Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 935

DEVELOPMENT OF MID-STORY ISOLATED STRUCTURE IN CHINA

Xiangyun HUANG [1] Fulin ZHOU [2] Xuehai LUO [3] Jin LIU[4]

ABSTRACT

Isolation technology has been accepted to the "Code for Seismic Design of Buildings" in China. There are also many isolation codes in other countries, such as the United States, Japan, and European Economic Community etc. But in these codes, the restrictions of using isolation technology are very strict, such as superstructure must be regular, the isolation layer must be located on the top of base (base-isolated structure) or under the top floor of the building (TMD). Because of the requirements of architecture and use function or the feasibility of technology, some restrictions have to be broken in practical projects. Sometimes isolation layer is set on the inter-story, to form the “mid-story isolated structure system”.

On the technology innovation aspect, the mid-story isolation system is not only the developments of base isolation system but also an excess of the current isolation code. It is conformable to newly-built and retrofit building and will be one of the developing tendencies of the isolation technology. In this paper, the developments of mid-story isolated structure system in China were introduced in four parts, including theoretical research, experimental investigation, application and the code for mid-isolated structure system in China.

Research Status of Mid-Isolated Structure

Mid-isolated system is mainly used on some irregular structures. For vertical irregular buildings, such as large platform and multi-tower structure which has one or several-story RC frame platform at the lower part and some multi-storey buildings in the upper part, base isolation is difficult to use. For special position of certain buildings, such as hillside structures, tilt or more elevation change of the foundations, isolation layer is not suitable setting on the base. In complex high-rise buildings with conversion story, it is easy to locate isolation layer between conversion story and lower structure. For building retrofit or adding story to an existing building, putting isolation layer between additional story and old story is not only saving investment but

[1] Dr., Earthquake Engineering Research & Test Center, Guangzhou University, Guangzhou, China, TN510405
[2 3] Professor, Earthquake Engineering Research & Test Center, Guangzhou University, Guangzhou, China, TN510405
[4] Dr., School of Civil Engineering, Guangzhou University, Guangzhou, China, NT510006

also easy to construct without interference with the existing building's original function. Its advantage can not be replaced by the base isolation.

Over the last decade, there are many studies on base isolation. Mid-isolated system is the innovation and development of base isolation. But the current research is rarely seen in literature, and most of researches are aimed at the design analysis of practice engineering, simulated shaking table test was carried out only on a few projects.

The research and application on mid-story isolated structure in Japan is more than other country. Many mid-story isolated structures have been built. In China, the research of engineering application of mid-story isolated structure is carried out before or simultaneous with scientific research. Although a number of mid-story isolated structures have been constructed, systematic research is still in early stages.

In this paper, based on shaking table test and finite element analysis of mid-story isolated structure, the theory and mechanism of mid-story isolated structure is discussed. The main influencing parameters, such as the location of isolation layer, mass, stiffness, frequency ratio, damping and hysteresis curve are investigated. The optimum combination relationship of these factors is presented and the design method for engineering application of mid-story isolated structure is suggested. An example of mid-story isolation system is 3 multi towers built on a large platform (3-story RC frame platform). Seismic capabilities of both platform and multi-towers are improved obviously by setting isolation layer between them. After Wenchuan earthquake, the newly revised seismic code added the items of mid-story isolated system, main contents relating to mid-story isolated technology were introduced in the end of this paper.

Theoretical Research

The early research of mid-story isolation system was carried out with specific practice engineering in China. Prof. Fulin Zhou worked at developing mid-story isolated technology. In 1995, a mid-story isolated system was first applied to Shantou museum, isolation layer was set on the top of columns of the first floor and dynamic analysis was carried out. From 2000 to 2005, mid-story isolated system was applied to a large platform and multi-tower structure named Tonghui garden in Beijing. Three-dimensional finite element model was established for dynamic analysis by using the SAP2000 program. Shaking table test was carried out. The calculated results are considered to be certainly accurate by comparison with the data of shaking table tests. Further more, the Modal Synthesis Method was used to set up a calculation model (12-lump) and simplified the whole structure into two parts-the structures up and below the isolation layer (superstructure and substructure), the results can reflect the dynamic properties of the structure.

