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Review on Research Progress and Application of Seismic Reinforcement Technology at Home and Abroad

Huiyi Sun, Lijie Ma

School of Civil Engineering and Architecture, North China University of Science and Technology, Tangshan 063210, China

Abstract: Earthquake disasters pose a serious threat to human life, property and infrastructure, and improving the seismic performance of existing buildings has become a global focus. Some existing buildings in China are in urgent need of scientific reinforcement due to problems such as low design standards and aging materials. The international community has also accumulated rich achievements in this field. In this paper, the seismic strengthening technology at home and abroad is systematically reviewed, which is divided into traditional technology (increasing section, wrapped steel), new material technology (FRP, steel fiber reinforced concrete), energy dissipation and shock absorption, isolation and self-centering technology. The principle, scope of application, advantages and disadvantages of each technology are deeply analyzed, and the differentiated strengthening requirements of masonry, reinforced concrete and steel structure are compared. Combined with typical cases such as reinforced-mortar strip reinforced masonry buildings and CFRP reinforced high-rise residential buildings, the technical effectiveness is verified. The research points out that the future seismic reinforcement technology will develop in the direction of green and intelligent materials, diversified technology integration, prefabrication and digitization of construction technology, perfection of theoretical norms and sustainable functionalization, providing key technical support for the construction of resilient cities.

Keywords: Seismic Reinforcement Technology, Traditional Reinforcement Technology, New Material Reinforcement, Energy Dissipation and Vibration Reduction, Base Isolation Technology, Self-Recovery Technology, Structural Type, Development Trend.

1. Introduction

As a major risk that threatens the safety of human life and property and the stability of infrastructure, earthquake disaster has always been the research focus in the field of global engineering. Among the existing massive existing buildings in China, some of them are difficult to meet the requirements of the current specifications due to low design standards, material aging or structural defects, so scientific and efficient reinforcement technology is urgently needed. At the same time, the theoretical research and engineering practice of the international community in the field of seismic reinforcement have also made significant progress. The multi-technical path provides a rich reference for improving the seismic resilience of structures.

This paper systematically reviews the development of seismic strengthening technology at home and abroad, and focuses on the technical systems of traditional technology, new material application, energy dissipation and shock absorption, isolation and self-centering, and deeply analyzes its working principle, applicable scenarios and performance advantages and disadvantages. By comparing the differentiated reinforcement requirements of masonry structure, reinforced concrete structure and steel structure, the technical effectiveness is verified with typical engineering cases, and the future development trend of green, intelligent and diversified is discussed in order to provide a systematic reference framework for academic research and engineering practice in this field.

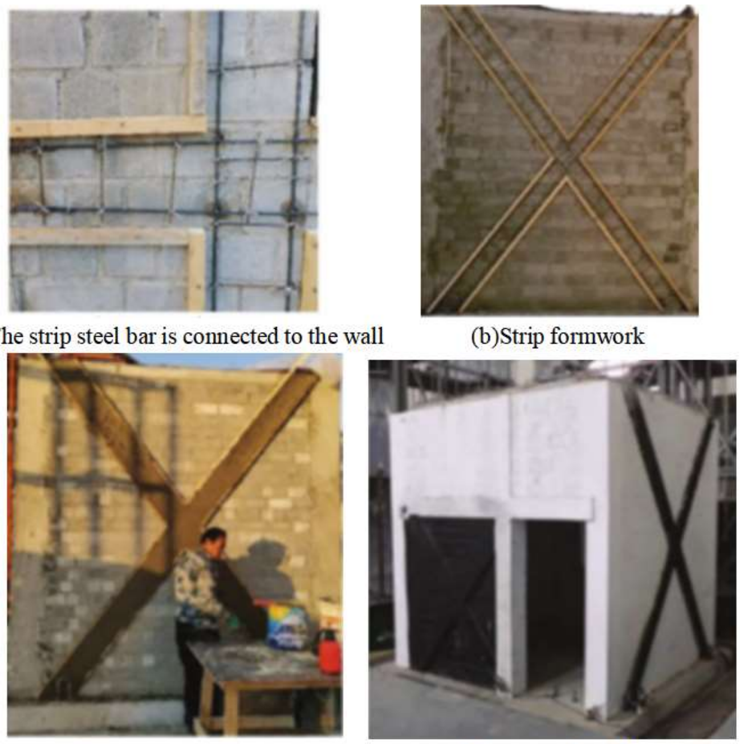
2. Classification and Research Progress of Seismic Reinforcement Technology at Home and Abroad

