The Structural Design and Analysis of a Symmetrical Twin-tower Conjoined Building with Vibration Absorber

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Abstract. Throughout the ages, earthquakes have caused numerous instability and destruction of buildings. With the increasing of the height and volume of modern buildings, the seismic force on the buildings gradually increases. To avoid serious damage and ensure the safety, seismic design has become a crucial element in the analysis and design of the structure. In traditional seismic design, increasing stiffness of the building is usually adopted to reduce the structural response during an earthquake. This approach is usually costly, and the effect of practical application is not obvious, which could not fundamentally enhance the bearing capacity of the structure. Basing on existing researches, both theoretical and physical model of symmetrical, conjoined twin tower is made, meanwhile, the reasonable design using damping vibration absorber with the function of energy dissipation, utilizes the movement of additional weight to reduce vibration amplitude of main body structure. The use of shaking table test on the analysis and verification of bearing capacity of the model of symmetrical, conjoined twin tower with vibration absorber, improves the seismic performance of the building. It helps propel innovative and practical design ideas in structural seismic design of symmetrical conjoined twin tower.

1. Introduction
With the continuous enrichment of both theoretical and practical knowledge in the construction industry, human beings present their demands for beauty in complex and beautiful architectural forms. As a special architectural form, the multi-tower conjoined buildings are widely loved and often exist as landmarks because of the aesthetic and visual impact brought by their combination forms and changes. For example, the Petronas Twin Tower, Kuala Lumpur, Malaysia, is the most representative of the world's tallest symmetrical twin tower. It consists of two separate towers, and the most prominent feature of which is a 58.4-meter-long arched, sky corridor, 170 meters above the ground, right between the 41st and 42nd floors of the two main buildings, connecting the two towers with a total of 88 floors, both 451.9 meters high [1]. For a building with a higher height, due to its small natural vibration frequency, the structure is subjected to greater seismic force and overturning moment, causing more damage [2]. Therefore, to ensure the seismic safety of high-rise structures and be economy, it is vital to carry out in-depth research on the aseismic structure and aseismic technology of high-rise buildings. The twin-tower building connected by a sky corridor is widely adopted because of its multiple strengths such as convenient communication and providing an escape passage during a fire. But a higher internal force in the corridors could occur under an earthquake, and the constructional details are very complex to address if the sky corridor is rigidly connected to the towers. On the other hand, a flexible connection (passive control devices) can overcome these weaknesses to a certain degree. The rational design of flexibly connected element parameters has become a key issue [3]. In the
conventional seismic measures, by adjusting the size and strength of the structure to increase structural stiffness, reduce structural seismic response. Such approach is always costly, and due to the increase of dead load when adjusting the structural size, accelerating the collapse during an earthquake. It cannot fundamentally improve the structural seismic performance.

This paper takes the Petronas Twin Tower as the prototype, building a scale model of the symmetrical twin tower with a sky corridor. By making a wooden structure model, mechanical analysis and vibration loading study of the vibration characteristics of the two towers with flexibly connected element, make the high-rise twin-tower conjoined structure meet the requirements of structural and seismic design. In recent years, many scholars at domestic and abroad have introduced energy dissipation and shock absorption equipment like vibration absorber into building structures [4]. Serving as an improvement on the traditional structural design, the vibration absorber can effectively reduce the damage of the main structure in the earthquake. In this study, in consideration of both economy and applicability, vibration absorber is utilized as the flexibly connected element to improve its seismic performance in the earthquake.