In 2003, an analysis program for a shear model of six-story of mid-story isolated building was established using MATLAB language. Dr. Lihong Wang calculated the earthquake response under Taft-wave, the result showed that the location of isolation layer was directly affect the earthquake response, the acceleration and the shear force under isolation layer may not be smaller than the non-isolated structures. In 2003, two-lump model was set up for a frame structure with multi-story masonry on the upper by Dr. Youfa Yang. Isolation layer was located between the frame and masonry. The vibration characteristic was analysed to get a combination damping ratio for such frame-masonry structure. The influence parameters such as the stiffness ratio and the mass ratio for the combination damping ratio was proposed. In 2006, using simple two lumped model, Prof. Ai Qi studied the mechanism of mid-story isolated system. If the frequency ratio of superstructure and substructure is appropriate, the displacement of substructure and acceleration of superstructure were significantly reduced; the great the damping ratio of isolation layer is, the better the seismic effect. In a certain frequency range, when the isolation layer is located higher, mid-story isolated system shows a similar working mechanism with the TMD; when the isolation layer is located lower, its working mechanism is similar as base isolation

The Kinetic Equation of Mid-Story Isolated Structures

The isolation layer of mid-story seismic isolation structure was located at any middle story; there is great difference between the stiffness and damping of isolation layer and those of superstructure and substructure, which leads to obvious difference between the responses above and below the isolation layer. Kinetic equations are introduced separately. The kinetic equations of superstructure, isolation layer and substructure are as follows:

$$\left[M^u\right]\{\ddot{u}_u\}+\left[C^u\right]\{\dot{u}_u\}+\left[K^u\right]\{u_u\}=-\left[M^u\right]\{I\}\left\{\ddot{u}_b+\{R\}^T\left[\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right]\right\} \tag{1}$$

$$\begin{aligned} m_b\ddot{u}_b+c_l\dot{u}_b+k_l u_b=&-\{I\}^T\left[M^u\right]\left\{\{I\}\left[\ddot{u}_b+\{R\}^T\left(\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right)\right]+\{\ddot{u}_u\}\right\}\\ &-m_b\{R\}\left(\{\ddot{u}_s\}+\{I_1\}\ddot{u}_g\right)-F_b \end{aligned} \tag{2}$$

$$\begin{aligned} &\left[M^d\right]\{\ddot{u}_d\}+\left[C^d\right]\{\dot{u}_d\}+\left[K^d\right]\{u_d\}\\ &=-\left[M^d\right]\{I_1\}\ddot{u}_g-\{R\}^T\left\{\left(\{I\}^T\left[M^u\right]\{I\}+m_b\right)\left[\ddot{u}_b+\{R\}\left(\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right)\right]+\{I\}^T\left[M^u\right]\{\ddot{u}_u\}\right\} \end{aligned} \tag{3}$$

Where $\lfloor M^u \rfloor$ and $\lfloor M^d \rfloor$ is the mass matrix of superstructure and substructure respectively. $\lfloor K^u \rfloor, \lfloor K^d \rfloor$ is the stiffness matrix of superstructure and substructure respectively. k_l , c_l is the additional stiffness and damping coefficient respectively. m_b is the mass of isolation layer. If the isolation layer only has LRB without any additional damper and spring, k_l , c_l are 0. $\lfloor C^u \rfloor$、 $\lfloor C^d \rfloor$ is the damping matrix of superstructure and substructure respectively. $\ddot{u}_g$ is the acceleration of ground motion, F_b is the horizontal restoration force vector formed by isolation device of isolation layer （such as LRB, friction slipping bearing, etc.）, including elastic-plastic restoration force and viscous damping force of each isolation device, $\{R\}$is the influence matrix of earthquake action, $\{R\}=\{0 \quad 0 \quad \cdots \quad 1\}$.