2.1. Traditional Seismic Reinforcement Technology

2.1.1. Increasing Section Reinforcement Method

Increasing the cross-section reinforcement method is a common reinforcement method for concrete structures and masonry structures by increasing the cross-section size and reinforcement of the members and improving the bearing capacity and stiffness of the structure. For concrete beams and columns, the method of wrapping concrete around can be adopted, and the new concrete and the original components can work together through interface treatment and planting bar technology[1].

In the masonry structure, the reinforcement of the steel mesh mortar surface layer is a typical application. By laying the steel mesh on both sides of the wall and spraying the mortar, the composite wall is formed to improve the shear and bending resistance of the wall[2-4]. For example, An Xiaoying et al[3]proved by shaking table test that reinforcement-mortar strip reinforcement (Figure 1) can reduce cracks in weak parts of single-layer masonry buildings and improve seismic performance. The principle of this method is simple and the applicability is strong, but the construction period is long and the amount of wet work is large, which has a great influence on the use function of the building, and the new load may have an adverse effect on the foundation[4].



(a)The strip steel bar is connected to the wall (b)Strip formwork

(c)Plastering mortar strip (d)Reinforced model

Fig. 1 Model reinforcement[3]

2.1.2. Method of External Packing-Steel to Strengthen

The steel-encased reinforcement method can significantly improve the bearing capacity and ductility of the components by wrapping steel or steel plates around the components and acting together with the original components through adhesives or welding, bolt connection, etc., which is especially suitable for the reinforcement of concrete columns, beams and masonry walls[1,5]. For steel structure, the reliability of joint connection can be enhanced by outsourcing steel[6]. Its advantage is that the construction speed is faster, the damage to the original structure is small, and the performance can be improved without significantly increasing the section size of the component. The disadvantage is that the amount of steel used is large, the cost is high, and the requirements for joint treatment are strict, and the anti-corrosion treatment needs long-term maintenance[7].For the reinforcement of steel structure joints, in addition to the traditional outsourcing steel technology, Ning Yongkang et al[8] proposed the external cable-stayed steel strand reinforcement technology, which provides a new path for improving the lateral stiffness of the structure through the coordinated force of prestressed steel strand and frame.

2.2. New Material Reinforcement Technology

2.2.1. Fiber Reinforced Polymer (FRP) Reinforcement Technology

FRP materials (such as carbon fiber CFRP, glass fiber GFRP) have become a research hotspot in the field of building reinforcement due to their advantages of light weight, high strength, corrosion resistance and convenient construction[8-11]. The principle is to paste the FRP cloth or plate on the surface of the component through the adhesive, and use the high strength characteristics of the fiber to share the load and improve the bending, shear and compression resistance of the component[8]. For example, Du Changchun et al[9] used CFRP to strengthen weak members in a high-rise residential building. Experiments show that the lateral stiffness and seismic capacity of the structure are significantly improved (as shown in table 1), and the inter-story displacement angle and the peak acceleration of the floor are reduced. FRP reinforcement is suitable for concrete, masonry and steel structures, especially for complex curved members[9,11]. However, the bonding performance between FRP material and matrix is greatly affected by ambient temperature and humidity. The long-term performance monitoring data is insufficient, and the high temperature resistance is poor, which is easy to fail under fire[6].

Table 1. Comparison of seismic performance of structures before and after CFRP plate reinforcement[9]

performance index	Before reinforcement	after reinforcement
Fundamental frequency (Hz)	0.357	0.485
The maximum inter-story displacement angle (rad)	1/108	1/186
Floor peak acceleration (m/s^2)	2.35	1.68
CFRP strain level (%)	--	0.38
seismic fortification level	Less than 8 degrees	8.0-magnitude

2.2.2. Steel Fiber Reinforced Concrete Reinforcement Technology

By adding steel fiber into ordinary concrete, steel fiber reinforced concrete improves the tensile, crack and shear resistance of concrete, and improves the energy dissipation capacity and ductility of the structure. Under the action of seismic load, steel fiber can inhibit crack propagation, absorb energy, and delay structural damage[12]. This technology is suitable for the reinforcement of beam-column joints, floor slabs and other parts. The construction technology is similar to that of ordinary concrete, but it is necessary to pay attention to the dispersion and dosage control of steel fiber. Its advantage is that the material has good toughness and strong compatibility with the original structure ; the disadvantage is that the cost is high, and there are certain requirements for construction equipment[6].

