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Exploring the Pathways To Enhance the Resilience Performance of Prefabricated Medical Buildings

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KEYWORDS

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ABSTRACT

This paper explores strategies to enhance the seismic resilience of prefabricated medical buildings, particularly in China, where urbanization has led to increasingly stringent seismic performance requirements for newly constructed hospitals. Prefabricated hospital buildings, utilizing green construction methods with healthy, age-friendly, and easily maintainable components, have become the primary model for the construction and renovation of emergency medical facilities. The study addresses the current limitations in seismic resilience, exploring paths to improve the structural toughness of medical buildings. It covers the application of precast concrete in hospital construction, a comparison of the economic benefits of precast concrete versus steel structures, seismic performance at varying levels of prefabrication, and the overall integrity of precast concrete structures. Additionally, the paper examines the synergy of concrete structures with seismic isolation and damping technologies. The findings underscore the importance of integrating advanced seismic isolation and vibration reduction technologies to maintain the functionality of medical buildings during and after seismic events, ensuring operational continuity in times of crisis.

1. Introduction

With the continuous advancement of urbanization in China, the requirements for the seismic performance of newly constructed hospitals are increasingly stringent. The "Regulations on Seismic Fortification Management of Construction Projects" clearly stipulate that new hospitals in high-intensity fortification areas should adopt seismic isolation and vibration reduction technologies to ensure that they do not lose their functional capabilities during the design-basis earthquake events in their regions[1]. Hospital buildings play an extremely crucial role in earthquake disasters, serving as a core component of the urban disaster prevention and mitigation system. They are responsible for critical functions such as post-earthquake casualty treatment, epidemic prevention and control, and public health services[2][3]. The continuity of their functions directly affects the life safety of the affected population and the stability of society. The ability of a hospital to quickly engage in rescue operations after an earthquake depends on the damage sustained by the hospital building and its internal medical equipment during the earthquake. Prefabricated hospital buildings, which utilize green construction methods and

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select healthy, age-friendly, and easily maintainable building components, are undergoing a revolution in construction technology and design philosophy. Since the outbreak of the COVID-19 pandemic in 2020, prefabricated construction has fully demonstrated its advantages of rapid construction and high quality, becoming the primary model for the construction and renovation of emergency medical facilities in various regions. Therefore, in-depth research on seismic isolation and vibration reduction technologies for medical buildings, and the enhancement of hospitals' seismic resilience, hold extremely important practical significance.

2. The Significance of Enhancing the Resilience Performance of Medical Buildings

2.1. The Key Role of Medical Buildings in Post-Earthquake Emergency Rescue

China is a country prone to frequent earthquakes, and each major earthquake has caused substantial economic losses and casualties. The urban medical system, as one of the critical subsystems within the urban system, serves as a vital node in the urban lifeline and an essential carrier for medical services. Under normal conditions, it is responsible for basic medical treatment, but after a disaster, it immediately participates in medical rescue operations[4]. The safe and stable operation of medical buildings during an earthquake is crucial for ensuring the continuity of medical services. Any interruption in the functionality of medical buildings directly threatens the efficiency of post-earthquake emergency response. Hospitals need to quickly initiate the treatment of casualties, diagnosing, treating, and nursing various types of injured individuals. They provide basic medical care for affected populations, which is essential for stabilizing social order in the disaster area, reducing casualties, and lowering the disability rate[5].