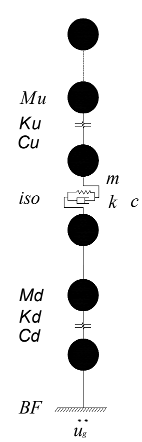


Figure 1. Calculation model

The Main Factors of Mid-Story Isolated Structure

Mid-story isolated system can also be seen as the results of base-isolated system transferring isolation layer to the upper part of the structure. According to the characteristics of structure, isolation layer can be located in some special story, such as the location which vertical stiffness is suddenly changed or structure type is changed, or any middle story of the structure, to form mid-story isolated system.

Control Target for Mid-Story Isolated Structure

For design of the mid-story isolated structure, the earthquake responses both of the superstructure and substructure need to be considered. Two targets must be controlled simultaneously: First target is to reach "seismic isolation". It obviously reduces the earthquake response of superstructure above 75% comparing with non-isolated structure. So it can be reduced one grade of earthquake intensity for designing superstructure to getting better economical effect. The second target is to reach "seismic reduction". It reduces the earthquake response of substructure and the whole structure to improve the seismic safety of building.

When the location of isolation layer is on the lower story, the design goal would reduce the stiffness of isolation layer to fall down the structure's natural vibration frequency. Earthquake response of structure will be isolated through the extension of the first period of structure far from the predominant period of the ground. Deformation will concentrated in the isolation layer and seismic energy will dissipate by the vibration of isolation device. When the location of isolation layer is higher, the extension of the first period of structure is not enough to isolate the earthquake response. The design goal of structural is on the one hand to fall down the vibration frequency, on the other hand to adjust the stiffness of isolation layer using tuned mass damping method to control and decay the vibration of structure.

Influence of Frequency Ratio α on Mid-Story Isolated Structure

Frequency ratio for superstructure and substructure of mid-story isolated structure $\alpha = \omega_u / \omega_d = \sqrt{k_u/m_u} \big/ \sqrt{k_d/m_d}$ is the main factor influencing mid-story isolated structure. Fig.2 gives the curve of transfer ratio of superstructure acceleration, substructure acceleration and base shear force with frequency ratio α, when damping of isolation layer ζ_u=0.10, damping of structure ζ_d=0.02, mass ratio μ is 1. The dotted line is for superstructure, the smaller the frequency ratio α, the smaller the transfer ratio of acceleration. It's similar to base isolation. For substructure acceleration and base shear force, there is an optimum frequency point. More than or less than this value, the response of substructure will increase. The optimum frequency will be changes with the change of mass ratio μ.

When $\mu \geq 1$ the location of isolation layer is lower, it can obviously reduce the response of superstructure above 75% and reduce the base shear force, can reduce one grade of earthquake intensity for superstructure. So two design targets can be realized, we name it as full isolation. When $0.5 \leq \mu \leq 1$ can reduce the response of superstructure but less than 75% and reduce the base shear force, but can not reduce one grade of earthquake intensity for superstructure. We name it as partial isolation. When $\mu \le 0.5$, the location of isolation layer becomes higher. We can reduce base shear force by turn frequency, but the response of superstructure is increased. We name it as turn frequency reduction.

Influence of Damping Ratio of Isolation Layer ζ_u on Mid-Story Isolated Structure

Generally, transfer ratio of structure can be reduced when damping is increased. Especially when the damping ratio ranges from 0 to 0.2, the influence of damping on transfer ratio becomes maximum, but the influence becomes less while damping ratio is greater than 0.2. The greater the mass ratio μ, the less the influence of damping ratio; the influence on transfer ratio becomes even larger when damping is increased. It should be noted that for mid-story seismic isolation structure, when mass ratio μ >0.5, corresponding optimal damping ratio is greater than 0.3, it is difficult to realized in practical engineering..

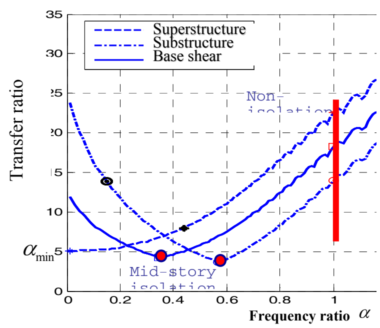


Figure 2. Change curve of transfer ratio of structure with frequency ratio α

Shaking Table Test Research and Comparison with Calculation Analysis

Plans of Shaking Table Test

(a) base isolation (b)bottom of 2nd st. (c) bottom of 3rd st. (d) bottom of 5th st.

