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Discussion on the Theory of Seismic Resistance of Structures

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Abstract

An earthquake is a sudden natural disaster that endangers the construction of the national economy and the safety of people's lives and property. In addition to causing personal casualties, earthquakes also damaged buildings; The interruption of public facilities such as transportation, power supply, water supply, gas supply, oil transmission, communications, etc., and then causing secondary disasters such as water, fire and disease, bringing extremely serious consequences to social life. Therefore, it is particularly important to analyze the seismic response of buildings, establish seismic theory, and take economic and reasonable seismic calculations and measures for buildings.

Keywords

Earthquake, Natural Disaster, Reaction Analysis, Theory.

1. Introduction

In recent years, with the rapid development of science, technology, and the social economy, the pace of life and human requirements have increased. However, the frequent occurrence of unpredictable natural disasters, such as earthquakes, poses a huge threat to human safety, and property losses are becoming increasingly severe. How to avoid or control structural seismic damage and property loss, and how to improve existing seismic design methods, have become primary challenges facing researchers and structural engineers in the modern construction industry [1].

Consequently, performance-based seismic design methods have emerged. Due to their reasonable design principles and scientific design criteria, they have been well-received by structural engineering researchers. These methods are regarded as the primary design theory for future structural seismic design and represent the direction of future development. Since the intensity and characteristics of seismic activity cannot be fully predicted, and greater structural strength implies higher seismic capacity, traditional seismic methods do not strictly guarantee structural safety. Instead, they may reduce economic efficiency and increase costs. Therefore, it is crucial to reduce the seismic response of structures reasonably by adopting safe, rational, and economical seismic design methods.

2. From Seismic Design to Recoverability

With the in-depth study of engineering seismology, the seismic theory of engineering structures began with static calculation theory. This early theory assumed that the seismic action on a building structure was unrelated to the structure's dynamic characteristics, the spectral characteristics of seismic waves, or site conditions. The magnitude was simply equivalent to a horizontal force, which obviously could not truly reflect the response of the structure under random ground motions [2].

Subsequently, the elastic response spectrum calculation theory was developed. By statistically analyzing the response of single-degree-of-freedom systems under multiple earthquakes, researchers derived relationship curves between the engineering structure's period and its

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seismic response (displacement, acceleration, velocity, etc.). However, this design theory assumes the structure remains in an elastic state and can only provide peak structural responses, not the full process.

Later, dynamic calculation theory overcame the shortcomings of response spectrum theory. It can accurately reflect the entire response process of a structure under seismic loads. However, its fundamental purpose remained based on the bearing capacity (strength) of the structure.

In the 1990s, American scientists and engineers proposed performance-based seismic design theory. This approach comprehensively considers factors such as the maximum response value of the structure under seismic action, the duration and spectral characteristics of seismic waves, the structure's hysteretic and damping energy dissipation, and site conditions. To a certain extent, it reflects the damage accumulation and performance degradation of structures under seismic action, establishing a diversified, specific, and personalized seismic design theory [3].

Traditional seismic theory primarily aims to protect life, preventing structural collapse under strong earthquakes through ductility design. The cost of this philosophy is allowing plastic deformation in main load-bearing members. However, the subsequent repair work poses a massive impact on the social economy. Therefore, researchers have proposed the concept of recoverable structures [4].

3. Research on Seismic Mitigation and Isolation Technology

3.1. Structural Seismic Control Technology

Structural vibration control technology mainly includes active control, passive control, semi-active control, and hybrid control [5].

Passive Control: This refers to placing damping devices in the building or modifying partial structural components to change the structure's dynamic characteristics. Passive control includes tuned mass dampers (TMD), base isolation, and energy dissipation systems. Passive control can effectively reduce the transmission of vibration within the building structure.

Active Control: This system requires an external energy supply to suppress ground vibration. Based on modern vibration suppression theory, it monitors the energy input from seismic waves and the dynamic response of structural changes at every moment. Through active control algorithms, the optimal dynamic force is calculated and applied to building components, limiting the energy response within prescribed limits and reducing damage. The active control force adjusts continuously with the energy response to seismic waves.

Semi-Active Control: Based on passive control, this method combines the advantages of passive and active systems. It uses a small amount of external energy to provide control forces and can adjust the damping force and parameters of the control device using control algorithms to reduce structural vibration. Common devices include magnetorheological/electrorheological dampers, variable stiffness control systems (AVS), and variable damping control systems (AVD).

Hybrid Control: This combines active and passive control, applying both to structural or equipment vibration reduction. The active and passive systems can work separately or jointly.