The vibration absorber, also called a tuned mass damper, or TMD. Early Ormondroyd used springs and dampers to hang mass blocks on the main structure as substructure attached, laying the foundation for the development of vibration absorber [5]. The principle of vibration absorber is that when the structure is forced to vibrate, the substructure and the main structure vibrate together, and the resulting energy reacts on the main structure through the inertial force, and part of the energy is consumed by the substructure to realize vibration reduction [6]. At present, vibration absorber has become one of the passive energy-dissipation vibration reduction control devices that is widely used in civil engineering and mechanical engineering around the world [7]. In different damping structures with multi-degree of freedom, the performance of dynamic vibration absorption varies. To further expand the application of TMD in civil engineering, researchers have designed, tested and applied vibration absorbers in a variety of complex environments. For example, Makoto Ohsaki from Japan deigned a tetrahedral tuned mass damper (TD-TMD), for three-directional seismic response reduction, which is composed of the viscous damper, the spring and the rigid bar. By utilizing the flexibility of the spring, the three-directional displacement of the viscous damper is increased, and vibration energy is effectively dispersed [8]. JaviDialesaadi A et al. from the United States designed a passive mass damper including physical mass and rotational mass, named rotational inertia double-tuned mass damper (RIDTMD). Compared with the traditional tuned mass damper, RIDTMD is expected to effectively reduce the response of the underlying main system [9]. Chiara Masnata et al. from Italy described an innovative passive control strategy, called the tuned mass damper inerter (TMDI), by working with the base isolated system (BI), to restrain the displacement of the base isolation structure under seismic excitation [10]. Seung-yong OK from Korea installed mass coordination damper on a symmetrical twin-tower structure in an asymmetric way to perturb the symmetry of the twin-tower structure and form an asymmetric coupled system, thus establishing an efficient vibration control system [11]. Therefore, an appropriate design of vibration absorber is vital. How to design the shape, size and mass of the vibration absorber reasonably, how to choose the position and number of the vibration absorber appropriately, and so on, all of which need to be studied in depth in this article and in the future to make sure the vibration absorber is functional during an earthquake. In comparison with the above works, by analysing and modelling existing building, this paper will demonstrate the process of designing and application of the vibration absorber, making the research results more convincing and providing others with research ideas.

2. Structural design and demonstration
This structural design is aimed at the symmetrical, conjoined twin-tower building, using the reduced-scale test to simulate the structural response in the actual working state.

2.1. Simplified structural model
To highlight its essence and basic characteristics. First of all, the simplification of actual structure and assumptions, application of AutoCAD software to map the structure calculation diagram under the two-dimensional plane, the structure design model of the overall building height is set to 600 mm,
layer number is 3, is divided into two columns, the height is 200 mm, the beam is located in the second layer, the span is 150 mm, caused by seismic horizontal load (Fx) constraints, simplified structure model, as shown in Figure 1.

![Figure 1. Schematic diagram of structural calculation.](image1)

Combined with the structural calculation diagram, the application of Ths-Unibim software to carry out three-dimensional modeling of the symmetrical double-tower joined structure building, the specific steps are as follows, the structural calculation diagram: structural three-dimensional model diagram = 1:10.

The first step is to design the dimensions of each component, including frame column, frame beam, connecting beam, plate, wall, etc. The second step, respectively draw the axis network, column, beam body (including the main beam, secondary beam and connecting beam), plate and wall the base layer, the first layer, the second layer. Taking the first floor as an example, the layout is shown in Figure 2.

![Figure 2. Layout of the first floor.](image2)

The third step is to display the layout of every floor in 3D, and carry out the operation of "multi-layer combination", as shown in Figure 3.

![Figure 3. Three-dimensional model of structure](image3)
2.2. Structural load test

In order to verify the correctness of the structural design and parameters, it is necessary to carry out load tests on the solid building structure. When loading, it is divided into the following two parts:

The first part is to detect the resistance and deflection of the structure by applying static load to the structure with a heavy object.

The second part is to test the seismic performance of the structure by using the shaking table to apply dynamic load to the structure.

The static load and dynamic load of this test were applied simultaneously. Under the condition of continuous seismic wave loading, the same weight was monotonically added on one side of the second floor and the third floor.

The loading design of seismic simulation shaking table test is very important. If the load is too large, the structure may soon enter the plastic stage or even collapse. If the load is too small, can not reach expectation, produce unnecessary repetition, and multiple loading can produce damage accumulation to the structure. In order to obtain the test data of the system, the design of the test loader must be carefully considered. The specific loading design is as follow:

(1) Static load: weight blocks with asymmetric mass are placed in a total of six floors. The order of weight block placement is: X, X, 1 kg from top to bottom on the left side; X, 1, 1 kg from top to bottom on the right. X is the added mass of different floors. The static monotone loading of the structure is adopted. In the test process, the static loading starts from X = 5 kg and gradually increases, with a single loading of X = 0.5 kg until the structure is destroyed.