Figure 3. Base isolation and mid-isolation models for shaking table tests

A series of steel frames including an 1-story frame, a 2-story frame, and a 3-story frame were used for shaking table tests. The isolation layers were set on the different place of the frames. Four LRBs (diameter 100mm with low hardness (GZY100G4)) were used for isolation layer. During test, isolation layer was set on from the bottom of 1st story (base isolation) to the bottom of 6th story, thus a series of mid-story isolated system were formed (Fig.3). In addition, base-fixed model (no isolation layer) is tested and analyzed in order to comparison with isolated structure system. Two modified earthquake accelerograms (El Centro wave, Tianjin wave) are used in test. Earthquake response analysis of model structure is carried out by finite element model and compared with results of shaking table test.

Vibration Characteristics

The structure's natural vibration characteristics are changed with different locations of isolation layer. Fig.4 shows the calculated values and test results of period of the model. Test results and calculated values are conformed well. If the location of isolation layer of mid-story isolation structure is lower (bottom of 2^{nd}, 3^{rd}, 4^{th} story) and the period is about 2 times comparing with the period of base-fixed structure, mid-story isolation structure almost has the same dynamic property with base-isolated structure. In this case, earthquake response can be reduced by lengthening the period of the whole structure system to attain the object of full isolation. If the location of isolation layer of mid-story isolation structure is high (bottom of 5^{th} ,6^{th} story), the mid-story isolation structure period is close to that of base-fixed structure, it is difficult to lengthen the period of mid-story isolation structure obviously. Earthquake response reduction may be performed by TMD effect.

The damping ratio of 1^{st} modal of base-fixed structure is 1.20%, the damping ratio of mid-story isolation is 7.45%~15.18%, damping ratio becomes very larger by setting isolation layer. Modal participating factors are different for the structures with different locations of isolation layer. The participating factor of the 1st modal of base-isolated structure extends to 99%. Generally the sum of participating factors of the first two modals of mid-story isolated structure is greater than 80% and determines the vibration characteristics. With raising the location of isolation layer, higher modal becomes one of the important controlling factors.

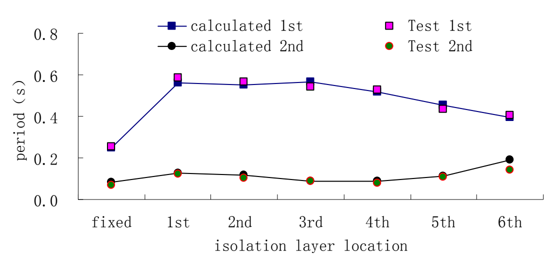


Figure 4. Relationship of structure's period with location of isolation layer

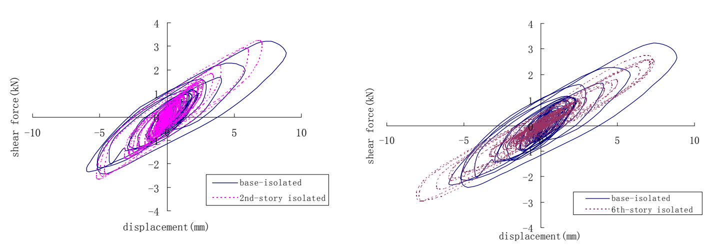


Figure 5. Hysteretic loop of bearing on 8 intensity fortification Earthquake (El Centro)