2.2. The Complexity and Vulnerability of Medical Buildings

The seismic capacity of medical buildings directly affects the regional disaster recovery capability[6] and is also a core indicator[7] for the restoration of social order after an earthquake. However, medical buildings themselves are complex system projects. A large number of high-precision, high-value, and vibration-sensitive medical devices, such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) equipment, face severe threats during earthquakes. In the 2011 Great East Japan Earthquake, many hospital buildings suffered structural damage, with walls cracking and collapsing. Non-structural components, such as ceilings falling and doors and windows deforming, were also affected. Numerous medical devices were damaged by violent shaking, not only rendering the hospital's internal facilities unusable but also severely impeding the hospital's medical service functions and significantly affecting the post-earthquake rescue operations. In the 2008 Wenchuan earthquake in China, many hospital buildings suffered heavy damage and even collapsed due to the imperfections of their structural systems and insufficient seismic measures. In the 2022 Luding earthquake of magnitude 6.8, medical buildings with unverified seismic design, such as those made of wood and masonry structures, were severely damaged, and the destruction of non-structural components directly led to the paralysis of hospital functions[3].

3. The Limitations of Current Seismic Resilience in Medical Buildings

3.1. The Limitations of Traditional Seismic Design in Medical Buildings

Traditional seismic design follows the principle of "minor earthquakes cause no damage, moderate earthquakes cause repairable damage, and major earthquakes do not cause collapse." This approach primarily focuses on ensuring the safety of the building structure during an earthquake to prevent casualties from structural collapse. However, this philosophy falls short of meeting the modern medical building's demand for functional continuity. Medical buildings designed according to current regulations often suffer significant damage to non-structural components during rare but severe earthquakes, leading to functional interruptions[6]. Under the action of high intensity earthquakes, although the traditional seismic design of medical buildings can ensure that the structure will not collapse, the excessive inter-story displacement angle and floor acceleration may lead to the damage of precision medical equipment[8]. There are fewer studies on the susceptibility of non-structural components such as flexible ducts and enclosures[9]. Comparison of seismic, damping, and isolation techniques reveals that traditional seismic strengthening can only maintain the original design objectives, but cannot effectively reduce the impact of floor acceleration on equipment[10].

In recent years, seismic resilience has become an important research direction in the field of earthquake engineering, with its core being the ability of buildings to "rapidly restore functionality" after an earthquake[13][14]. The seismic resilience of medical buildings not only relies on structural safety but also needs to achieve rapid post-earthquake functional recovery through seismic isolation, vibration reduction technologies, and non-structural protection strategies. Ma[4] have proposed constructing a resilience framework for urban medical systems from three aspects: robustness (R1), redundancy (R2), and efficiency (R3), to ensure that medical facilities do not interrupt their treatment functions during earthquakes and that personnel can more quickly enter a state of rescue. Seismic isolation technology can keep the upper structure elastic under rare earthquakes and reduce the floor acceleration to 1.69 m/s^2, significantly reducing the risk of equipment tipping over[9].

by using liquid viscous dampers, the structural displacement damping rate is increased to 20% - 40%, verifying the effectiveness of vibration reduction technology in high-intensity areas (Zhang Xinzhi, 2022). Therefore, traditional seismic design can no longer meet the needs of medical buildings to ensure structural safety and normal

