Structural Design and Seismic Analysis of Connecting Corridor in High-rise Buildings

Zhiqi Wang[1, *]

[1] Department of MACE, The University of Manchester, Manchester, United Kingdom

* Corresponding Author Email: zhiqi.wang@student.manchester.ac.uk

Abstract. With the development of the society, the demand on high-rise buildings has increased remarkblly due to some reasons. Meanwhile, connected corridor structure become a popular design on high-rise buildings which allow different towers to be linked. Due to the complexity of the structure system, it is necessary to indicate the existing issues and the approaches to deal with them or reduce the effect. By reviewing various papers, several conclusions have been drawn. Steel truss is the most efficiency composition of both structure and material in bearing loads, where flexible connection are more likely to be applied with it and has the greatest ability in against the seismic effect.

Keywords: High-rise building; connected corridor; seismic control.

1. Introduction

In recent decades, the population has grown substantially (especially in China), and more and more young citizens prefer to live in the central area of a city. It is obvious that traditional constructions are not available to contain such many people in limited area. As a result, with advanced technology and materials, an increasing number of engineers start to study on how to build more floors on one building in order to higher the utilization rate of land. A high-rise building can be commercial or residential, but in any case, most of the high-rise buildings are in the service of human. For this reason, the design of connected structure has been applied between some of the towers. Specifically, it is usually a sky-bridge linking two towers on a high position. On the one hand, it contributes much on aesthetic as it offers more feasibility on both construction and interior design. Separate towers are merged into a global system and the partial blank between makes it possible to achieve uncommon shape with unconstrained ideas of architecture designer. On the other hand, the connected structure provides various advantages on operational functions. Firstly, partial natural condition can be improved due to the connection of sky-bridge. Residents in the middle apartments are able to enjoy with better air ventilation and day lighting. Meanwhile, it allows people to directly shuttle between two towers instead of by going downstairs and upstairs. This means that the speed of transport can be enhanced, and new routes are opened up when mapping out the flow of people, which is also a great contribution to the society [1].

However, the raised in height of building leads stronger reaction of the structure to the effect induced by lateral loads. This is because that the displacement increases due to larger vibration at higher floors of the building. Moreover, the connected design makes it more challengeable to reach the structural stability of a high-rise building. Therefore, this paper is going to discover different techniques applied in structural design of the connected high-rise structure to improve its ability in several aspects. Regards to the basic components, each type of structures and connections are discussed and compared, with their own physical characteristics. Moreover, seismic performances of some typical or valuable cases of muti-tower system with sky-bridges are analyzed and indicating how and which part in the cases contributes in improving seismic resistance.

2. Structural Design of Connecting Corridor in High-rise Buildings

The reactions of dynamic loads on the connected muti-tower structure are remarkably more complex than it on the single-tower structure due to the connection of sky-bridge. Each tower will have similar behavior under seismic loads if the connected structure is in symmetrical shape. There is not much difference between the frequencies or displacement of the vibration of two towers so that the connected part between gives less effect to the whole structure. However, many high-rise buildings with corridor are designed in asymmetric shape, where the motion of towers is not likely to be synchronized. This means that the reactions to the connected structure are more significant since relatively vibration become stronger. Meanwhile, when the loads transferring horizontally, there will be torsional behavior occurs on the connected structure [2]. The increasing influence from torsion to the sky-bridge by higher asymmetry of connected muti-tower structure makes it more challengeable in structural design. As a result, it is necessary to indicate the advantage and disadvantage of each type of critical factors, in order to choose the most suitable composition to apply under different situations.

2.1. Structure and Material

2.1.1 Beam and slab

The corridor made by reinforced concrete can be composed with prestressed beam-slab structure or composite beam-slab structure, where connected to the main structure by casting in place. This structure provides more possibility in architecture to achieve uncommon shape. The vertical components do not play a main role in supporting so that they can be opened. However, due to the irregularity in structure, it is highly unfavorable to seismic performance and increase the difficulty of construction. As a result, the reinforced concrete beam-slab structure is more likely to be applied in sky-bridge with smaller span and at lower floor.

