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Advancements in Seismic Isolation Technologies for Super High-rise Buildings

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

With the progress of modern building technology and the rapid development of social economy, super high-rise buildings have become an important part of urban landscape, and the number and height of construction in the world are rising. Therefore, it is particularly important to ensure the safety of these buildings and their internal facilities, especially the seismic performance in earthquake-prone areas. In this context, seismic isolation technology has been widely used as an effective seismic solution. The traditional seismic design method mainly resists the earthquake by enhancing the strength and stiffness of the structure itself, while the damping or shock insulation reduces the impact of the earthquake on the building by introducing energy-consuming components or isolation layers. In addition, seismic isolation is the hybrid systems of damping and shock insulation, which combines the advantages of both. Compared with a single method, which not only reduces the energy dissipation, but also improves the overall stability of the structure, and provides a more comprehensive and efficient guarantee for the seismic design of super high-rise buildings.

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Keywords: Seismic isolation; hybrid systems; energy dissipation; earthquake-prone areas.

1. INTRODUCTION

The earthquake is the ground vibration caused by the plate movement on the earth, and it is a natural disaster with great destructive power. Such as landslides, mountain rupture, rock fall and so on. The vibration of the ground will also cause the destruction of buildings, such as house damage or even collapse, bridge fracture, dam cracking, railway track deformation, etc., which poses a great threat to the safety of people 's lives and property. According to statistics, from January 1,2008 to November 25,2019, 567 earthquakes with a magnitude of more than 5 occurred in China. In particular, an 8.0-magnitude earthquake occurred in Wenchuan in 2008, killing and injuring nearly 100,000, which brought great pain to the people of the whole country. Earthquakes pose a great threat to people 's lives and safety, so the seismic design of building structures is particularly important. In recent years, there have been more and more high-rise buildings in China. As of the end of May 2018, 170 super high-rise buildings with a height of more than 250 m have been built in China, and 84 super high-rise buildings with a height of more than 250 m are under construction. The completed super high-rise buildings are mainly distributed in areas with 6 degrees and 7 degrees (0.1g), and the proportion of high-intensity areas with more than 8 degrees is 7 %. The distribution of super high-rise buildings under construction is still dominated by 6 degrees and 7 degrees, but the proportion of high-intensity areas with 8 degrees and above is significantly increased, accounting for 14%. With the gradual increase of super high-rise buildings in high-intensity areas, the seismic design of their structures has become particularly important.

The original design scheme of modern buildings can not meet the requirements of seismic fortification (Wei et al., 2022). Targeted to strengthen the weak links of building structure (Tang et al., 2021). In the super high-rise building structure, there are many factors affecting the seismic resistance (Zhu, 2019). The most traditional seismic structural system used in the current construction industry is the ductile structural system (Wu, 2018). The idea of structural vibration reduction has become a revolutionary milestone in the design of structural vibration reduction methods (Wang, 2022). Different structural systems have different scope of application in the seismic design of structures (Li, 2022). The commonly used methods for structural seismic design include traditional seismic methods, damping or shock insulation methods, and damping-shock insulation hybrid application methods (Yu, 2021). The corresponding damping device and vibration isolation bearing are set outside the isolation layer to achieve mixed application (Li & Li, 2022). The damping technology is to reduce the influence of seismic waves on the upper part by connecting the changes of the connecting members when the earthquake occurs (Cui & Zhu, 2021). Seismic isolation technology is an important means to effectively resist earthquake disasters and improve urban safety (Wang et al., 2022).

2. THE DEVELOPMENT OF ENGINEERING EARTHQUAKE RESISTANCE

Earthquakes will cause huge economic losses to human beings and pose a threat to people 's lives. The impact of earthquakes is long-lasting. We usually take various measures to resist the damage caused by earthquakes, including early warning before earthquakes, earthquake prevention and disaster reduction, and engineering earthquake resistance. At present, we still can not accurately predict the occurrence time of the earthquake, so we can only reduce and prevent the disaster caused by the earthquake through the seismic design of the building structure. The seismic design methods of structures are divided into traditional seismic design methods and structural vibration control methods.

2.1 Traditional Seismic Methods

The traditional anti-seismic thought can be simply summarized as ' to overcome the rigid'. Traditional earthquake resistance closely connects the foundation with the upper structure, which causes the structure to vibrate and deform. The structure dissipates seismic energy through the bearing capacity and deformation capacity of its own seismic components. Therefore, the seismic energy dissipation components of the structure are particularly important for the safety performance of the structure. Once some factors cause problems in the seismic components of the structure, it will seriously damage the seismic performance of the structure, causing serious damage to the structure during the earthquake, and the main area of the structure will be damaged, and the building will be difficult to repair, causing irreversible damage. The traditional structural seismic design has the following disadvantages:

(1) Security is difficult to guarantee

The traditional structural seismic design method is based on the 'seismic fortification intensity', which will cause many problems. When a super-intensity earthquake occurs, the building structure will be seriously damaged or even collapsed. On the other hand, the earthquake is random. Because of this, the traditional seismic design method is difficult to control the degree of structural damage, and the safety of the structure is difficult to guarantee.