(2) Apply dynamic load: in order to improve the reflection performance of the system and reduce the distortion of the acceleration waveform, the acceleration signal input method is used for simulation control by using the electric shaking table. Two kinds of natural seismic waves, Taft and El-Centro, were input from the table to simulate seismic excitation. The seismic wave was unidirectional, and the vibration only proceeded along a single direction. The acceleration signal of seismic wave is amplified by D/A conversion and analog control system to drive the shaking table about 13 times, that is, the acceleration amplitude is about 0.4 g. Computer system of the shaking table analyses and calculates the input seismic waves according to the frequency spectrum characteristics of the shaking table. After processing, D/A conversion and simulation amplification are carried out to make the shaking table reproduce the seismic waves, so as to load the structure, and the seismic waves add A weight to the structure at the end of each cycle until the structure is destroyed.

The overall force analysis of the structure shows that the bearing capacity of the beam is mainly tested when the structure is under static load. Generally speaking, the deflection of the trabecular beam can be effectively reduced by increasing the cross-section area, i.e. increasing the EI of the beam. And because the weight block mass is larger and the distribution is uneven, so the inertia force is larger, higher requirements for the column, which is also the need to focus on the problem to be solved in the design. In general, the vibrating load is more harmful to the structure.

3. Structural design of vibration absorber

In order to effectively analysing the damping effect and the shock absorption of the vibration absorber, the tower structure is modelled by AutoCAD. And the simplified model of the structure without vibration absorber and with a single vibration absorber is shown in Figure 4.

The building is ideal truss structure, which is composed of straight bars, and all the nodes are smooth hinge joints. For the ideal truss, all the bars only bear axial force, so only the axial deformation of the bars is required when calculating the displacement of the truss. To simplify the solving process of axial force, use symmetrical truss and calculate each two layers as one layer.

With the equivalent base shear method, basing on the statics analysis, to simplify the seismic action as an inertial force system act on the object of study. The shear force on the bottom of the structure shares the same horizontal seismic load as equivalent mass point, take the side with larger load for analysis, equivalent inertia force to a periodic transverse load, to reflect the dynamic characteristics of the load.
3.1. Displacement amplitude

MATLAB is used to solve the global stiffness matrix and the mass matrix. Firstly, basic information about the structural components and the magnitude, direction of external load is required to generate the mass matrix and the stiffness matrix. And the vibration absorber is installed on the node under external load. The number of node displacements is increased by one, so is the dimension of the matrix. The displacement is obtained by decoupling the stiffness matrix and mass matrix of increasing order and the external force, and the node displacement diagrams with no vibration absorber, one vibration absorber, two vibration absorbers and three vibration absorbers are shown in Figure 5 (a), (b), (c) and (d). The MATLAB procedure is shown in Appendix A.
Obviously, at 1-kg-weight place and 5-kg-weight middle tier (X = 5, X is the added mass of different floors), the vibration absorber has a good damping effect to bear the vertical load. Damage is caused to the column footings when there is so vibration absorbers, and the bearing capacity is very low, only 3kg. After adding 1 or 2 vibration absorbers to the structure, the bearing capacity has more than doubled to a maximum of 6.5kg. Displacement under dynamic load decreases significantly. Vibration absorber greatly reduces the structural response under the seismic load. The change of displacement of using 3 vibration absorbers is not obvious compared with using 2 vibration absorbers. With comprehensive consideration of both economy and damping effect, 1 or 2 vibration absorbers are recommended.

3.2. Final scheme design

In order to achieve the function of vibration absorber, the study makes use of paulownia strips and other materials to make a physical model of rocking vibration absorber. Vibration absorber design is mainly divided into cable design, platform design and displacement limiting device design.

3.2.1. Cable design of vibration absorber. Vibration absorber cable is made of 10mm wide, 205mm long and 1mm thick wood along the grain direction, the board requires better toughness to ensure a good tensile capacity. Every vibration absorber is designed with 4 cables, and the top segment is attached to the inner side of the beam ends of the second and third floors.