2.1.2 Truss

Steel truss structure is a more suitable choice in supporting the structure between high-rise buildings, which has already been widely applied in amounts of projects. Relatively, steel has lower unit weight and higher affordability. This makes it available to be installed on middle or higher floors between towers, even with longer span. However, different ways to connect the steel truss structure to the main structure may give various impacts, and this will be detailing explained later in this paper.

In addition, how the members in truss are arranged also have a certain effect to the structural stability. However, now there is not a universal method to be applied in practice. As there is much difference between each project, it is hard to identify specific types. Therefore, the exact plan of members in truss may depend on the actual situation. For example, in many projects with steel structure covered by glass certain, it is required to minimize the amounts of diagonal web members in truss for aesthetics. For this reason, Xu [2] studied on how different form of diagonal member influences the static performance of corridor structure. Three forms have been modeled and analyzed by the author, as shown in Fig. 1. It can be seen in Fig. 1 that Model 1 has diagonal web members along full span; Model 2 has diagonal web members on two sides with straight web members in the middle, and Model 3 has straight web members along full span.

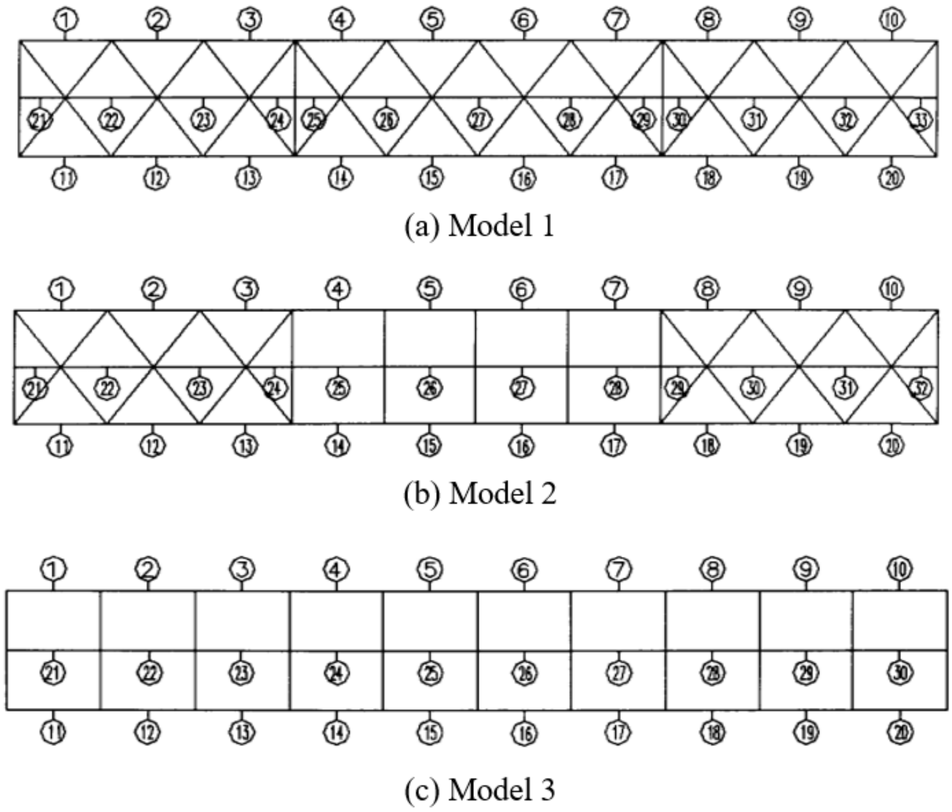

Fig. 1 Truss with different form of diagonal members [2]

By comparing the value of bending moment and torque on three models under estimated wind loads, the value on straight web members is several times of the value on diagonal web members. Meanwhile, the ultimate bearing capacity of three models has been compared with ANSYS. The Model 3 has the worst ultimate bearing capacity which is only half to that of Model 1. As a result, the arrangement with diagonal web members along full span of truss is the most efficiency structure, where the other two forms fail in playing the role of truss.