(2) Adaptability is limited

The traditional seismic design method mainly aims at not collapsing under large earthquakes, allowing structural members to be damaged to a certain extent during earthquakes. However, such a simple seismic design of buildings has limitations, because it does not consider the seismic resistance of equipment and instruments in the house, which is not applicable to some special buildings.

(3) Poor economy

The traditional seismic method is that the structure relies on its own seismic resistance to resist earthquakes, and the seismic design of the structure in high-intensity areas will cause more material consumption.

2.2 Structural Vibration Control Method

Due to the limitations of traditional seismic design, many scholars have proposed a new seismic design method-structural vibration control method. Structural vibration control mainly includes base isolation, passive energy dissipation, active and semi-active control, hybrid control, and intelligent control.

3. STRUCTURAL DAMPING ENERGY DISSIPATION COMBINATION SYSTEM

3.1 Structural Energy Dissipation

Damping control is mainly divided into the following five categories: (1) Passive control technology. Some energy dissipation devices are set up in the building structure, which can greatly consume the energy transmitted from the earthquake to the interior of the structure when an earthquake occurs. (2) Semi-active control technology. Real-time control of parameters such as stiffness or damping ratio of the structure to reduce the response of the structure, although only less energy is required for control, the control process is more dependent on structural response and external excitation information. (3) Active control technology. It refers to monitoring the dynamic response and external excitation of the structure, and using the calculation system to feedback the solution results of the structural response to the servo system, so that the dynamic response of the structure can be controlled to a certain extent, and finally the active vibration control is completed. However, the realization of the control system not only relies heavily on the structural dynamic response and is susceptible to external information interference, but also requires the input of external energy. (4) Intelligent control technology. The actuators and dampers in the system are made of intelligent materials, which are simple in structure and easy to drive and adjust. (5) Hybrid control technology. Combine the advantages of both and make up for the shortcomings of both.

The displacement-dependent energy dissipator effectively increases the structural damping ratio and shortens the period of the structure. The effect of the displacement-dependent damper on reducing the total base shearing force of the structure is sometimes not significant, and the effect on controlling the displacement of the structure is significant. By increasing the damping of the structure, the velocity-dependent energy dissipator can dissipate the energy and shock of the structure without changing the stiffness and period of the structure, and can achieve the effect of reducing the base shear force and interlayer displacement.

3.2 Structural Isolation

The seismic isolation design of the structure refers to the arrangement of the isolation device on a certain layer of the building structure, which separates the upper structure of the building from the lower foundation, reduces or even avoids the transmission of seismic energy from the bottom to the upper structure, so as to effectively protect the upper structure and internal personnel, important equipment and so on. Compared with the traditional structure, the isolation design helps the structure to resist earthquake by ' softness and rigidity ', which effectively prolongs the natural vibration period of the building structure, increases the structural damping, and reduces the dynamic effect of the earthquake on the superstructure. At present, structural isolation is divided into two categories : base isolation and inter-story isolation.

(1) Base-isolated structure

Base isolation design has been widely used in multi-storey and low-rise buildings, especially for some buildings with special requirements, such as buildings with important equipment, key information command center buildings, buildings with explosives, high-risk laboratories, etc., base isolation design can be given priority. In high-intensity areas, the use of base isolation technology to design the structure can appropriately increase the building height limit specified in the specification and solve many problems in practical engineering design. Compared with the traditional seismic design method, the base isolation design technology has the following advantages:

① The isolation layer is used to consume seismic energy, increase the natural vibration period of the structure, and reduce the inter-story shear force and inter-story displacement of the superstructure.

② The design of the building structure is optimized. According to the standard design, some complex components may need special treatment. When the base isolation design is adopted, only the design of the isolation layer needs to be considered, which greatly reduces the workload of the structural design.

③ Select the appropriate isolation device and layout position to increase the economic benefits of the entire structural design and reduce the overall cost of the building structure.

(2) Inter-story isolated structure

In practical engineering, there may be some limitations in the design of base isolation. Layer isolation design is a new isolation method developed on this basis. The interlayer seismic isolation technology is still under exploration. The interlayer seismic isolation technology is suitable for the following construction projects:

①Inshore buildings. In offshore areas, the rising tide of sea water may erode the base isolation bearing and accelerate the aging of the bearing. Generally, the isolation layer is set on one or higher floors.

