

# Analysis of Seismic Performance of Masonry Structures Strengthened by External Steel Frame and Isolation Combination

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**Abstract:** The combined strengthening technology of external steel frame and isolation is conducive to improving the seismic performance of masonry structures. Their combination enhances structural integrity and bearing capacity through the external steel frame, while giving full play to the role of the isolation layer to weaken seismic energy, forming a collaborative working mechanism. Analysis shows that this combined scheme helps improve the dynamic characteristics of the structure and controls the damage of the main structure within a reasonable range by reducing responses. This study focuses on explaining the working mechanism and effectiveness of this strengthening method, aiming to provide useful references for seismic retrofitting of buildings.

**Keywords:** External steel frame; Isolation combination; Masonry structure; Seismic performance

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## 1. Introduction

Currently, there are a large number of masonry structure buildings in China. These buildings were constructed relatively early, many during the period when seismic codes were not yet perfect, resulting in obvious insufficient seismic capacity and vulnerability to damage during earthquakes. How to solve this problem has become one of the important issues facing engineering practitioners<sup>[1]</sup>. Traditional strengthening methods have many drawbacks, such as complex construction leading to high costs. The external steel frame strengthening method starts from the overall structure, which is conducive to improving its performance and bearing capacity, while isolation technology protects the upper structure by blocking the input of seismic energy. This paper focuses on exploring the working mechanism of the combined strengthening system of external steel frame and isolation, analyzing its comprehensive improvement effect on the seismic performance of masonry structures, aiming to provide useful references for seismic retrofitting of buildings<sup>[2]</sup>.

## **2. Seismic weak links and strengthening needs of masonry structures**

### **2.1. Inherent characteristics and seismic damage characteristics of masonry materials**

Masonry structures include blocks and mortar, and material properties directly affect seismic effects. For example, masonry materials have insufficient tensile and shear strength, poor deformation capacity, and are brittle materials. When an earthquake occurs, if the principal tensile stress exceeds the material strength, it will have an adverse impact on the masonry structure, i.e., generating diagonal and cross cracks. Analysis of these cracks shows that they initially mainly appear in stress-concentrated parts, such as the corners of door and window openings or the connections of walls. If they penetrate, they will cause local or overall instability and collapse of the walls. This is because the masonry structure is weak overall, and the connections between various components are not firm. Both the connection between floor slabs and walls and between walls are relatively weak, so when an earthquake occurs, each component cannot work synergistically, which is prone to local damage and even sequential collapse<sup>[3]</sup>.

The seismic damage forms of masonry structures are highly typical. Damage modes include shear cracks in walls, V-shaped cracks at wall corners, etc. Damage modes are affected by many factors, such as wall aspect ratio and opening conditions. Understanding their inherent characteristics and seismic damage characteristics can not only create favorable conditions for formulating scientific and targeted strengthening schemes in the future but also provide an important foundation for evaluating strengthening measures<sup>[4]</sup>.

### **2.2. Common seismic defects of existing masonry structures**

At present, many masonry structures were constructed relatively early and based on outdated seismic fortification standards, resulting in insufficient systematicness in their seismic design. For example, in terms of the structural system, problems such as excessive spacing between transverse walls and limited support from transverse walls for longitudinal wall load-bearing are prominent, leading to a large deviation between the stiffness center and mass center of the structure, which will produce torsional effects when an earthquake occurs. In terms of structural measures, there are problems with the setting of ring beams and structural columns, some of which are even completely missing, which not only affects structural integrity but also adversely affects its spatial collaborative working capacity, leading to out-of-plane instability and damage of walls<sup>[5]</sup>.

Original design and construction defects are only one aspect; on the other hand, with the continuous increase of service life, many problems begin to emerge, such as material aging and increased load due to the loss of some service functions, which reduce the seismic capacity of existing masonry structures. When these defects overlap and act comprehensively, the seismic capacity of such buildings is insufficient. Therefore, comprehensive measures should be taken during strengthening to improve system integrity, ductility, and energy dissipation capacity<sup>[6]</sup>.

