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Current Status and Development Trends in Seismic Resistance and Vibration Reduction Technologies for Existing Wooden Buildings

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Abstract. Ancient Chinese wooden structures demonstrate exceptional seismic performance through their unique structural systems. Their core advantage lies in employing semi-rigid connections such as mortise-and-tenon joints and dougong brackets, which effectively dissipate seismic energy via friction, sliding, and rotation. The lightweight, high strength, and toughness of timber further reduce seismic inertial forces and permit plastic deformation. Nevertheless, these ancient structures remain vulnerable to earthquakes, material aging, and biological damage. The core objective of this research is to systematically elucidate the intrinsic seismic mechanisms and damage patterns of traditional Chinese timber structures, while exploring modern reinforcement techniques aligned with the principle of "restoring old structures to their original state." Its significance lies in: providing critical technical support for the scientific preservation and safe longevity extension of precious cultural heritage sites like Foguang Temple and the Yingxian Wooden Pagoda; uncovering the seismic wisdom of ancient craftsmen embodied in mortise-and-tenon joints and dougong brackets, exploring their insights and references for modern seismic isolation and energy dissipation theories as well as timber structure design codes; and discussing the seismic safety applications of modern timber structures within the green building trend.

Keywords: Wooden Buildings, Structural damage, Seismic Technology.

1. Introduction

Ancient Chinese architecture primarily employed timber-frame systems, with core structural forms including the beam-and-post, mortise-and-tenon, and well-frame styles. Among these, the beam-and-post system—the most widely used—creates a stable triangular load-transferring framework by placing beams atop columns and stacking purlins upon beams, effectively distributing roof loads to column bases. Wood, as a lightweight, high-strength natural material with excellent toughness and damping properties, endows traditional timber structures with superior seismic performance. Its low density reduces seismic inertial forces, while its anisotropic properties allow load-bearing members to maximize compressive and flexural strength along grain direction. Additionally, construction details such as mortise-and-tenon joints and dougong layers dissipate energy through friction,

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sliding, and rotation, forming a seismic mechanism that "uses flexibility to overcome rigidity" [1]. In recent years, scholars worldwide have conducted systematic research on the seismic performance of ancient timber structures. Since the 1981 publication of Chinese Ancient Architecture: Woodworking Techniques first scientifically identified the energy-dissipating mechanism of mortise-and-tenon joints, methods such as shake table testing, quasi-static testing, and finite element analysis have continuously deepened our understanding of node mechanical behavior and overall structural seismic mechanisms [2,3]. Japan has also accumulated extensive experience in seismic technologies like the traditional wooden pagoda "central pillar" system and through-timber construction. These studies not only reveal the seismic wisdom of ancient architecture, but also provide crucial scientific foundations for conservation and reinforcement. This research aims to systematically summarize the current seismic technologies of extant ancient timber structures, analyze their seismic performance and damage mechanisms, and explore appropriate seismic reinforcement pathways for preserving existing ancient timber buildings. This work seeks to extend the lifeline of historical and cultural heritage, promote traditional construction wisdom, and offer insights for seismic design in modern timber structures.

2. Mechanism of earthquake damage to timber structures

During an earthquake, seismic waves (including P-waves, S-waves, and surface waves) induce complex reciprocating motions in the foundation. Energy is transmitted through the foundation to the superstructure, subjecting the building's foundation to intense excitation from varying directions and frequencies. The structure's own mass generates inertial forces when impacted by ground motion, causing swaying vibrations. If the structure's natural frequency is close to the seismic wave frequency, resonance occurs, amplifying destructive effects. In traditional Chinese timber structures, semi-rigid connections like mortise-and-tenon joints dissipate energy through friction, sliding, and rotation during earthquakes. However, exceeding their limit displacement can cause tenon pull-outs, mortise tear-outs, or even tenon breakage. This degrades joint stiffness, reduces energy dissipation capacity, increases structural deformation, and may ultimately lead to structural failure. Primary load-bearing members like wooden beams and columns may fail due to insufficient bending, compressive, or shear strength. Intrinsic wood defects (e.g., knots, grain direction) or aging accelerate this process. Typical failure phenomena in timber structures include beam and column cracking, buckling instability, and localized crushing.

3. Seismic technology

3.1. Application of seismic design techniques for lower foundation structures

The reinforcement of foundations for timber structures aims to prevent significant deformation and cracking of the superstructure caused by foundation failure. Therefore, to extend the service life of ancient buildings, it is essential to restore the foundation as much as possible to its original level state without noticeable subsidence, while ensuring it possesses sufficient bearing capacity.

When cavities or localized subsidence occur near the building foundation, to prevent extensive water seepage beneath the foundation and the expansion of foundation deformation zones, current protective measures typically involve constructing open drainage ditches around the historic structure.

For severe weathering and cracking in plinth masonry, repairs typically involve replacing old ashlar stones, installing steel mesh between old and new brick layers, and grouting the joints.

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For wooden structures where foundation bearing capacity diminishes due to surrounding construction or aging, driving wooden or concrete piles is employed. This compacts the foundation soil, enhancing load-bearing capacity and effectively preventing differential settlement of the foundation.

