just near to the link with the growth of the connection height instead. One of the link positions that shows a greater condition for both buildings shears (it decreases in one tower while in the other one rises up with the connection height) is depicted in the case c in the above Figure 5. This scenario the towers are subjected to an increasing (T2 LBS just near the link) but such variation does not assume so different values if compared to the unconnected system. The last case d, where the link is placed on the top of the smaller tower shows the best condition for T1 LBS but on the other side, it shows, the worst scenario for the T2 LBS stories. In fact, while the floors shear on the first are slightly different from those of the T1, in T2 LBS stories can be noticed a considerable increasing of about 300% of the shear; such variation interests just the floor of the connection and few lower stories even if in minor wideness.

The response was then observed in the y-direction as shown in Figure 6

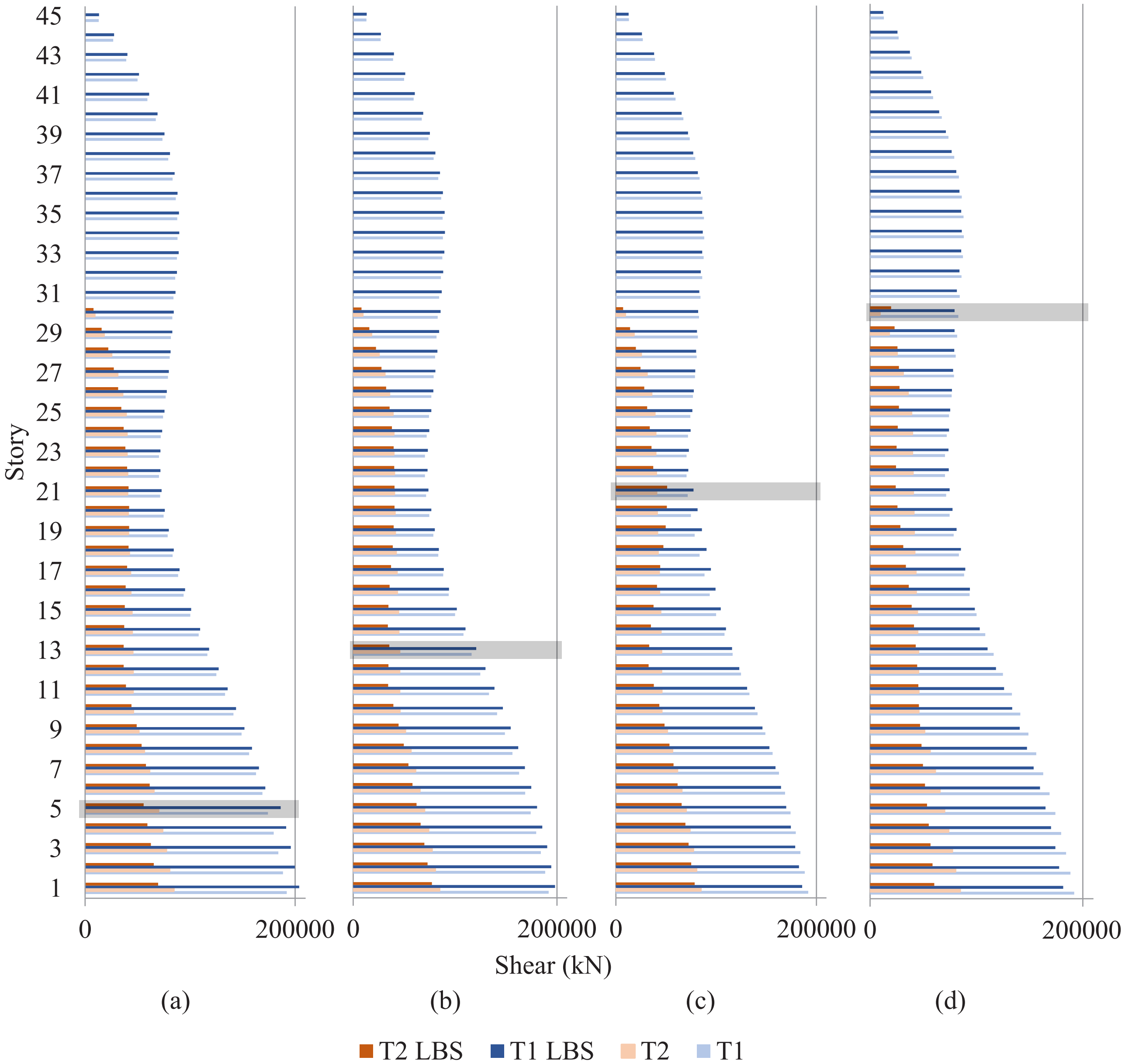


Figure 6. Floors shears of the individual and LBS buildings in the y-direction with a link placed at the (a) 5th, (b) 13th, (c) 21st, and (d) 30th story. Gray bar highlights the location of the link in each plot.

Findings

Through this investigation along the y-direction it can be noticed in average no considerable variations between the connected and unconnected towers. However, lower positions of the link have a greater influence on the bottom stories of the taller tower; the other one shows an improving of its floors shear instead. With the growing of the connection height up, a little portion of the shear slowly moves through the taller to the other one. In such cases, while there is betterment of the T1 LBS floors shear, on the other side it occurs an aggravation of the T2 just in few stories near the link; besides, on the other stories cannot marked variations of the shear be noticed. To conclude, in all of 4 cases, the T2 floors are just subjected to a little increasing of the shear except for the last case where there is a huge increasing of the shear in the stories near the link. On the other side, the T1 floors shear decreases placing the rigid element far from the base; the number of these stories growths up with the distance of the link from the ground.

CONCLUSIONS

As seen in this study, the position of the rigid connection influences the shear distribution of the LBS. As expected, the connection acts to combine the dynamic motion of the towers. In fact, the arrangement of the link induces significant changes in the direction of excitation due to the increased stiffening. However, it is also important to note that some of the increases observed are concentrated in stories surrounding the link point. For example, when the link is at the top story of T2, the shear increases by nearly 350% but this occurs only in few adjacent floors. This is greatly contrasted by the T2 results of the link placed near bottom of the towers. In this case, the shear is spread out over more floors with a maximum increase of approximately 30% for the two towers. This behavior interestingly enough is then contrasted by T1 which shows nearly the complete opposite response. Placement of the link at the top of T2 leads to an increase in shear across a larger range of stories while the lower level connection shows a variation in a concentrated number of stories. As a result, this shows there is a level of optimization to be conducted to achieve the desired performance of both structures. Since the link mainly affects the system along the direction of excitation, it can be noticed the almost same trend of the LBS base shear curves under the two different earthquakes. Lastly, it was observed that rigid link is not a kind of connection that can be easily designed. In fact, when two towers are coupled together by an infinitely stiff skybridge (or link), the motions of themselves induce a huge amount of shear inside the members of the link that goes through one tower to the other one. This could be reduced or avoided by rising the cross sections skybridge members or by increasing the dimension of itself. However, such intervention is not so recommended because it would induce either more towers floors shear or the axial stress inside the skybridge concrete columns (because of the notable skybridge weight). This study presents a major step forward in understanding the role of skybridges in the potential dynamics optimization of structures. But this is just the first few steps in a series of future study to understand the impact of link stiffness and bi-directional excitation.

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