## **3. Working mechanism and synergistic effect of the combined strengthening system**

### **3.1. Working principle of the external steel frame strengthening method**

The external steel frame strengthening method refers to adding a frame system outside the original masonry structure, which includes steel columns and steel beams. This external frame and the original structure work synergistically through reliable connections, forming a composite structural system. The working principle of this strengthening method is as follows: First, the external frame serves as an additional seismic line of defense, bearing part of the horizontal seismic action, which is conducive to reducing the burden on the original masonry

walls. The steel frame has good ductility and energy dissipation capacity, which can effectively absorb and dissipate seismic energy. Second, the external frame also plays an important role in restricting the deformation of the masonry structure. Through the connection between floor beams and the original floors, the masonry walls are provided with new support, which mainly comes from the out-of-plane direction, preventing out-of-plane collapse and improving structural stability<sup>[7]</sup>.

### **3.2. Basic mechanism and introduction of the purpose of isolation technology**

The principle of isolation technology is to set an isolation layer at the bottom or a certain part of the building. By extending the natural vibration period of the structure and providing damping through isolation devices to consume seismic energy, the seismic action transmitted to the upper structure is reduced. Adding isolation technology to masonry structures aims to abandon the “hard resistance” structural seismic strategy and adopt a more effective “isolation” strategy. The strengthened “external frame-masonry” composite system generally sets the isolation layer at the bottom, aiming to isolate strong ground motion and significantly reduce the seismic force borne by the upper structure<sup>[8]</sup>.

Adding isolation technology to the combined strengthening system is to protect the upper main structure after being strengthened by the external steel frame, especially the original masonry part. When a strong earthquake occurs, the isolation layer fully plays its role, filtering out high-frequency and high-acceleration seismic wave components, making the movement of the upper structure seem to be on a gentle moving platform. This way ensures that the damage to the original masonry walls is small, that is, through effective control, their historical value is protected and their service functions are guaranteed. At the same time, it is also conducive to maintaining the working state of the newly added external steel frame. In short, the introduction of isolation technology makes the strengthening goal no longer to prevent collapse but to ensure service functions from being affected by major earthquakes<sup>[9]</sup>.

### **3.3. Collaborative working mechanism of the combined strengthening system**

The combined strengthening system of external steel frame and isolation is not a simple technical superposition but focuses on the synergistic effect between the two. The collaborative working mechanism of the combined strengthening system emphasizes multi-level division of labor and cooperation. Vertically, the isolation layer mainly undertakes the isolation function, which mainly refers to isolating most of the horizontal seismic input and establishing the first line of defense for the upper structure; while integrating, the external steel frame also focuses on improving structural integrity, and the remaining seismic action after being significantly reduced by the isolation layer is mainly borne by the frame. Horizontally, the isolation layer plays a major role, that is, significantly reducing the base shear force; the composite system composed of the upper external steel frame + original masonry structure helps maintain structural performance by providing stiffness and bearing capacity, mainly referring to performance under wind loads and small earthquakes<sup>[10]</sup>.

This combination achieves complementary advantages between “isolation” and “strengthening”. For example, isolation technology avoids the problem caused by using an external steel frame alone for strengthening; that is, seismic action will still be transmitted to the upper structure. The external steel frame helps solve the drawbacks of the pure isolation scheme, that is, the insufficient integrity of the upper masonry structure, which may lead to instability under large deformation. The steel frame provides strong constraints for the originally fragile masonry part and provides overall protection, enabling it to maintain basic functions when the isolated structure undergoes large displacements.

## **4. Comprehensive analysis of seismic performance of the combined strengthening system**

### **4.1. Changes in structural dynamic characteristics**

The strengthening measure of “external steel frame + isolation combination” has a profound impact on the original masonry structure, that is, changing its dynamic characteristics and providing a physical basis for improving its seismic performance. First, extend the basic natural vibration period of the structure. After adding an isolation layer at the bottom, coupled with the large horizontal flexibility of the isolation layer, the natural vibration period of the structural system will be significantly extended, often several times that of the original structure. Second, change the structural mode shape. After isolation, the first mode shape of the structure is reflected in the horizontal shear deformation of the isolation layer, and the upper structure is in an overall translation state, which is conducive to reducing the relative deformation and internal force inside the upper structure.