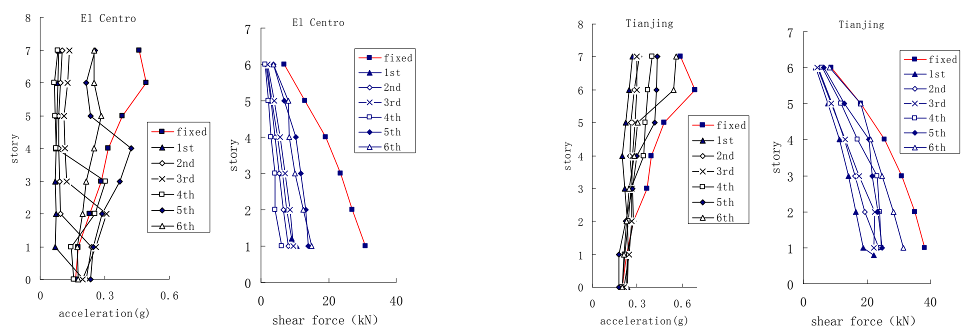
Hysteretic Loop of Isolation Layer

Fig.5 shows the measured hysteretic loop of bearing under El Centro wave. When the location of isolation layer is higher, the bearing of the vertical pressure decreases and yield strength reduces subsequently. Hysteresis curve narrows so that the energy dissipation diminishes.

Earthquake Response and Analysis

Analysis of Acceleration Response and Story Shear Force

Fig. 6 is envelops of comparison of peak acceleration and story shear force response. For El Centro wave, the maximum acceleration happens below isolation layer, and larger than that at corresponding story of base-fixed structure. Acceleration at the stories above isolation layer reduces very obviously, far less than that at corresponding story of base-fixed structure, although the acceleration at stories below isolation layer is greater than that of base-fixed structure, story shear force of each story is smaller than that of corresponding story of base-fixed structure. So it belongs to full isolation or partial isolation. For Tianjin wave, acceleration above isolation layer changes greatly, when the location of isolation layer is higher (bottom of 5^{th} or 6^{th} story), it is even greater than that of base-fixed structure and corresponding story shear force is also greater. But the base shear force is decreased. So it belongs to partial isolation or turn frequency reduction.



(a) El Centro wave (b) Tianjin wave

Figure 6. Comparison of peak acceleration response and story shear force response

Story Drift Response

For isolation structure, the deformation of structure concentrates at isolation layer and story drift of isolation layer increases obviously. Comparing the story drift of various isolation structure systems with the base-fixed structure, the story drift of all, except isolation layer, is smaller than that of base-fixed structure, and the effect of isolation is obvious. Raising the location of isolation layer, the story drift of substructure increases gradually, but the story drift of superstructure does not change basically with the location of isolation layer.

Application of Mid-story Isolated Structure

Project Overview

This building is a large platform and multi-tower structure. It is reinforced concrete frame shear wall. The total height is 40.9m. The lower part is a large platform of 3 stories, with height of 19.8m, and the upper are three 7-story residential towers with height of 21.1 m. Isolation layer is located between the large platform and 7-story towers to form mid-story isolated system. Earthquake intensity is 7, the predominant period of the ground Tg = 0.35s, ground soil category is type II.

Isolation Layer

There are total 51 rubber bearings in the isolation layer with 4 types, including 16 bearings of LRB-D700, 22 bearings of LRB-D800, 5 bearings of LNR-D900 and 8 bearings of LNR-D700. Because the viscous damper is no stiffness damper, it can reduce the seismic shear force and deformation without affecting the isolation results. 10 dampers were chosen and set in isolation layer in X and Y directions. Eccentricity of isolation layer was controlled less than 3%.

Calculation and Analysis of Isolated Structure

Calculation Model

Three-dimension finite element model, which shows in Fig.7, was established using international non-linear version of the ETABS program. Three earthquake waves were used, including a synthetic wave and two earthquake records which were modified according to the standard seismic coefficient curve in China code.