2.2. Connections

2.2.1 Fixed connection

Fixed connection restrains force from all directions which makes it become the strongest one among all types of connections. The relationship between different towers has been strengthened by this way. However, higher strength and stiffness of corridor is required to apply fixed connection. This is because that the rigidly connected corridor shall balance the uneven deformation of each tower under horizontal and vertical loads, besides bearing its own dead and live loads. And larger bending moment and shear force is produced at the joint. Moreover, with the analysis from Baby and Antony [3], it is found that the most efficiency way to install sky-bridge with fixed connection is to build it at three quarter height of the tower.

2.2.2 Pinned connection

Pinned connection releases the restrain of vertical loads compared to fixed connection. The internal force of end members has been reduced with no local moment. Nevertheless, positive moment in the middle along the span will increase. As a result, it is not usually used in practical projects [4].

2.2.3 Roller connection

With roller connection, the end joint will not be restrained in both vertical and horizontal direction. This is normally applied on one side of the corridor with roller connection on the other side. It is suitable for sky-bridge with low strength as the stress on the structure will be relatively small.

However, what should be noticed is to control its horizontal movement. In order to avoid unwanted sliding or collapse, the amount of movement on horizontal direction shall be estimated and installing the device which can reset it to original site when at limit position. As a result, generally only corridor with smaller span and at lower floor is connected with the combination of roller and pinned connection [4].

2.2.4 Flexible connection

Different to the three traditional types of connection above, flexible connection is a more reasonable method which can balance the two functions of reducing the deformation and enhancing bearing force. Rubber bearing and viscous damper is used as flexible connection. By adjusting to a suitable rigidity, the maximum displacement between storeys has been reduced significantly, while local displacement increases slightly. Therefore, the integrity of structure has been improved as relative movement between sky-bridge and main structure decreases. Meanwhile, the torsional vibration is effectively reduced with the application of damper at the end of corridor so that the internal forces in structure decrease [4].

Furthermore, Huang et al. [5] compared the seismic performance of flexible connection to that of fixed connection by analyzing with shaking table test and finite element analysis on a chosen case. Besides reporting the advantages of flexible connection on extending the lifespan of structure, less axial force in diagonal members, releasing the seismic energy, the authors still indicated that sufficient space shall be reserved between the corridor and the main structure in order to prevent colliding when experiencing the earthquake, especially a serious one.

3. Seismic Analysis of Connecting Corridor

Seismic load is one of the most significant loads which induce the lateral effect to the building. Due to the characteristic of earthquake, this type of accident occurs randomly and is hard to be predicted while the damage caused by it is unacceptable. The high-rise buildings usually contain more people and it is unlikely for human to survive from failed structure under earthquake. Indeed, the seismic degree of each area has already been leveled with geographical experiences. Based on the levels, the requirement on seismic strength of a building can be determined. However, it is always a challenge to improve the seismic performance in towers, especially the ones with sky-bridge connected. The increased height in high-rise building and the asymmetry shape with corridor leads more sensitive reactions of structure to the lateral forces. As a result, it is extreme important to develop the ability of the complex structure to against seismic effect. What shall be achieved is that the deformation of structure is controlled to not exceed the service limit state under moderate earthquake, and the structure does not collapse under heavy earthquake so that people may have enough time to leave and move to a safe area.

3.1. Modeling Analysis

Firstly, it is necessary to identify the vibrational characteristic of tower with sky-bridge under seismic loads before discovering further optimized scheme.

Ji et al. [6] have built a finite element model of building with 20 storeys where the corridor is connected at the top floor. It is assumed that the corridor is constructed by reinforced concrete plates. There are several types of vibration modes of building are found from calculation, which are translational, longitudinal, local, torsional, composite space modes. Also, it is indicated that the translational vibration mode has lower priority to the natural vibration with first and second order. However, what shall be noticed is that there is only one model calculated in this study. It is hard to decide if the resultant pattern is a universal one.