3.2. Application of seismic technology in superstructures

As a wooden structure, the upper load-bearing components are most susceptible to issues that compromise seismic performance, including severe decay of wooden columns, significant insect infestation, and splitting at column tops. Rafters also exhibit decay and may even develop noticeable sagging deformation. Additionally, the connection points between columns and beams, as well as between columns and purlins, are prone to developing issues over time, such as loosening, deformation, slippage, and even failure.

3.2.1. Repair and reinforcement of decayed sections following the earthquake

Wood, as a biological material, consists of organic polymers such as cellulose, hemicellulose, and lignin. These materials serve as nutrients for certain insects and wood-decaying fungi. Consequently, when wood remains in warm and humid environments for extended periods, these harmful organisms proliferate rapidly, causing structural decay.

Common decay locations in wooden columns are at the base. Traditional repair methods include chiseling and filling, wrapping and embedding, and butt jointing. For minor decay, repair involves removing the decayed section and filling the void with dry wood. When decay covers more than half the column's circumference but less than one-fifth of its diameter, the wrapping method is applicable. This involves removing the decayed section and preparing wrapping material tailored to the length, depth, and curvature of the column. For severely decayed column bases, butt jointing is employed. This involves cutting off the decayed section, replacing it with new material, and connecting the old and new sections at the joint using mortise-and-tenon joints. When decay exceeds one-third of the column height or the column is fractured beyond repair by butt jointing, replacement or the addition of auxiliary columns is necessary [4]. The three aforementioned repair methods for wooden columns can effectively preserve the structural integrity of the components. However, these interventions are often irreversible and may compromise the authenticity of the materials to some extent. Additionally, the newly inlaid materials do not possess identical properties to the original wood. Over time, the bond strength between the two materials may diminish, potentially affecting the long-term performance of the structural elements.

3.2.2. Repair and reinforcement of post-earthquake cracks

Cracks primarily form during the drying process of wood. Additionally, prolonged exposure to external forces can degrade the wood's mechanical properties, leading to crack formation. For column cracks, traditional repair methods primarily involve filling techniques: When crack width is less than 3 mm, putty can be directly applied to fill the gap. For cracks between 3 mm and 30 mm wide, wooden strips can be inserted into the crack and secured with adhesive. For cracks exceeding 30 mm in width, in addition to wooden strip filling, iron hoops must be applied externally. When the crack depth exceeds one-third of the column diameter or the crack results from column tilting or twisting, structural realignment must precede wooden strip filling, followed by reinforcement with iron hoops [4].

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Horizontal members such as beams and lintels experience different stresses than column members, primarily subjected to bending moments and shear forces. Therefore, for such members, minor cracks can be directly reinforced with iron bands. However, for wider cracks, iron bands should be added alongside filling. When cracks are long but decay is not severe, epoxy resin should be poured into the cracks before reinforcing with iron bands. However, when crack widths exceed specified limits, the member's load-bearing capacity must first be verified. If it meets structural requirements, the filling method may still be used. If not, reinforcement methods are required. Reinforcement methods include shoring and mechanical reinforcement. The shoring method primarily involves supporting columns beneath beams and joists to prevent member sagging and failure. Mechanical reinforcement utilizes additional materials such as chiseled connectors, wooden boards, or steel plates to restore the strength of timber components, addressing cracks caused by insufficient shear resistance. When damage to a timber component is so severe that neither method can meet its load-bearing requirements, replacement of the component is necessary [4].

3.2.3. Repair and reinforcement of insect-damaged sections

Insect infestation has minimal impact on most areas of timber structures under static conditions, and even when numerous insect holes appear, the load-bearing capacity of columns retains a margin of safety. However, insect holes appearing at the bottom of eaves purlins in the midspan pose the greatest threat to the structural integrity of the purlin itself, as they ultimately lead to failure due to excessive deflection of the timber member. Additionally, the critical areas for insect holes in inserted beams are the bottom of the midspan and the underside of through tenons. Insect damage to beams may cause failure due to excessive shear stress around or on both sides of the tenon heads near the holes. Therefore, pest prevention is more important than repair for timber structures. Common prevention methods currently include spraying, brushing, injection, and impregnation.

The latest eco-friendly termite control method involves directly spraying termiticide powder into termite exit holes and damaged areas. Termite bait stations are placed around ancient structures to attract and eliminate termites. Utilizing monitoring devices within the termite bait control system, a "monitor -baiting-elimination-remonitoring" cycle to control termite populations and prevent damage spread.

Wood-boring wasps require flowering plants within their activity range to collect pollen for feeding their offspring. Addressing the biological habits of wood-boring wasps, flowering plants are typically removed from their activity range to deprive them of essential survival and reproduction conditions. Additionally, wood-boring wasps exhibit aversion to paint. Applying a mixture of raw lacquer and tung oil to the surfaces of wooden structural components ensures protection against their damage [5].