2.3. Energy Dissipation Technology

By setting energy dissipation dampers (such as viscous dampers, buckling restrained braces, metal dampers, etc.) in the structure, the energy dissipation technology takes the lead in energy dissipation under earthquake action and reduces the seismic response of the main structure[13-15]. Buckling-restrained brace (BRB) has both the stiffness and energy dissipation capacity of the brace. It provides stiffness under frequent earthquakes and yields energy under rare earthquakes, which can effectively control structural deformation[13-14]. For example, Li[13] took the reinforcement project of a community health service center in Shanghai as an example. After BRB reinforcement, the inter-story displacement angle of the structure was significantly reduced and the seismic performance was improved. The viscous damper dissipates energy through the damping force of the viscous fluid, does not provide additional stiffness, and is suitable for reducing seismic forces[14]. The combined seismic reduction technology (such as the combination of BRB and viscous dampers) can take into account the stiffness and energy consumption requirements, and obtain better seismic reduction effect. The advantages of this technology are high damping efficiency, convenient construction, and small changes to the original structure ; the disadvantage is that the design and arrangement of dampers need to be combined with the dynamic characteristics of the structure, and the performance degradation after long-term use needs to be paid attention to[15].

2.4. Isolation Technology

The isolation technology extends the natural vibration period of the structure and reduces the transmission of seismic energy to the upper structure by setting the isolation layer between the foundation and the upper structure (such as rubber isolation bearing, sliding bearing, etc.), so that the structure is in an elastic state during the earthquake. This technology is suitable for important buildings and buildings in high intensity areas, such as hospitals and schools[16]. In foreign studies, a school building in Japan adopts the additional substructure reinforcement of external prestressed precast frame and steel support to change the original structural system, reduce the natural vibration period and improve the seismic performance[17]. The advantage of isolation technology is that the damping effect is remarkable, which can achieve ' no damage under small earthquakes and repairable under large earthquakes ' ; the disadvantage is that the initial cost is high, the site conditions and isolation layer design requirements are strict, and the durability and maintenance of the isolation layer need to be considered[6].

2.5. Self-reset and Recoverable Function Reinforcement Technology

Aiming at the problem of large residual deformation and difficult repair of traditional reinforcement technology after strong earthquakes, self-centering technology makes the structure rely on prestress to restore the initial position and reduce damage after earthquakes through prestressed steel strands, energy-consuming steel bars and other components[18]. Song Jiaye[18]studied two self-centering reinforcement methods (external self-centering beam and external cable-stayed support). Experiments show that both can improve the self-centering ability and seismic performance of the structure. Among them, the external cable-stayed support is more significant in terms of stiffness and bearing capacity, while the external self-centering beam can better control the degree of damage. This technology represents the transformation of the seismic concept from " life safety " to " functional recovery, " and has broad application prospects. However, most of the current research focuses on the experimental stage, and there are few practical engineering applications. The design theory and specification still need to be improved[16,18].

3. Comparison of Reinforcement Technology Application of Different Structural Types

3.1. Strengthening of Masonry Structure

The masonry structure has weak seismic performance due to its large self-weight and poor ductility. The focus of reinforcement is to improve the shear resistance, bending resistance and integrity of the wall[2,4,19,20]. Traditional methods, such as steel mesh mortar surface layer and concrete slab wall reinforcement, constrain masonry deformation by increasing surface stiffness and reinforcement[2-4]. New technologies such as outer door frame-prestressed tie rod reinforcement, using external steel frame and tie rod to bear horizontal load, reduce the dependence on the original wall, suitable for old residential areas where it is difficult to be reinforced[20]. In contrast, the construction of the steel mesh mortar surface layer is simple and the cost is low, but the weight of the wall is increased ; the reinforcement effect of concrete slab wall is remarkable, but it has a great influence on the use space. The jacket rigid frame technology has little intervention on the original structure and is suitable for complex environment, but the construction difficulty is high[2,20].