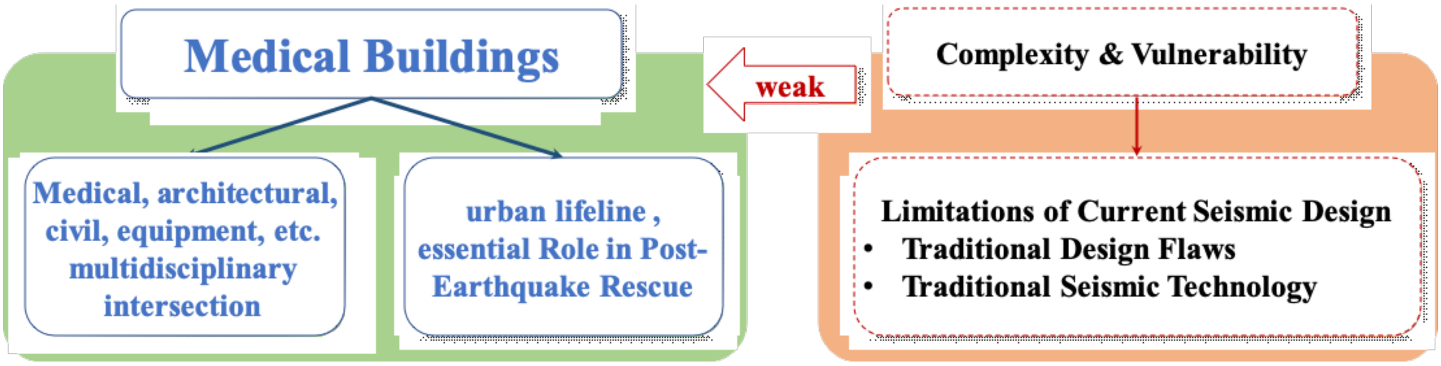

Figure 1 | Mismatch between level of seismic toughness and needs in healthcare buildings

operation of equipment during earthquakes, and there is an urgent need to explore new seismic isolation and vibration reduction technologies to enhance the seismic performance of medical buildings. The structural displacement damping rate was increased to 20-40% by liquid viscous dampers, which verified the effectiveness of the damping technology in high intensity zones[1]. Therefore, traditional seismic design can no longer meet the needs of medical buildings to ensure structural safety and normal operation of equipment during earthquakes, and there is an urgent need to explore new seismic isolation and vibration reduction technologies to enhance the seismic performance of medical buildings.

3.2. The Limitations of Traditional Seismic Technology in Medical Buildings

Due to the particularity of their functions, medical buildings impose higher demands on the seismic performance of their structures. Current seismic design for medical buildings still faces issues such as insufficient multidisciplinary collaboration and difficulties in data integration. Research on the structural systems of medical buildings and their seismic isolation and vibration reduction implementation plans not only helps enhance the seismic capacity of medical buildings but also provides new ideas and methods for the development of seismic technology in the entire building structure field. Cheng[12] proposed a multi-level functional assessment model based on BIM, which integrates component vulnerability data with functional logical relationships to achieve department-level functional coupling analysis. Ning[13] developed an evaluation method for seismic safety and resilience, providing a quantitative basis for the performance grading of medical buildings. Zhai[14] presented a basic approach for seismic resilience design of buildings through resilience concept design and computational design methods, constructing a five-step process for seismic resilience design of buildings, which includes determination of resilience targets, structural safety design, seismic resilience concept design, post-earthquake functional verification of buildings, and rapid functional recovery strategies. Fang[15] demonstrated that point layout can improve the post-earthquake treatment efficiency of the emergency department through the optimization of spatial combination patterns.

4. Path to Improved Toughness Performance in Medical Buildings

4.1. Research on Precast Concrete Structures and Technical and Economic Comparative Analysis With Steel Structures

4.1.1. Current Application Status of Precast Concrete Structures in Hospital Construction

A comprehensive survey of domestic and international hospital projects that have adopted precast concrete structures is conducted. Design drawings, construction records, cost data, and user feedback are collected. First, the characteristics of precast concrete structures used in hospitals of different regions and scales are analyzed, including types of precast components, production processes, transportation, and installation methods. Second, a classification of medical buildings into large general hospitals, specialized hospitals, and primary healthcare centers is established based on their categories, functions, and volumes, forming a case library for medical buildings. The advantages and shortcomings of precast concrete structures in meeting the functional demands of hospitals are studied to provide a practical basis for technical and economic comparisons and optimized design.

4.1.2. Economic Comparison of Precast Concrete Structures and Steel Structures

4.1.2.1. Construction Cost Comparison

Cost Calculation: Detailed cost calculations are performed for the construction costs of precast concrete structures and steel structures in hospital construction projects. Differences in material costs, labor costs, and equipment rental costs between the two structural forms are analyzed. Management costs during the construction process, including temporary facility costs and construction management fees, are also compared. Based on the case library of medical buildings, a cost model is established to predict the construction cost range for hospitals of different scales and functional requirements using precast concrete structures and steel structures.