Meanwhile, a more detailed study on the rules of first-order vibration of the corridor between towers with rigid connection is taken by Meng et al. [7] In this paper, the freedom degree of the chosen substructure is simplified to one or two in order to analysis how vertical conjoined factors vibrate along horizontal direction. It is concluded that there is a significant deformation in vertical connecting direction due to torsional effect which should be particularly noticed in design stage. Besides, the authors have verified the result with practical projects, which makes the theory more reliable. Also, even this article only provide the theoretical basis, the method of simplified analysis it has used can still be instructive for a more complex model.

Moreover, there is another research by Mahmoud [8] which compare the seismic effect to high-rise building with sky-bridge connected at different floors. The twin-tower model is referred to the Capital Tower and motions from 8 groups of earthquake have been combined to form the simulated environment. The seismic performance is analyzed by time-history method where corridor is connected at one quarter, half, three quarter and top height of towers. The result shows that the sky-bridge fixed on the top of high-rise buildings gives out the worst seismic performance with remarkable high shearing force at the base. In summary, although there is only one model analyzed, this study can also be guidance on structural design of high-rise connected structure since its model is built as a more general one.

3.2. Shaking Table Test

Shaking table test is one of the major experimental techniques which can embody the behavior of structure under earthquake effect. By fixing the specimen on the testing platform and shaking it by simulated seismic motion till the structural failure state has been reached, the performance of structure at failure point can be recorded and be analyzed.

There is a shaking table test on a building with typical high-rise connected structure in Zhoushan taken by Zhou et al. [9] The corridor is designed with a circular opening in the middle and is connected at the top floor of the two towers, where both characteristics raise the difficulty of seismic resistance. After simulating the effect from earthquake with minor, moderate and major intensity, it is found that there is some obvious structural cracking with moderate shaking and damage with major shaking, while both deformations are acceptable which will not lead the collapse of the tower. Also, as predicted, the stiffness has been reduced due to the circular hollow, but the rigid connection balanced the difference in vibration of two towers.

Another test taken on an asymmetrical connected twin-tower in Shenzhen is analyzed by Guo et al. [10] The position of two corridors in the middle floors contributes to seismic performance while connection at the diagonal of corner of two buildings is an unfavorable factor. With the consideration of service level earthquake, design-based earthquake, and maximum considered earthquake, it is indicated that there is a defect at the roof where the connection is very sensitive at vertical direction due to heavy whiplash effect.

Lu et al. [11] have modeled a complex composed system of two high-rise building in Shanghai. One of the towers has double height to another one while the sky-bridge is connected at the half floor of the higher one. The rigid connection not likely to be used in this project due to the large axial and shearing force transferred. By analyzing the testing result, it is found that there is an obvious time lag on the deformation at top floor to that at connected floor of higher building because of torsional effect. Meanwhile, the damage is concentrated at the lower floors of lower tower and floors with truss connected of higher tower. So the authors suggest that the bearing capacity and ductility of key components shall be enhanced by more supports on connection for horizontal stability or raising reinforced level of concrete at corners for torsional resistance.

In another study of Lu et al. [12], an example of four-tower system with high-rise connected structure has been chosen to take the shaking table test. It is a great challenge to guarantee the seismic performance of this muti-tower system in Chongqing, one of the worst earthquake regions in China. Not only because the corridor is designed to be placed on the top of four towers, but also reasoned by its curved shape and circular cross-section. There is also cantilever part at two end of the sky-bridge which beyond the exterior wall of the side towers. Under the test with major earthquake level, the structure of corridor still remains in the elastic state with some acceptable cracks. This is benefited from the application of curved surface sliders and viscous dampers at the joints of connection, where the sliding displacement also stays with a safe value. What shall be cared is to prevent the fatigue of seismic isolation system in servicing period by measures such as dustproof.