3.2. Reinforced Concrete Structure

The reinforcement of reinforced concrete structures needs to address the problems of insufficient bearing capacity of beam-column joints and components. FRP bonding, increasing cross-section, energy dissipation and other technologies are commonly used[8,10,11,21]. FRP reinforcement is suitable for flexural members, which can effectively improve the flexural capacity and the construction is fast[8,11]. The slotted-corner FRP reinforcement technology proposed by the research team of Isfahan University[21] can improve the seismic ductility of square columns by more than 20 % by optimizing the bonding interface structure, which provides an experimental basis for the reinforcement of complex cross-section members. The enlarged section method is suitable for a variety of components, but the construction period is long ; the energy dissipation technology improves the seismic performance without significantly changing the structural form by setting dampers or BRBs, which is especially suitable for frame structures[14,21]. For example, Fang Jiao[11] used carbon fiber cloth in the reinforcement of a factory building in Hefei. The finite element simulation shows that the ductility and energy dissipation capacity of the structure are significantly improved. Zhang Guosheng reduced the inter-story displacement angle of the frame structure by 43 %[21] by installing a single inclined rod support damper. The research of Chengdu University of Technology[22] shows that PC strand reinforced cylinder can significantly improve the confinement effect of concrete, and its seismic performance is better than that of traditional steel fiber reinforced concrete, which provides a high-performance solution for the reinforcement of axial compression members.

3.3. Strengthening of Steel Structure

The reinforcement of steel structure focuses on the connection of joints, the stability of components and the improvement of overall stiffness. The methods of outsourcing steel, adding supports and adding dampers are commonly used. Encased steel can enhance the strength and stiffness of the joints. Adding steel braces can improve the lateral displacement resistance of the structure, and viscous dampers can effectively dissipate seismic energy. For example, Long Lu et al[6] analyzed the reinforcement technology of steel structure high-rise buildings, and pointed out that the seismic performance can be significantly improved by improving the longitudinal and transverse stiffness and adding dampers. For the non-ductile soft RC frame, the Indian Institute of Technology[23] compared the reinforcement effect of viscous dampers and buckling restrained braces, and found that the combined damping technology can reduce the inter-story displacement angle by 45 %, which verifies the applicability of multi-technology collaboration in complex structures.

4. Analysis of Typical Engineering Cases

4.1. Reinforcement Case of Masonry Structure: Reinforcement-mortar Strip Reinforcement of Single-layer Masonry Buildings

Ghimire Abhishek et al[24] pointed out that the seismic reinforcement of masonry structures should give priority to the identification of structural performance to clarify the damage mechanism. The optimization method of reinforcement scheme based on dynamic characteristic monitoring proposed by Ghimire Abhishek et al[24]provides a theoretical framework for the fine reinforcement of old masonry buildings. An et al[3] designed a full-scale single-story masonry structure model, which was reinforced with reinforcement-mortar strips, and the seismic response was analyzed by shaking table test. The results show that the reinforced structure is in an elastic state before the 8-degree fortification earthquake, the cracks in the weak parts are reduced, and the trend of natural frequency and inter-story displacement angle is more stable. It is proved that this method is suitable for unreinforced masonry buildings in villages and towns, and has the advantages of simple structure and flexible arrangement[3].

4.2. Reinforcement Case of Reinforced Concrete Structure: CFRP Reinforced High-rise Residential Building

Du Changchun et al[9] adopted CFRP reinforcement scheme for seismic weak components of a high-rise residential building. The shaking table test and numerical simulation show that the lateral stiffness of the structure is improved after reinforcement, the inter-story displacement angle is reduced by more than 30 %, the peak acceleration of the floor is reduced, and the comprehensive benefit is good. This case shows the high efficiency and applicability of FRP materials in high-rise building reinforcement.