Considering the bearing capacity of loading 1kg weight at the vibration absorber and 5kg weight at the vibration absorber is different, so at the 1kg-weight use a thick layer of wood to make cable, at the 5kg-weight use two layers of thick wood to make cable (use two pieces of 1mm thick wood to stick). After shaking table test, the cables of the first and second floors fully meet the requirements of bearing capacity.

3.2.2. Platform design of vibration absorber. The material of the vibration absorber platform is the wood rod with the closed lap around, and the sectional area of the rod is appropriately increased to ensure a good loading bearing capacity. The end of the cable is clamped with 4 pieces of wood with the size of B × H × L =3mm×5mm×100mm in pairs to keep the platform level slightly higher than the nearby beam, and two pieces of wood with the size of B × H × L =3mm×5mm×90mm are overlaps above the wood and inside the cable to make up the platform of the vibration absorber.

The platform design of vibration absorber is not universal, so different designs are applied to the platform at the 5kg weight and the platform at the 1kg weight. At 5kg weight, the sectional area of the wood rod of the vibration absorber platform is larger than that used at 1kg weight, which makes the platform stiffness at 5kg weight is larger and the deformation is smaller under the external force. With partial deflections within a controllable range, and the friction due to contact, it enhances shock absorption. Shaking table tests have also been carried out to verify that the first and second floor platforms could fully meet the bearing capacity requirements.

3.2.3. Design of displacement limiter. One of the highlights of the design of the vibration absorber is the utilization of the displacement limiter. In the shaking table test, it is found that the swing amplitude of the vibration absorber is large under seismic wave, which will lower the bearing capacity and generate eccentric load. Therefore, a displacement limiter is made for the vibration absorber.

The displacement limiter is located below the platform and consists of two main parts. One part is glued to the lower side of the two lapped wooden strips on the platform. The part under each lapped wooden strip is composed of two small wooden blocks with the size of B × H × L =5mm×6mm×18mm and a piece of wood chips with a width of 9mm, a length of 54mm and a thickness of 1mm. The wood blocks are clamped between the wood chips and the wood strips, and the distance between the two wooden blocks is 18mm, leaving a gap for vibration absorber swing; Another part is with a size of the b * h * l = 3 mm * 5 mm * 200 mm batten, four dimensions of b * h * l = 3 mm * 5 mm * 7 mm small block and two film is 15 mm, 5 mm wide, 1 mm thick, the small
board, wood through space and lap between on its vertical beam, wood with four pieces of wood on both ends after two clamping, paste with two pieces of wood on its cover, the general structure of the displacement restrictor. When the vibration absorber swings beyond a certain limit, the wood blocks at both ends will limit the displacement of the attached wood strips below the platform. When the vibration absorber swings from side to side, the excess displacement will be confined by the wood strips below the platform, thus providing the vibration absorber with restoring force. The limit of displacement is based on the maximum displacement under the seismic wave obtained by many tests and then reduced to a certain extent to get the reasonable displacement limit, which could not only realize the function of vibration absorber, but also could limit the displacement. After several pre-loading tests, it is obvious that the vibration absorber works, the damage caused by seismic waves of the whole structure is greatly reduced, and the vibration absorber consume a certain amount of energy. The physical model of vibration absorber is shown in Figure 6.

![Physical model of vibration absorber structure.](image)

**Figure 6.** Physical model of vibration absorber structure.

### 4. Analysis of structural bearing capacity

Considering the safety, durability and practicability of the structure, a further analysis of the bearing capacity of the symmetrical, conjoined twin tower is necessary. The physical model of the symmetrical, conjoined twin tower is made and shown in Figure 7.