3.2. Building Isolation Bearings

(1) Rubber Isolation Bearings Rubber isolation bearings consist of alternating layers of steel plates and rubber. The steel plates serve as stiffening materials, altering the low vertical stiffness characteristic of the rubber body, enabling it to reduce horizontal seismic action while bearing large vertical loads. Currently used laminated rubber bearings utilize the combined advantages of steel and rubber. When applied in buildings, they increase the structure's ability to resist horizontal and vertical earthquakes as well as torsion. An improved version is the Lead Rubber Bearing (LRB). To reduce seismic action, LRBs incorporate a lead core through an opening, increasing compressive capacity and reducing the displacement of the isolation layer.

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(2) Sliding Isolation Bearings Sliding isolation involves placing sliding materials (such as low-friction graphite, sand, or talc) in the isolation layer. This ensures the foundation transmits only limited seismic forces to the superstructure, thereby protecting it. Its dynamic characteristic is that before sliding, the system's natural period is the same as the structure's period. Once sliding occurs, the stiffness of the isolation layer becomes very small, and the system's natural period becomes very large. Theoretically, sliding isolation can avoid resonance effects from most seismic waves. The sliding friction surface typically uses tetrafluoroethylene (PTFE) in contact with stainless steel plates, which offers the strongest stability.

(3) Hybrid Isolation Bearings Since sliding friction bearings lack self-centering capability, they may produce uncontrollable displacement during major earthquakes. Conversely, while laminated rubber bearings have self-centering capability, their damping is limited, offering no advantage in dissipating seismic energy. Therefore, composite isolation systems that combine restoring capability and energy dissipation characteristics are favored by researchers and engineers. Current composite bearings include the parallel use of rubber bearings and sliding bearings, the parallel use of rubber bearings and dampers, and composite devices possessing both elastic horizontal restoring force and damping. Hybrid isolation systems generally have two natural periods: the structural natural period and the isolation structure period. The system's natural period can be extended by increasing the number of rubber bearings. Hybrid isolation is generally used in high-rise isolation projects.

4. Performance-Based Seismic Design Method

4.1. Concept and Basic Ideology

The concept of performance-based structural seismic design was proposed by the University of California, Berkeley, and the Federal Emergency

Management Agency (FEMA) in 1995 and was incorporated into the US "Performance Code for Buildings and Facilities" in 2003 [6]. It represents a transition from macroscopic qualitative design goals to specific, quantified multi-indices. It determines structural performance objectives based on the building's use, characteristics, and owner requirements, proposing different seismic fortification standards. This ensures the building meets expected fortification goals under future earthquakes of varying magnitudes. Simultaneously, by selecting reasonable seismic performance goals and structural measures, the building can satisfy local performance requirements, ensuring that the degree of damage and property loss in future potential earthquakes remains within limits acceptable to the owner.

4.2. Core Issues

The core content of performance-based seismic design theory mainly includes determining seismic fortification standards, defining structural seismic performance levels and objectives, and establishing performance-based design methods.

Seismic Fortification Standards: These are based on a specific design reference period and the probability of earthquakes of different intensities recurring within that period (probability of exceedance). Current codes macroscopically divide fortification intensity levels into three levels: Minor Earthquake (Frequent Intensity), Moderate Earthquake (Basic Intensity), and Major Earthquake (Rare Intensity).

Performance Levels: Existing performance-based seismic fortification levels are divided into four categories: "Operational," "Immediate Occupancy," "Life Safety," and "Collapse Prevention"[7].

Performance Objectives: These are determined by comprehensively considering factors such as structural function, importance, investment and benefit, historical value, and ease of repair after damage. China's current code sets the seismic design goal as "No damage under minor

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earthquakes, repairable under moderate earthquakes, and no collapse under major earthquakes."

Design Methods: These mainly include Displacement-Based Design and Energy-Based Design. Displacement-based design starts from a target displacement, determining the structure's stiffness matrix and corresponding strength based on deformation-stiffness and displacement-strength relationships. Energy-based design focuses on the energy input into the structure and the energy dissipated by the structure. It selects reasonable calculation parameters to quantitatively calculate the damage degree under repeated seismic action, compensating for the inability of other methods to perform nonlinear analysis [8].

5. Conclusion

(1) Since the Wenchuan earthquake, seismic mitigation and isolation technology has developed vigorously in the domestic engineering field, and relevant codes and technical standards are gradually being perfected. With the development of new isolation devices and resilient structures (components), it is crucial to propose performance-based seismic design methods that consider the effects of aging and environmental factors on the mechanical properties of bearings.

(2) In mitigation and isolation design, attention should be paid to detailing, specifically the reasonable matching of bearing deformation capacity with design displacement and gap size. Numerical simulations must prioritize the simulation methods of boundary conditions to correctly evaluate the seismic response of the structure.

(3) Based on the design concept of "Self-centering, Low damage, Controllability, and Rapid post-earthquake recovery," combining third-generation structural design theories to develop new resilient bridge structural systems has become a major trend in engineering seismic resistance. Issues such as the variation of mechanical properties of isolation devices over time and environment throughout their life cycle, health monitoring, and post-earthquake damage detection and assessment also require simultaneous consideration and research.

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