In summary, a general limitation on study of shaking table tests is that only one example has been tested. This may because that there are many restrictions on taking such a test and much time will be spent. However, what can be discovered is that most of the buildings chosen to be tested are the ones with distinctive design in structure instead of normal or regular ones. This means that the techniques applied in these complex projects which can effectively against seismic effects may provide instructive ideas to future structural design.

3.3. Improvement on Seismic Performance

With the understanding of reaction on connected structure between towers to the seismic effect, it is feasible to explore the techniques which can significantly enhance the seismic performance of high-rise buildings with corridor. The application of flexible connection is one of the major techniques, where numerous researches study on how its composition contributes to against the lateral force due to earthquake.

The research taken by Lee et al. [13] has studied on how the coupling effect of building is controlled by different types of connectors. The chosen example as investigated model is a residential high-rise building in Seoul with connected structure at the upper half floor. Under the simulation with earthquake and wind excitations, it is indicated that the use of lead rubber bearing (LRB) contributes in releasing the energy to reduce the coupled effect. Meanwhile, the linear motion bearing (LMB), which can leave horizontal movement free while restrict the motion on other directions, shall be installed in the middle of the corridor with amount of only one to limit the reaction and member forces.

Based on the application of rubber bearings, Dai et al. [14] have compared the effect of combination with or without the use of viscous dampers. The case studied is a base-isolated building system which is connected by sky-bridge. The authors have proposed the collision potential index to quantify the seismic performance of different connections. As a result, it is found that the viscous dampers help to reduce the risk of collision under earthquake to the maximum extent possible, while the ability of balancing the movement of two buildings is relatively worse by only using the lead rubber bearing (LRB) and the ordinary-rubber bearing (LNR). However, there is an obvious defect in this study where the torsional effect has not been fully considered.

Meanwhile, Guo et al. [15] have assessed another technique worked with flexible connection to reduce the stiffness of the connected structure. The technique is assessed on the model of two towers connected by two corridors with steel truss structure at the corner of 6th to 8th floor and 34th to 37th floor respectively. What is applied is the rotational friction negative stiffness damper (RFNSD) which is composed by negative stiffness device (NSD) and rotational friction damper (RFD) and is installed with the lead rubber bearing (LRB). By simulating the seismic effect to the structure, it is concluded that this technique significantly contributes in reducing the displacement between stories, shear response and structural damage, where the rotational friction damper (RFD) also effectively control the deformation due with flexible connection to not reach its limit value. Moreover, the author indicated that the assessed technique is also available for bridge structure to against earthquake, while its practical function still need to be verified.

In addition, Nishimura et al. [16] introduced a system which has already been applied in reality and analyzed how it takes advantage to improving seismic performance of the building. The actual construction in Japan is composed by three towers which are aligned in triangular shape and are connected by each platform at low, medium, and high storey zone. Under the analysis of seismic response and vibration test, it is shown that the Super-Flex-Wall in each tower has taken off most of seismic effect, and also reduced the lateral and torsional stiffness induced by the bizarre arrangement of buildings. Meanwhile, the combined usage of broad-band damper (BB damper) and oil damper on connection has effectively diminished the reaction of structure to both slight excitation such as seasonal wind and larger excitation such as earthquake. Moreover, the authors mentioned that some of the work shall be completed before installing vibration control dampers during the construction period, in order to prevent any sloping or pre-collision of the dampers.

4. Conclusion

Because of the high altitude and irregular shape, it is quite challengeable for the structure of high-rise building with connected sky-bridge between to against dynamic loads. In this study, several methods have been explored from different aspects to reduce the reaction of structure to various effects in order to the enhance the stability and serviceability of the muti-tower connected structure by reviewing amounts of papers.

(1) Due to the characteristics of structure and material, steel truss is more suitable for high-rise connected structures while reinforced concrete beam and slab may only be used at lower floors, where the truss with diagonal web members along full span is the most efficiency one to bearing loads.

(2) Some of the connected structures with lower seismic requirement use the fixed connection which can effectively reduce the displacement but leading higher stiffness. In most of the connected structures, flexible connection is chosen to be applied at the connected joint which reduce the damage from seismic effect by lower the possibility of collision.