4.3. Application Case of Energy Dissipation Technology: Buckling Restrained Brace Reinforced Hospital Complex Building

Hou et al[14] used the combination technology of buckling restrained brace and viscous damper in the reinforcement of a hospital complex building. Through the mode decomposition response spectrum method and time history analysis, it was found that the stiffness of the reinforced structure was improved under frequent earthquakes, and the energy consumption was significant under rare earthquakes. The inter-story displacement and seismic force were effectively controlled, which verified the superiority of the combined damping technology[14].

4.4. Foreign Case:External Additional Substructure Reinforcement of Japanese School Buildings

Marusaka Hitoshi et al[17] took a school building in Japan as an example, using external prestressed precast concrete frame and steel support reinforcement, changed the original structural system, reduced the natural vibration period by 0.845 times, improved the floor stiffness, effectively solved the problem of excessive deformation and insufficient seismic performance, and reflected Japan 's emphasis on structural system optimization in seismic reinforcement[17].

5. Development Trend of Seismic Reinforcement Technology

5.1. Material Innovation and Greening

In the future, more attention will be paid to the development and application of environmentally friendly and high-performance materials, such as low-carbon FRP, recyclable steel fiber, ecological mortar, etc., to reduce the environmental impact of reinforcement projects[4,25]. At the same time, the introduction of smart materials (such as shape memory alloys, self-sensing fibers) can realize real-time monitoring and self-healing of structural performance[16].

5.2. Technology Integration and Diversification

The limitations of single reinforcement technology promote the development of composite reinforcement technology, such as the combination of FRP and energy dissipation technology, self-centering and damper working together to take into account stiffness, energy consumption and recoverable function[14,16,18]. According to different structural types and damage degrees, it is necessary to formulate personalized and diversified reinforcement schemes to promote the application of performance-based design concepts[16].

5.3. Modernization of Construction Technology

Prefabricated and modular reinforcement technologies (such as prefabricated concrete slab walls and fabricated steel supports) will improve construction efficiency and reduce wet work on site and impact on use functions[25].The popularization of digital technology (BIM, finite element simulation) will realize the precise design of reinforcement scheme and the intelligent monitoring of construction process[4,18].

5.4. Theoretical Research and Normative Improvement

Strengthen the research on the long-term performance of reinforced structures (such as material aging, fatigue damage), and establish more accurate calculation models and design methods[18,26]. Combined with the research results at home and abroad, improve the seismic reinforcement norms and standards, and promote technical standardization and internationalization[4].

5.5. Sustainable Development and Functional Improvement

Seismic reinforcement will be combined with urban renewal and building energy-saving renovation. While improving the seismic performance, it will improve the building function and environmental comfort, and achieve the unity of economic, social and environmental benefits[4,20].

6. Development Trend of Seismic Reinforcement Technology

The seismic reinforcement technology at home and abroad has evolved from traditional single component reinforcement to new material application and structural system optimization, and has formed a multi-system covering traditional technology, new material reinforcement, energy dissipation, isolation and self-centering technology. Traditional technologies (such as increasing cross-section and outsourcing steel) have simple principles and strong applicability, but there are limitations such as long construction period, large amount of wet work, and significant impact on building functions. New material technology (such as FRP, steel fiber reinforced concrete) has become a research hotspot due to its advantages of light weight, high strength and convenient construction. However, it faces challenges such as environmental impact on bonding performance and insufficient long-term performance monitoring data. Although energy dissipation and isolation technology can significantly reduce the seismic response, there are some problems such as complex damper design, high cost of isolation layer and prominent demand for durability maintenance. Although the self-centering technology represents the advanced concept of " functional recovery, " it is limited in practical engineering applications because it is in the experimental stage and the design theory and specifications are not yet perfect.

In the future, the seismic reinforcement technology will develop in the direction of material innovation and greening (research and development of low-carbon FRP, recyclable steel fiber, intelligent materials, etc.), technology integration and diversification (combined reinforcement technology, personalized scheme), construction technology modernization (prefabrication, modularization, BIM and finite element simulation and other digital technologies), theoretical research and specification improvement (long-term performance research, accurate calculation model, specification standardization and internationalization), sustainable development and function improvement (combined with urban renewal and energy-saving transformation), so as to provide more solid technical support for the construction of resilient cities.

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