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Review of Research Progress and Applications of Rolling Isolation Bearings

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Abstract

Rolling isolation bearings, as an important type of base isolation technology, isolate and dissipate seismic energy through rolling friction. This paper summarizes the structural types, mechanical performance analysis methods, and engineering application cases of rolling isolation bearings, illustrates their technical characteristics and development history with specific studies, points out the limitations of current research in aspects such as three-dimensional isolation matching and long-term material performance, and prospects future development directions based on existing achievements. Practical applications show that innovations in multi-dimensional isolation and complex scenario adaptation of rolling isolation bearings provide multiple solutions for seismic resistance of engineering structures.

Keywords

Rolling isolation bearings; structural seismic resistance; numerical analysis; engineering applications.

1. Introduction

Earthquake disasters often cause sudden damage to engineering structures. Traditional seismic design resists earthquakes by increasing structural stiffness, which easily leads to structural internal forces exceeding the bearing limit and subsequent damage. Base isolation technology has become an important method to improve structural safety by installing isolation devices between structures and foundations to block the transmission of seismic energy[1]. Due to their low rolling friction coefficient and strong reset capability, rolling isolation bearings have gradually become a research hotspot since the 2010s. From early simple rolling element designs to composite systems integrating new materials, their development has always centered on the three core goals of "efficient isolation, reliable reset, and scenario adaptation". Based on research results over the past decade, this paper reviews structural innovation, performance analysis, and engineering applications to provide references for theoretical research and engineering practice.

2. Structural Types and Technical Characteristics of Rolling Isolation Bearings

The development of rolling isolation bearings reflects the mutual promotion of structural forms and functional requirements, forming three technical systems: basic type, material composite type, and combined type.

2.1. Basic Rolling Isolation Bearings

In 2011, Wang Linjian first proposed a rubber circular tube-bearing composite bearing. He used ANSYS software to simulate and determine the contact parameters between the rubber circular tube and steel plate, and achieved the synergy of horizontal isolation and vertical load-bearing after size optimization[2]. The innovation of this bearing lies in using the elasticity of rubber to absorb vertical impact and reducing horizontal seismic transmission through bearing rolling, which significantly reduces the acceleration response of the tower top in high-voltage transmission tower model tests.

The spring-eccentric bearing developed by Liu Shutang et al. limits the displacement of the rolling plate within a certain range through springs to ensure the automatic reset capability of the rolling isolation bearing. The orthogonal bearing system solves the problem of synchronous movement of rolling balls, greatly improving reset reliability[3]. SIMULINK simulations show that this system can effectively reduce the transmission of seismic energy to the superstructure, making it suitable for isolation needs of flexible structures such as transmission towers.

2.2. Material Composite Isolation Bearings

The integration of Shape Memory Alloy (SMA) and disc springs is an important innovation direction in this field. The SMA-ball bearing proposed by Wang Shanshan uses the superelasticity of SMA materials to achieve reset, while cooperating with disc springs to enhance vertical stiffness. ANSYS simulation results show that this bearing can significantly reduce the inter-story drift angle of five-story frame structures, achieving obvious shock absorption effects[4]. Sun Xiaodong optimized the SMA-rolling disc spring bearing on this basis. Under EL-Centro, KOBE, and TAFT waves, the inter-story displacement and acceleration of the superstructure decreased significantly under rare earthquakes, demonstrating the remarkable isolation effect of this new bearing[5].

The plastic energy dissipation characteristics of mild steel have also been successfully applied to rolling isolation bearings. The mild steel-rolling bearing developed by Li Xiongyan et al. releases temperature stress through shear deformation of mild steel sheets and achieves isolation by combining ball rolling. In grid structures, it can significantly reduce axial force response and temperature stress[6][7].

2.3. Combined Three-Dimensional Isolation Systems

To address the limitation that traditional bearings cannot simultaneously achieve horizontal and vertical isolation, An Junhai proposed a series system of disc springs and RFPS (Roller Friction Pendulum): the RFPS bearing is responsible for horizontal isolation, and the disc spring undertakes vertical isolation. By adjusting the friction coefficient and the number of disc springs, the three-dimensional stiffness can be optimized. Both horizontal and vertical isolation effects are significant in frame structure simulations[8].

The ball-lead rubber composite system (arranged in a 20:7 ratio) studied by Liu Hongwei shows good isolation performance in all directions, which is better than the full rubber bearing scheme[9]. The U-shaped steel bar-rolling isolation bearing proposed by Li Zhihao et al. enhances the limit and reset capabilities by adding U-shaped steel bar dampers. ANSYS simulations show that it can reduce the displacement and acceleration of the superstructure to a greater extent[10].