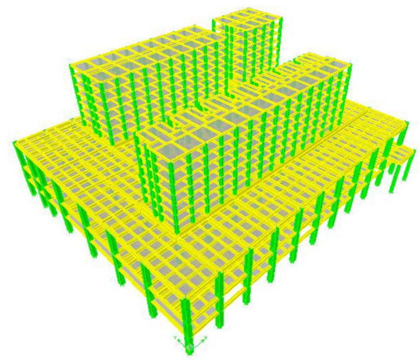


Figure 7. Three-dimension finite element model

Vibration Characteristics of Structure

Comparing with the non-isolated building and isolated building, calculation results show that the first period was changed from 1.365s to 2.579s (in Y direction) and the second period was from 1.191s to 2.516s (in X direction). However, the mass participation factor of these two periods was reached 40%, respectively. And these two periods play a major role in controlling response of structure. Further more, the mass participation factor of the tenth mode(Y direction), eleventh and twelfth mode(X direction) in each direction has reached 50% and also controlled the vibration of the structure.

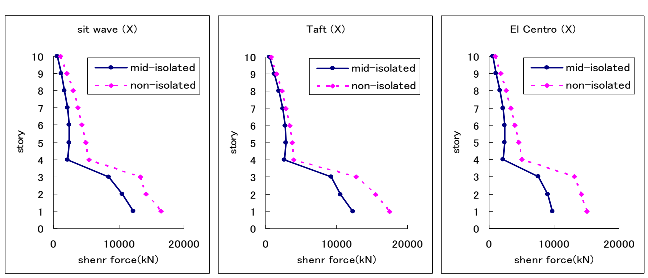


Figure 8. Envelop of shear force of a tower under frequently occurred earthquake in X direction

Calculation of Shear Force

Under frequently occurred earthquake, for superstructure the shear force of isolation structure is reduced 14% ~ 56% and 26% to 59% of non-isolated structure in the X and Y direction, respectively. And for substructure the shear force of isolation structure is reduced 30% ~ 35% and 17% ~ 21% of non-isolated structure in the X and Y direction, respectively. By setting isolation layer, the seismic performances, both superstructure and substructure, have also been enhanced.

Drift Angle of Isolated Structure

For superstructure the maximum drift angle of isolation structure is 1/2208 and 1/1972 in the X and Y direction, respectively. And for substructure the maximum drift angle is 1/2688 and 1/1923 in the X and Y direction, respectively. The superstructure and substructure are both in the elastic state under frequently occurred earthquake and the maximum drift angles are satisfied with the limit of seismic code of 1/550 for frame structure. Under rare earthquake, for superstructure the maximum drift angle of isolation structure is 1/485 and 1/434 in the X and Y direction, respectively. And for substructure the maximum drift angle is 1/330 and 1/270 in the X and Y direction, respectively. The maximum drift angles of superstructure and substructure are both satisfied the limit of seismic code of 1/50 for frame structure.

Maximum Horizontal Displacement of Isolation Layer

Under rare earthquake, the maximum horizontal displacement of isolation layer is 165mm and 180mm in the X and Y direction, respectively. Which are less than the maximum allowable displacement of isolation layer of 385mm. Calculated results also show that tensile stress does not appear in the bearings under rare earthquake.

The dynamic characteristics of the whole structure are improved by using mid-story isolation technology in this large platform and multi-tower structure. Not only improves the seismic capability of 7-story tower, but also reduces the earthquake response of the lower platform structure.

China Earthquake Specification Requirements on Mid-Story Isolated Structure

After Wenchuan earthquake, seismic code of China was amendment and extended the scope of application of isolation technology in order to reduce the damages caused by earthquake. In view of theory research, testing and engineering application of the mid-story isolated system, seismic code took it well. The main contents related to mid-story isolated technology are as follows:

Isolation layer location was limited to between the foundation and superstructure (called base isolation) in the code of 2001 edition. The draft amendment of new code will allow isolation layer setting in the middle of structure. It provides a new approach to isolate complex and irregular structure. The capacity of isolation buttress, columns and associated components below isolation layer should be checked using the vertical force, the horizontal force and moment under rare earthquake. The structure below isolation layer including basement and the relevant components which supporting the isolation structure directly, should be met the requirements of stiffness ratio and the seismic capacity under the fortification intensity earthquake and then checked shear capacity under rare earthquake. The drift angle of substructure under the rare earthquake limits to 1/100, 1/200 and 1/250 for the reinforced concrete frame structures, reinforced concrete frame-shear wall structures and reinforced concrete shear wall structure, respectively.

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