4.1.2.2. Lifecycle Operation and Maintenance Cost Comparison

Lifecycle Cost Analysis: The operational, maintenance, and demolition costs of precast concrete structures and steel structures over the lifecycle of hospitals are studied.

Given the long service life of hospital buildings, maintenance and operational costs account for a significant proportion of the total lifecycle costs. The cost of adaptability and functionality changes in medical buildings to meet new medical demands is also investigated. The convenience of construction modifications to meet new medical requirements is analyzed, considering the need for adjustments in ventilation, fire protection, and vibration-sensitive control in existing medical areas.

The comprehensive construction costs and lifecycle cost benefits are synthesized to provide an economic basis for investment decisions in hospital construction projects.

4.2. Research on Seismic Performance of Structures Under Different Prefabrication Rates

4.2.1. Establishment of Structural Models With Different Prefabrication Rates

According to relevant standards and practical engineering requirements, a series of concrete precast structural models with different prefabrication rates (30%, 50%, 70%) and different structural forms (frame structures, frame-shear wall structures, etc.) are designed and established. The impact of changes in prefabrication rates on the seismic performance of different structural forms is investigated through numerical simulation and experimental research.

4.2.2. Seismic Performance Analysis of Structures Under Earthquake Actions

4.2.2.1. Seismic Response Analysis

Using seismic isolation and vibration reduction techniques, dynamic characteristic analysis is conducted on structural models with different prefabrication rates and structural forms. Parameters such as the natural vibration period, frequency, and mode shapes of the structures are calculated. The influence of prefabrication rate changes on the dynamic characteristics of structures is studied, and the differences in vibration characteristics under different prefabrication rates are analyzed. Different seismic waves are input to perform seismic response analysis on the established structural models. Response parameters such as inter-story drift angle and floor acceleration of the structures under earthquake actions are calculated. The seismic performance of models with different prefabrication rates and structural forms is evaluated. The damage patterns and injury distribution under earthquake actions are analyzed, revealing the impact of prefabrication rates on structural damage mechanisms.

4.2.2.2. Seismic Resilience Indicator Assessment

Based on the evaluation method of building seismic performance using full probability theory, the calculation methods for measurement standards such as repair costs, repair time, casualties, and environmental impact are clarified. The seismic resilience levels of medical buildings with different prefabrication rates are analyzed. A vulnerability database for precast concrete medical buildings is established. Combined with the three-star resilience grading standard proposed in the "Standard for Seismic Resilience Evaluation of Buildings" (GB/T38591-2020), a seismic resilience indicator evaluation system for precast concrete medical buildings that is compatible with China's seismic fortification standard system is proposed.

4.2.3. Research on Rational Design and Connection Construction

4.2.3.1. Design Optimization for High Prefabrication Rate Structures

Combining the functional requirements and seismic demands of hospital buildings, seismic isolation and vibration reduction techniques that match the medical functions are selected to improve the seismic resilience level of medical buildings. The dimensions and shapes of precast components are optimized to enhance their load-bearing and deformation capacities. Considering the overall requirements of the structure, the cast-in-place parts are reasonably arranged to strengthen the collaborative work between precast components and cast-in-place parts.

4.2.3.2. Connection Construction Measures Research

The key parts of the connection nodes in precast medical building structures are determined. Through experimental research and numerical simulation, indicators such as the strength, stiffness, ductility, and energy dissipation capacity of the connection nodes are analyzed. Key factors affecting the seismic performance of high prefabrication rate structures, such as the construction form of connection nodes, dimensions, and shapes of precast components, are analyzed. Rational connection construction design methods and structural optimization measures are proposed, such as increasing constraints on connection nodes and using high-performance connection materials, to ensure the seismic resilience safety of precast medical buildings.

4.3. Research on the Integrity of Precast Concrete Structures

4.3.1. Impact of Connection Nodes on Structural Integrity

This research investigates the influence of connection nodes on the collaborative performance of components during the overall force transmission process of the structure. By establishing comprehensive structural models and simulating the force distribution under various connection node properties, the study quantitatively assesses the extent to which nodes affect the overall structural behavior. Based on these findings, optimized design methods for connection nodes are proposed to enhance the structural integrity and performance of precast concrete structures.