3. Methods for Analyzing Mechanical Performance

The nonlinear mechanical behavior of rolling isolation bearings needs to be described by combining theoretical modeling and numerical simulation, and a relatively complete analysis system has been formed.

3.1. Theoretical Modeling

The Lagrange equation in multi-body dynamics is a core tool for constructing motion equations. An Junhai derived a three-dimensional motion equation including horizontal, vertical displacements, and rotation angles for the disc spring-RFPS system. Solving via the Newmark-

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β method shows that reasonably selecting the radius of the arc slideway and friction coefficient can significantly reduce the dynamic response of the superstructure[8].

Wei Biao et al. compared displacement calculation methods for pure rolling systems. The compiled numerical analysis program is more accurate than the traditional rigid-plastic force-displacement curve method, with conservative calculation results. It also confirms that the maximum relative displacement of structures under earthquakes may exceed the maximum absolute displacement of the ground[11].

3.2. Numerical Simulation

Finite element software is widely used in mechanical property analysis. Based on Hertz contact theory, Li Xiongyan et al. simulated the static mechanical properties of mild steel-rolling bearings through ANSYS, and found that they have good mechanical performance and ideal hysteretic energy dissipation performance, with low hysteretic energy dissipation of balls[12].

Li Xiang established a finite element model of the ring beam rolling isolation device using ADINA. The analysis shows that the equivalent horizontal stiffness and damping ratio of the composite foundation are related to loading frequency and vertical compressive stress, and proposed stiffness and damping ratio expressions meeting design requirements[13][14]. Sui Jieying et al. studied soil-structure interaction through ANSYS and found that considering this effect increases the natural vibration period and displacement of rolling isolated structures, with a more significant impact on frame-shear wall structures[15].

4. Engineering Application Practice

Rolling isolation bearings have been verified in various structures such as transmission towers, storage tanks, subways, and bridges, showing good scenario adaptability.

4.1. High-Voltage Transmission Towers and Spatial Structures

Wang Linjian applied the rubber circular tube-bearing bearing to the foundation of high-voltage transmission towers. Dynamic response analysis under frequent and rare earthquakes shows that this device can effectively reduce structural responses[2]. SIMULINK simulations by Liu Shutang et al. show that the spring-eccentric bearing isolation system can significantly reduce the transmission of seismic energy to the superstructure[3]. In spatial structures, the mild steel-rolling bearing developed by Li Xiongyan et al. is applied to single-layer cylindrical reticulated shells, which can effectively release temperature stress and reduce seismic axial force response[7].

4.2. Vertical Storage Tanks

The ring beam rolling isolation and sand cushion composite foundation designed by Li Xiang significantly reduces key parameters such as hydrodynamic pressure, tank wall stress of 150,000 m^3 storage tanks. The design of its equivalent stiffness and damping ratio needs to consider loading frequency and vertical compressive stress[13][14]. The variable stiffness limited rolling system proposed by Xu Bo for near-fault earthquakes can effectively control bearing displacement, and the base shear force is still significantly reduced compared with non-isolated conditions[16].

4.3. Underground and Transportation Engineering

Tao Lianjin et al. applied bidirectional RFPS bearings to the middle columns of subway stations, achieving an isolation efficiency of 50%~70% and significantly reducing the internal force and deformation of middle columns[17]. Zeng Yongping studied high-speed railway simply supported beam bridges in 9-degree seismic zones and proposed a double curved spherical bearing + shock absorption tenon scheme, which effectively limits the relative displacement between piers and beams and solves the risk of beam falling under near-fault strong earthquakes[18]. Chen Yongqi's analysis of foreign cases of seismic isolation bridge failures reminds us to pay attention to the durability of rolling bearings under the combined action of temperature and earthquakes[19].

5. Research Limitations and Future Prospects

Current research has confirmed the effectiveness of rolling isolation bearings, but there are three limitations: first, insufficient matching of three-dimensional isolation performance with limited vertical stiffness adjustment range; second, lack of long-term performance data for new materials (such as SMA), with no established specifications for performance attenuation rate after multiple cycles; third, need to strengthen research on adaptability to complex sites (such as near-fault areas), as bearing displacement control under near-fault earthquakes still relies on additional devices.

Future research can focus on three directions: 1) Developing intelligent adaptive systems, such as the system combining MR dampers and rolling bearings proposed by Yan Guiyun et al., which adjusts damping force in real-time through fuzzy semi-active control to adapt to earthquakes of different intensities[20]; 2) Conducting full-scale tests and long-term monitoring to establish material deterioration models; 3) Expanding applications in new structures such as prefabricated buildings and developing modular bearings to adapt to rapid installation needs.

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