② Storey of old buildings. For the old building storey-adding design, due to the increase of building height and weight, the seismic resistance of the original structure can no longer meet the seismic demand of the structure. Setting the isolation layer on the original structure will reduce the dynamic response of the structure and improve the seismic resistance of the original structure to a certain extent.

③ Seismic reinforcement of old buildings. For some buildings with cultural heritage value that need to improve the seismic performance, it can be considered to set the isolation layer under the building roof, which can not only improve the seismic resistance of the structure, but also maintain the original appearance of the building to a certain extent.

④ Building reinforcement of important departments. For some buildings that can not interrupt the operation of the machine, such as post and telecommunications room, information command center and so on, it is very difficult to use the traditional reinforcement method. The interlayer seismic isolation technology can better solve the problem.

3.3 Structural Seismic Isolation Hybrid System

With the wide application of energy dissipation structures and isolation structures in practical engineering, some scholars and designers have found that the combined application of damping and isolation devices can effectively improve the seismic resistance of structures compared with the application of single shock absorption and isolation devices. The combined application of damping and shock insulation is to add energy dissipation damper on the isolation structure, which can not only make up for the poor seismic effect of single energy dissipation design, but also make up for the problem that the displacement of isolation layer of isolation structure is too large.

The arrangement of viscous dampers in the isolation layer can effectively reduce the displacement of the isolation layer under large earthquakes. The damping effect of the structure using the damping-isolation hybrid application technology is better than that of the structure using the damping or isolation technology alone.

4. DAMPING AND ISOLATION DEVICE

The isolation device is generally composed of an isolator and a damper, which has sufficient vertical stiffness and large damping to ensure that the system has good restoring force. Its horizontal lateral stiffness can not be too small to prevent the risk of overturning of the structure.

The energy dissipation system is generally equipped with energy dissipation components on the structure. The energy dissipation component is in the elastic stage when the structure is subjected to small earthquakes, and resists the earthquake action together with the whole structure. When the structure is subjected to fortification earthquakes and large earthquakes, it first enters the elastic-plastic stage to provide greater damping to the structure, so as ensure that the main structure is not destroyed and achieve the effect of damping.

4.1 Isolation Device

The isolation device system is generally divided into two categories according to its functional characteristics:

(1) Separation type: It is composed of independent isolators, dampers, etc., so that they can exert their respective isolation energy dissipation and reset capabilities. The common types of dampers are shown in Fig. 1. It includes elastic-plastic damper, viscous damper, oil damper and so on.

(2) Compound type: The isolation system not only has the stiffness of the upper structure of the vertical support, but also has a large horizontal viscous damping. In the analysis of the system, not only consider whether the vertical bearing capacity is satisfied, but also consider the characteristics of its restoring force. HDR-S (high damping rubber bearing) and LRB (lead rubber bearing) are all functional composite isolation device systems.

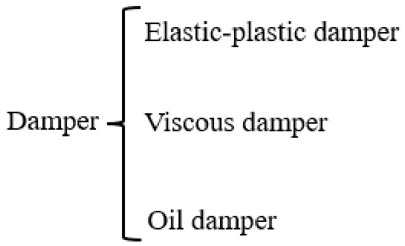

Fig. 1. Type of damper

At present, the most widely used in practical engineering is laminated rubber bearing. According to the different materials, laminated rubber bearings can be roughly divided into the following two categories, each with its advantages and disadvantages:

Natural rubber production (LNR) combines thin steel plates and rubber plates together, so its vertical stiffness is large, elastic properties are good, almost no damping performance, and its isolation energy consumption under earthquake action is poor. Generally, it needs to be used with other bearings or dampers with good damping performance.

The lead rubber bearing (LRB) is based on the ordinary laminated rubber bearing. Thick connecting steel plates are arranged in the upper and lower parts, and the lead core is inserted in the center of the bearing. The steel plate and rubber plate are used to bear the vertical load of the superstructure and constrain the horizontal movement of the lead core. On the one hand, the lead core in the center of the bearing improves the energy dissipation capacity of the isolation bearing, and on the other hand, it can provide certain damping. The most widely used.