(3) To maximize the role of flexible connection, what is normally applied is the combination usage of one type of rubber bearing which is usually the lead rubber bearing (LRB) and another device such as the linear motion bearing (LMB), the viscous damper, or the rotational friction negative stiffness damper (RFNSD) and so on, which depends on the specified purpose in different cases.

In summary, there is still some limitation in this study as not all issues in structural design of high-rise buildings with connected corridor has been discussed such as wind excitations. Meanwhile, the existed restriction in reviewed researches may also affect result in this paper. Therefore, more improvements are required to be explored in future studies.

References

[1] Doroudi R., Lavassani S. H. H. Connection of coupled buildings: A state-of-the-art review. Structures, 2021, 33: 1299-1326.

[2] Xu Wenhua. Analysis and Design of long span skybridge Between High-rise Towers. Tongji University, 2007.

[3] Baby C., Antony J. Parametric Study of High Rise Building with Skybridge. Lecture Notes in Civil Engineering, 2022, 171.

[4] Chen Weijun, Liu Yongtian, Su Yantao. Research on jointing method for high-rise buildings with connecting corridor. Journal of Building Structures (Supplementary Issue 1), 2009.

[5] Huang Xiangyun, Diao Yunyun, Tan Ping, Shen Chaoyong. Flexible connection design and test research in muti-tower high-rise building with corridor structure. Journal of Earthquake Engineering and Engineering Vibration, 2007, 27(6): 112-118.

[6] Ji Dongyu, Song Chuncao. Dynamic Characteristics Analysis of High-rise Connected Structure. 2014.

[7] Meng Fantao, Ruan Xingqun, Zhao Jianfeng, Qiu Jiangrui, Meng Lei, Peng Hou. Analysis of horizontal vibration characteristics of unequal height twin towers of rigid connected structure. Journal of Building Engineering, 2022, 50: 104-146.

[8] Mahmoud Sayed. Horizontally connected high-rise buildings under earthquake loadings. Ain Shams Engineering Journal. 2019, 10(1): 227-241.

[9] Zhou Y, Lu X, Lu W, Qian J. Study on the seismic performance of a multi-tower connected structure. The Structural Design of Tall and Special Buildings, 2009, 20(3): 387-401.

[10] Guo W, Zhai Z, Wang H, Liu Q, Xu K, Yu Z. Shaking table test and numerical analysis of an asymmetrical twin-tower super high-rise building connected with long-span steel truss. Struct. Design Tall Spec. Build., 2019.

[11] Lu X, Chen L, Zhou Y, Huang Z. Shaking table model tests on a complex high-rise building with two towers of different height connected by trusses. Struct. Design Tall Spec. Build., 2009, 18: 765-788.

[12] Lu X, Lu Q, Lu W, Zhou Y, Zhao B. Shaking table test of a four-tower high-rise connected with an isolated sky corridor. Struct. Control Health Monit., 2018.

[13] Lee D, Kim H, Ko H. Evaluation of coupling–control effect of a sky-bridge for adjacent tall buildings. Struct. Design Tall Spec. Build., 2012, 21: 311-328.

[14] Dai Kaoshan, Luo Xiang, Lu Yang, Li Bo, Zhong Jie, Zhang Shiming, Zhang Ruifu, Ge Qingzi. Seismic collision potential of adjacent base-isolated buildings with corridor bridges subjected to bidirectional near-fault pulse-like ground motions. Soil Dynamics and Earthquake Engineering, 2020, 135: 106-202.

[15] Guo Wei, Guo Longlong, Zhai Zhipeng, Li Shu. Seismic performance assessment of a super high-rise twin-tower structure connected with rotational friction negative stiffness damper and lead rubber bearing. Soil Dynamics and Earthquake Engineering, 2022, 152.

[16] Nishimura A, Yamamoto H, Kimura Y, Kimura H, Yamamoto M, Kushibe A. Base-isolated super high-rise RC building composed of three connected towers with vibration control systems. Structural Concrete, 2011, 12: 94-108.