The changes in structural dynamic characteristics are of positive significance. The extended period effectively avoids the short-period segment where common seismic ground motion energy is concentrated, which is conducive to reducing resonance risks. The overall translation mode shape of the upper structure makes the seismic response of each floor more uniform during an earthquake, avoiding the drawback that weak layers of traditional structures are prone to damage. In addition, isolation systems can often provide large additional damping, which greatly helps to quickly attenuate structural vibrations caused by earthquakes.

### **4.2. Evaluation of seismic response and performance improvement**

When the seismic action is strong, the seismic response of the combined strengthening system is quite different from that of the unstrengthened structure and the singly strengthened structure. For the overall structural response, the isolation layer will significantly reduce the base shear force and floor acceleration transmitted to the upper structure. That is to say, both the original masonry walls and the newly added external steel frame bear less horizontal seismic action compared with traditional strengthening schemes. This way controls the damage of the original masonry walls within a reasonable range, that is, only slight cracks may occur, and some can still maintain an elastic state. After a major earthquake, such masonry walls do not need to be repaired or only need minor repairs. This plays an important role in protecting historical buildings and the internal functions of important buildings.

Analyzing the response at the structural component level, it is found that their performance has been comprehensively improved. The requirements for both shear deformation and bending deformation of the original masonry walls have decreased significantly, effectively improving their safety margin. At this time, the internal force of the external steel frame is also at a low level, which is easier for members and connection nodes to maintain elasticity, improving the reliability of the second line of defense. The isolation bearing is an energy-consuming component, which can consume seismic energy in addition to generating the expected horizontal displacement.

### **4.3. Discussion on design key points and application scope**

To improve the effectiveness of the combined strengthening system of external frame and isolation, the key design points should be grasped. First, focus on the design of the isolation layer. Carefully select isolation bearings, including their types, arrangement, and parameters, to ensure sufficient support in terms of vertical bearing capacity and horizontal reset capacity. When designing the displacement of the isolation layer, safety

margins should be reserved in accordance with code requirements, and factors such as construction deviations and long-term use should also be considered. Second, in the design of the external steel frame, first ensure the stiffness to integrate the upper structure, and in addition, have sufficient bearing capacity and ductility to ensure a good safety reserve. The connection between the frame and the original structure should be firm and reliable to transmit vertical loads and residual horizontal forces, and leave room for relative deformation to effectively avoid adverse effects on the original structure.

The combined strengthening system has a wide application scope, especially in the following cases: important masonry buildings that require high seismic fortification and should be focused on protection, including hospitals and historical buildings; masonry structures with slight damage to the original structure and obvious insufficient seismic capacity; projects where building functions lack conditions for large-scale internal transformation and wet operation construction. However, this application is also restricted by some conditions, such as the need for sufficient space around the building for corresponding settings, such as external frames and construction operation surfaces; for buildings with irregular plane shapes and significant damage to the original structure, more detailed analysis and auxiliary strengthening should be carried out. In engineering practice, refined analysis and design should be conducted on the premise of comprehensive research to give full play to the advantages of this strengthening technology.

## 5. Conclusion

In summary, combining the external steel frame and isolation technology has opened up a new path for the seismic strengthening of masonry structures, which is highly practical and forward-looking. This combined system integrates the concepts of isolation and strengthening, focusing on their synergy. While significantly improving the overall seismic performance of the structure, it achieves a performance leap, that is, no longer pursuing collapse prevention but moving towards damage control. This method emphasizes both safety and economy, and is particularly suitable for historical buildings and important public buildings. In the future, in-depth research is still needed on the standardization and long-term performance monitoring of this technology.

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## Disclosure statement

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