4.2 Energy Absorber

Energy dissipation damper, as an innovative damping technology, plays a vital role in building and bridge engineering. It dissipates the energy generated by earthquakes or other vibrations through mechanisms such as friction, elastic-plastic deformation or viscoelastic deformation, significantly reduces the dynamic response of the structure, and improves the seismic performance and safety of the structure. The application of this technology not only improves the stability and integrity of buildings in earthquakes, reduces the risk of secondary disasters caused by structural damage, but also brings economic benefits, such as reducing the amount of materials used in the seismic design of new or existing structures. In addition, the wide applicability of energy dissipation dampers makes it an effective means to improve the comfort and functionality of sensitive facilities, thus playing an indispensable role in ensuring the safety of people 's lives and property and improving the comprehensive performance of buildings and infrastructure. Passive dampers are widely used in building structures, and the classification of energy dissipation dampers is

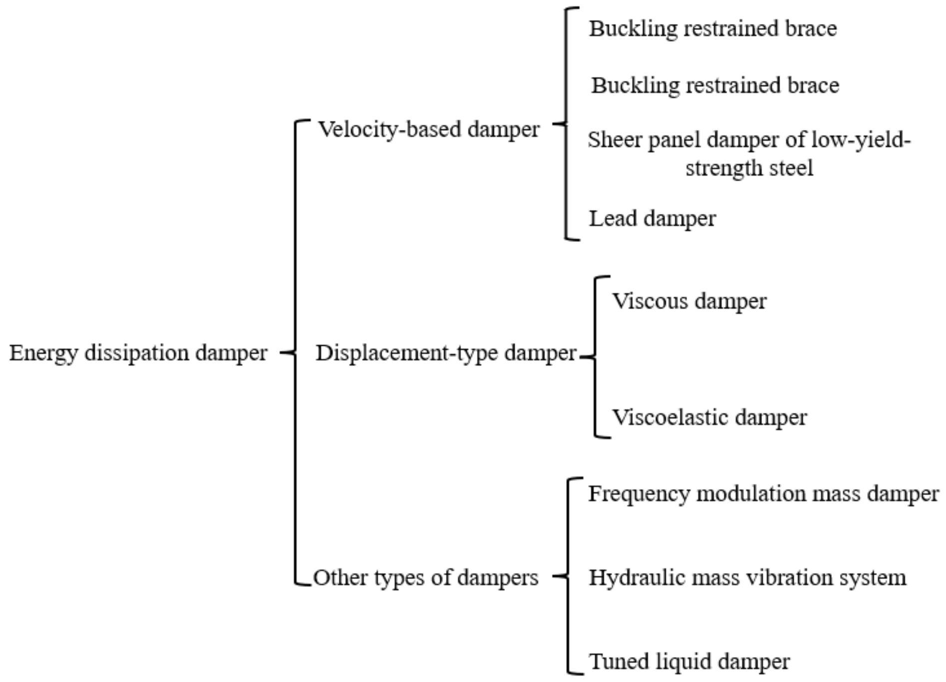

Fig. 2. Classification of energy dissipation shock absorbers

shown in Fig. 2. It includes bulking restrained brace, bulking restrained brace, sheer panel damper of low-yield-strength steel, lead damper, viscous damper viscoelastic damper, frequency modulation mass damper, hydraulic mass vibration system, tuned liquid damper and so on.

5. APPLICATION OF SEISMIC ISOLATION DEVICE

Seismic isolation technology plays a vital role in the field of disaster resistance and mitigation of building structures. It effectively isolates and dissipates seismic energy by installing isolation layers and energy dissipation dampers in key parts of the structure, and significantly reduces the dynamic response of the structure. The technology has a wide range of applications. It not only covers modern engineering projects such as super high-rise buildings, bridges, and important infrastructure, but also plays an important role in the protection and restoration of historical buildings, reflecting its comprehensive benefits in improving structural safety and functionality.

Internationally, some typical structures adopt advanced seismic isolation technology, such as San Francisco International Airport International Terminal in the United States, Wellington Parliament Building in New Zealand and Tokyo Sky Tree in Japan. These cases show the remarkable effect of seismic isolation technology in resisting earthquake disasters and ensuring building safety. Although the seismic isolation technology faces the challenges of design complexity, high initial investment cost and gradual improvement of market acceptance, its innovation and development are still important directions for the progress of building science and technology.

The popularization and application of seismic isolation technology not only improves the seismic capacity of building structures, but also promotes the development of related disciplines, such as structural dynamics, material science and seismic engineering. In addition, with the advancement of computational simulation technology and the development of new materials, the efficiency and effectiveness of seismic isolation technology have been continuously improved, providing strong technical support for the construction industry to move towards safer and more efficient goals.

6. CONCLUSION

(1) The application of seismic isolation technology makes the rapid development of high-rise buildings, greatly improving the seismic performance of the contact. Compared with the

traditional seismic system, the base isolation system and the lower damping-layer isolation hybrid system can effectively extend the natural vibration period of the structure and reduce the impact of the earthquake on the structure.

(2) The seismic isolation combination can effectively reduce the anti-vibration effect of the superstructure, so that the seismic performance of the structure can be effectively improved. For this kind of seismic isolation composite structure, the superposition analysis method can be applied to the design part of the seismic isolation composite structure. For the design, it is necessary to check the damping efficiency according to its overall analysis. In this process, the function of seismic isolation combination is increased by means of superposition analysis.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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