![Physical model of the symmetrical, conjoined twin tower.](image)

**Figure 7.** Physical model of the symmetrical, conjoined twin tower.

The load-displacement relationship curve cannot be directly obtained so the analysis is mainly basing on the bearing capacity and the experimental phenomenon. According to the initial loading, and further reinforcement of the vibration absorber, it is estimated that the bearing capacity of the structure
simulated by the physical model could reach 6.5kg, high safety factor. The force on the vibration absorber with the bearing capacity of 6kg is rather large, and the safety margin is not big. In the end, there was no overall structural damage after applying seismic force, and the vibration absorber effectively played the role of reducing the overall vibration amplitude. The following conclusions can be drawn from the analysis of structural bearing capacity:

1. The sky corridor of twin tower could improve the overall stiffness and shorten the natural vibration period of the structure. However, because of the sky corridor, the directional factors of the vibration of the whole structure will be changed and the vibration will be more diverse at the middle and higher level, which makes the vibration of the twin tower more complex than that of the twin-tower structure without sky corridor. However, the sky corridor only has a little influence on the natural vibration period of the structure, and a great influence on the displacement of the top floor and the displacement between floors of the tower.

2. Vibration absorber could effectively consume energy, so that the bearing capacity of structure is more abundant. While ensuring the bearing capacity, the vibration absorber can also be set to reduce the use of the material of the structure itself, so that the cost of the overall structure is reduced, and the coordination and unification of structural performance and cost can be realized.

3. Vibration absorber could reduce the amplitude of vibration effectively. As economy factor is considered, the design of the structure with 1-2 vibration absorbers can give full play to its damping function, and to produce a good result.

4. When the vibration absorber swings beyond a certain limit, the wood block will prevent the displacement of the wood strip connected under the platform. When the swing exceeds the limit, the vibration absorber will be confined by the wood strip below the platform, which provides the vibration absorber with restoring force, limiting the displacement of the vibration absorber. The limit of the displacement is the maximum displacement under the seismic wave obtained from several tests, which is then reduced to a certain extent to obtain the optimal, safe displacement limit, which can not only make full use of vibration absorber, but also limit the displacement effectively.

5. Summary and discussion
This paper develops tall building structure seismic design by respectively designing and analysing the symmetrical, conjoined twin towers and vibration absorber. On the one hand, using the static load test and the shaking table test was carried out on the analysis of physical model structure bearing capacity, on the other hand, using the software for graphical modelling and digital simulation of the structure. And verify the swing type of vibration absorber having good damping effect on high-rise, conjoined towers, and reasonable placement of vibration absorber, so as to achieve the aim of improve seismic performance of structure itself.

The design of vibration absorber is one of the highlights of this research project in seismic design. Through the research and analysis of this paper, different from other seismic means and measures, the optimization of building structure by introducing vibration absorber can be summarized as the following three points:

5.1. Economy
In the conventional structural design, the response of the structure under earthquake is usually reduced by increasing the structural stiffness. By simply increasing the structure stiffness will inevitably lead to the increase of quality, for the high-rise building, it is often expensive, and the practical application is not very effective, could not really improve the seismic performance of the structure, the introduction of vibration absorbing device can effectively reduce the structural weight, reduce the use of building materials, so as to reduce the cost.

5.2. Universality
At present, there are a large number of researches, aiming at one specific building type under the high-rise twin-tower conjoined structure, according to different engineering examples, in terms of material selection and construction techniques, specific seismic design schemes are made, but they are not highly universal for other engineering examples or building types. As a common damping structure,
vibration absorber can be placed and applied in the retrofitting stage of existing buildings besides the anti-seismic application of the structure in the design stage and construction stage.

5.3. Fundamental
Vibration absorber effectively resist vibration, radically reduce the vibration amplitude of main structure, to reduce the vibration destruction of the connecting and even the overall structure, Vibration absorber can be effective on the system energy consumption, guaranteeing bearing capacity at the same time, by setting the energy consumption structure to reduce the quality of the buildings themselves, to improve the seismic performance.

It can be seen from the foregoing that the swinging vibration absorber designed in this study is successfully applied to the symmetrical twin-tower conjoined structure. It is always the key and foundation of successful seismic design to do a good job in structural conceptual design. However, taking the Petronas Towers in Kuala Lumpur, Malaysia as an example, the application of dynamic vibration absorber to such a high-rise building still needs further research and discussion, mainly from the following two aspects:

- To realize the optimization of shock absorption effect of vibration absorber. Applied in the actual cases, the environment should be considered and the corresponding technical problems, such as the quality and how to implement the vibration absorber which is used to the balance of shock absorption band width, on how to ensure making full use of the vibration absorber when earthquake, how to reasonably select vibration absorber with good quality, appropriate spring stiffness and the effective position so as to realize the optimal damping effect.