4.3.2. Role and Optimization of Cast-in-Place Concrete Areas

This section examines the impact of the location, size, and construction techniques of cast-in-place concrete areas on the structural integrity of precast concrete buildings. A rational layout scheme for cast-in-place concrete areas is developed, which includes scientifically determining the critical locations, dimensions, reinforcement details, and high-performance cast-in-place concrete materials for post-pour strips. Through the optimization of these cast-in-place concrete areas, the study aims to further improve the overall integrity and seismic performance of precast concrete structures.

4.4. Research on the Impact of Assembly Construction Sequence and Construction Accuracy on Structural Seismic Performance

4.4.1. Impact of Assembly Construction Sequence on Structural Seismic Performance

4.4.1.1. Construction Process Simulation Analysis

Finite element analysis software is utilized to simulate the assembly construction process of precast concrete structures. Structural models that account for the construction sequence are established, with prefabricated components added incrementally in accordance with the actual construction process, and the connection processes between components are simulated. The force states and deformation of the structure under different construction sequences are analyzed, and the redistribution patterns of internal forces and the stability of the structure during the construction process are investigated. Through construction process simulation analysis, a rational assembly construction sequence is determined to ensure the safety of the structure during construction and to provide a foundation for subsequent seismic performance analysis.

4.4.1.2. Long-term Impact of Assembly Construction Sequence on Seismic Performance

The long-term impact of the assembly construction sequence on the seismic performance of the structure after completion is examined. The internal force changes and deformation of the structure during long-term use due to factors such as concrete shrinkage and creep, temperature variations, etc., under different construction sequences are analyzed. Long-term monitoring and numerical simulation are employed to assess the long-term impact of the assembly construction sequence on the seismic performance of the structure, providing a basis for the development of rational construction plans to ensure good seismic performance throughout the structure's lifecycle.

4.4.2. Potential Impact of Construction Accuracy on Structural Seismic Performance

4.4.2.1. Determination of Construction Accuracy Indicators and Monitoring Methods

Construction accuracy indicators that affect the seismic performance of precast concrete structures, such as dimensional deviations of prefabricated components, installation position deviations, and construction accuracy of connection nodes, are identified. Effective real-time monitoring methods for construction accuracy indicators based on detection techniques such as ultrasonic waves and ground-based synthetic aperture radar (GB-SAR) are proposed to ensure precision control during the construction process. A construction accuracy database is established to record various accuracy indicator data during construction.

4.4.2.2. Impact Analysis of Construction Accuracy on Structural Seismic Performance

The impact of construction accuracy deviations on structural seismic performance is analyzed through experimental research and numerical simulation. Structural models considering construction accuracy deviations are established to simulate the force performance and failure modes of the structure under seismic actions under different accuracy deviation conditions. The influence patterns of construction accuracy deviations on seismic performance indicators such as displacement, internal forces, and inter-story drift angle of the structure are studied, and the potential risks of construction accuracy to structural seismic performance are assessed.