Preventing and controlling powderpost beetles presents challenges due to their minuscule exit holes. Without visible dust accumulation, infestations are difficult to detect with the naked eye. Therefore, a dual approach combining chemical injection (using medical syringes to administer pesticides) and surface treatment of wooden structures with preservative coatings is necessary. Regular reapplication of these treatments is essential to achieve effective eradication [6].

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4. Application and development trends of seismic technology

4.1. Application

Among the current seismic repair and reinforcement techniques for China's ancient wooden structures, a representative example is the major dismantling and reconstruction of the Manjusri Hall at Foguang Temple in Shanxi Province following the founding of the People's Republic of China. This extensive restoration involved filling gaps and reinforcing damaged dougong brackets, largely preserving their original form. Given that Foguang Temple is located in Wutai County, Xinzhou City, Shanxi Province - an area situated within an active seismic zone - the region has experienced numerous earthquakes of varying magnitudes since the major restoration. However, during a comprehensive inspection in 2021, no significant structural issues were identified beyond foundation settlement at the northeast corner of the Manjusri Hall and some cracking and deformation in certain wooden components. This demonstrates that the repair and reinforcement methods for common cracks mentioned earlier have proven highly effective in enhancing the seismic resistance of ancient wooden structures in practical applications. Furthermore, addressing the progressive tilt of Yingxian Wooden Pagoda - which severely compromised its seismic performance - involved implementing reversible biomimetic iron hoops to enhance the bending load-bearing capacity of structural joints. This was complemented by a temporary adjustable steel truss support system and the layered wrapping of damaged components with CFRP fabric. These measures rapidly reduced the tilt rate and significantly strengthened the structure's seismic resilience.

4.2. Development trends

In the future, seismic resistance of timber structures can be achieved through wood enhancement. Fiber-reinforced polymers (FRP) possess advantages such as high strength, light weight, corrosion resistance, low density, and high elasticity, and have been widely applied in the construction industry [7]. Research indicates that FRP reinforcement significantly enhances structural stability, with the critical load of simply supported FRP-reinforced timber columns increasing with both FRP elastic modulus and reinforcement ratio [8].

Furthermore, reinforced joints can effectively enhance a structure's capacity to dissipate seismic energy. Research indicates that after reinforcing mortise-and-tenon joints with CFRP fabric, although the frame's energy dissipation capacity slightly decreases, the joint's pull-out resistance reduces, while the frame's lateral stiffness and load-bearing capacity increase. Moreover, the reinforced frame retains good deformation capacity [9]. Therefore, this experiment confirms that CFRP fabric provides effective reinforcement and can serve as a reinforcement method for future restoration projects of ancient timber structures to enhance their seismic resistance.

Finally, upgrading joints can also improve the seismic performance of timber structures. Experimental data indicates that Resilient Slip Friction Joint (RSFJ) or conventional friction damping supports at joints, arranged parallel to the backing bending frame, enhances structural performance while minimizing residual displacement [10]. This approach holds significant feasibility for future post-disaster reconstruction projects.

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5. Conclusions and outlook

This paper reviews the current status and development of seismic resistance and vibration reduction technologies for existing ancient wooden structures. The conclusions indicate that the seismic wisdom embodied in China's ancient architecture - such as mortise-and-tenon joints and dougong brackets – has withstood the test of millennia, with its superior energy dissipation mechanisms scientifically validated by modern experiments and theories. The current reinforcement technology system, integrating the essence of traditional craftsmanship with the advantages of modern materials, has achieved significant results in addressing typical issues such as foundation settlement, component decay, cracks, and insect damage. It has provided critical technical support for the preservation of important cultural heritage sites like Foguang Temple and the Yingxian Wooden Pagoda. Nevertheless, current techniques face challenges: the irreversibility of traditional craftsmanship may compromise heritage authenticity; long-term compatibility and durability between new materials and ancient timber require further investigation; and refined seismic assessment and reinforcement design for complex structural wholes still hold room for improvement.

The development of seismic technologies for ancient timber structures will more deeply implement the conservation principle of “restore as it was,” emphasizing the integration of scientific traditional craftsmanship with modern technology compatibility. Future research will focus on quantifying the structural mechanisms of traditional techniques like mortise-and-tenon joints and dougong brackets. Through modern detection technologies and numerical simulation methods, the scientific evaluation of their seismic performance degradation patterns will provide a basis for “minimal intervention” reinforcement design. Simultaneously, exploring integration points between traditional craftsmanship and modern technology - such as incorporating reversible modern connection techniques into traditional methods like doweling and inlaying - will be pursued. The development and application of new materials and technologies will increasingly emphasize “reversibility,” ensuring reinforcement measures do not compromise the historical authenticity of ancient structures. For instance, developing removable friction damping devices for timber joints or employing composite materials (such as CFRP) compatible with wood properties for concealed reinforcement will enhance structural performance while maximizing preservation of the building's original appearance.

Through these developmental directions, future seismic protection for ancient timber structures aims to become more refined, scientific, and human-centered. This approach will genuinely achieve safety assurance while maximizing the preservation of historical information, architectural craftsmanship, and material authenticity.

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