- Reduce the occupancy of the vibration absorber inside the building. The Taipei 101 building takes up the ball vibration absorber which occupy 88th-92nd floors. Although achieved good vibration reduction effect, but to a certain extent reduce the efficiency of the space. A deeper study of the structural design is required for ensuring a good damping performance while occupying less space.

6. References
[1] Thornton C H, Hungspruke U, Joseph l. m. the Design of the world ’s tallest buildings – Petronas Twin Towers at Kuala City Centre [J]. The Structural Design of Tall buildings, 1997, 6 (4): 245-262.
[2] Code for seismic design of buildings: GB 50011 - 2010[S].2016 edition. Beijing: China Architecture and Building Press, 2016. (in Chinese)
[3] Qing,Lyu, Wensheng,Lu, Weiqiang,Wang, Yue, & Chen.(2020).Mechanism and optimum design of shared tuned mass damper for twin‐tower structures connected at the top by an isolated corridor. Structural Design of Tall and Special Buildings,29(8).
[4] Research on seismic design of building structure design [J]. China Residential Facilities, 2017(02):15-16. (in Chinese)
[5] Ormondroyd J, Den Hartog J P. The theory of the dynamic vibration absorber [J].Transactions of the American Society of Mechanical Engineers, 1928, 49, 50: A9-22.
[6] Zhang Fan, Li Chunxiang, Research on the Control of Structural Enhanced Tuned Mass Damper [J]. Structural Engineer,2019,35(05):119-125. (in Chinese)
[7] Jing Ming, Dai Junwu. Earthquake Engineering and Engineering Vibration,2017,37(03):103-110. (in Chinese)
[8] Makoto Ohsaki, Seita Tsuda, Toma Hasegawa. Parameter optimization of tetrahedral tuned mass damper for three-directional seismic response reduction[J]. Elsevier Ltd,2016,126.
[9] Javidielasadi A, Wierschem N E. Optimal design of rotational inertial double tuned mass dampers under random excitation [J]. Engineering Structures, 2018, 165(jun.15):412-421.
[10] Chiara Masnata, Alberto Di Matteo, Christoph Adam, Antonina Pirrotta. Smart structures through nontraditional design of Tuned Mass Damper Inerter for higher control of base isolated systems [J]. Mechanics Research Communications,2020,105
[11] Seung-Yong Ok. Tuned mass damper asymmetric coupling system for vibration control of adjacent twin buildings [J]. Advances in Structural Engineering, 2020, 23(5).
7. **Appendix A**

Function `[ M1,K1,num ] = Slow( M,K )`

```matlab
num=input('Please enter the number of vibration absorbers: 
');
e=zeros(37,1);
a=zeros(num,1);
s=zeros(num,1);
ks=zeros(num,1);
ms=zeros(num,1);
for i=1:num
    s(i,1)=input('Please enter code number:
');
a(i,1)=2*s(i,1)-1;
    ks(i,1)=input('Please enter the stiffness of the spring connected to the vibration absorber:
');
    ms(i,1)=input('Please enter the mass of vibration absorber:
');
e(a(i,1),1)=1;
end
K1=zeros(37+num,37+num);
M1=zeros(37+num,37+num);
for i=1:37
    for j=1:37
        K1(i,j)=K(i,j);
    end
end
for i=1:num
    for j=1:37
        K1(a(i,1),a(i,1))=K1(a(i,1),a(i,1))+ks(i,1);
        K1(37+i,a(i,1))=-ks(i,1);
        K1(a(i,1),37+i)=-ks(i,1);
        K1(37+i,37+i)=ks(i,1);
    end
end
for i=1:37
    for j=1:37
        M1(i,j)=M(i,j);
    end
end
for i=1:num
    M1(37+i,37+i)=ms(i,1);
end
end
end
```