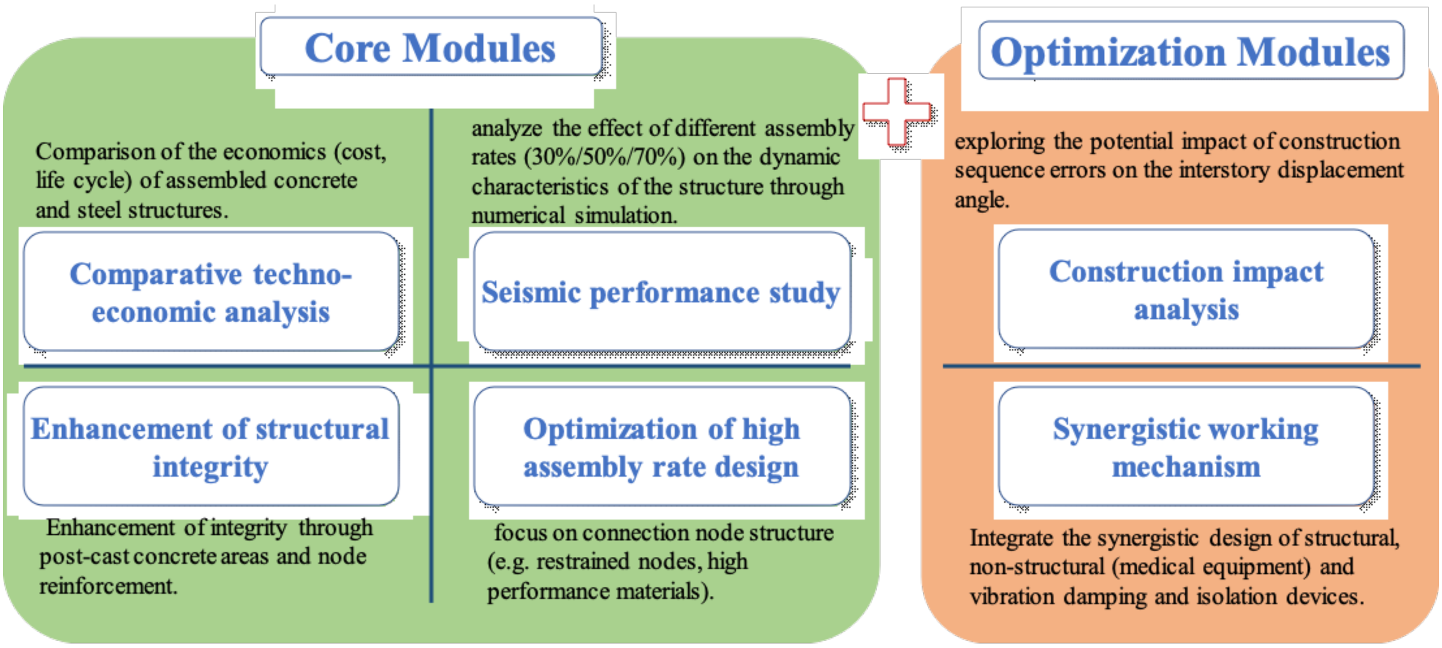

Figure 2 | Path to Improved Toughness Performance in Medical Buildings

4.5. Research on the Synergy of Concrete Structures and Seismic, Isolation, and Damping Devices

4.5.1. Research on the Synergy of Seismic, Isolation, and Damping Devices

This research focuses on the synergistic working mechanisms of seismic, isolation, and damping devices tailored to the functional demands of medical buildings. Through theoretical analysis, experimental testing, and numerical simulation, mechanical models for seismic isolation bearings (such as natural rubber bearings and lead-rubber bearings) and damping devices (such as viscous dampers and metallic dampers) are established. The study identifies key factors influencing the seismic control effectiveness of different devices and clarifies their mechanical characteristics under various loading conditions. A collaborative design method for precast medical building structures and seismic isolation and damping devices is proposed to enhance the overall seismic performance.

4.5.2. Research on the Synergy of Structural and Non-Structural Components

Based on the seismic and functional requirements of medical buildings, a performance-based collaborative design approach is adopted, fully considering the role and impact of non-structural components. The research explores the working synergy between non-structural and structural components, aiming to ensure the normal functionality of medical buildings under moderate seismic actions, with no impact on structural deformation and equipment operation. Under severe seismic actions, the structure should remain essentially intact, and the devices should effectively dissipate energy to ensure the continuation of medical services. Clear design parameter requirements for structures and devices under different performance targets are established, and a collaborative design process for precast structures and seismic isolation and damping devices is developed to provide specific design methods and recommendations for practitioners.

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