

Article

Design and Performance Study of Stiffness-Reduced Rubber Isolation Bearings

Xianjie Wang¹, Chengpeng Lu¹, Linjian Wang^{2,*}, Yiming Chen¹, Jiayun Yang¹ and Shifang Deng¹

¹ School of Architecture and Planning, Yunnan University, Kunming 650504, China; xianjiawang@ynu.edu.cn (X.W.); 13683417893@163.com (C.L.); 18457071090@163.com (Y.C.); 15331739752@163.com (J.Y.); dsf70556845@163.com (S.D.)

² Yunnan Earthquake Agency, Kunming 650225, China

* Correspondence: wanglinjian1985@163.com; Tel.: +86-13700679713

Abstract

To address the poor vertical vibration reduction in laminated rubber bearings, the high cost and low practicality of combined three-dimensional isolation bearings, and the low load-bearing capacity of thick-layer rubber bearings, this paper proposes a stiffness-reduced rubber isolation bearing. Based on the deformation coordination principle and the incompressibility of thick-layer rubber, theoretical formulas for the horizontal and vertical stiffness of the proposed bearing are established. Compression–shear tests and finite element simulations are then conducted to investigate its mechanical properties under vertical compressive stress. The results show that the theoretical predictions agree well with the simulation and experimental results. The maximum error of horizontal stiffness is no more than 5.6% relative to the finite element simulation and no more than 3.3% relative to the experimental results, while the maximum error of vertical stiffness is no more than 7.9% and 2.3%, respectively. Compared with the traditional laminated rubber bearing, the stiffness-reduced rubber isolation bearing reduces the average vertical stiffness by 35.8% while maintaining stable horizontal mechanical performance and overall integrity within the tested range. Furthermore, parametric analysis indicates that the stiffness can be effectively adjusted by changing the inner-diameter/outer-diameter ratio. A case study based on measured metro-induced vibration time-history curves further shows that the proposed bearing has potential for achieving the dual objective of horizontal isolation and vertical vibration reduction.

Keywords: seismic and vibration dual-control; rubber isolation bearing; mechanical performance; experimental study; finite element simulation



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1. Introduction

Over the past two decades, laminated rubber bearings and lead-rubber bearings have been widely used in seismic isolation engineering [1]. These devices provide reliable horizontal seismic isolation and can effectively improve the seismic resilience of building structures [2–4]. However, their relatively large vertical stiffness limits their ability to mitigate vertical vibration. With the rapid development of urban rail transit, metro-induced environmental vibration, especially in the vertical direction, has become an increasingly important issue for buildings located above or near metro lines. To address both horizontal earthquake effects and vertical vibration, the concept of dual control—namely, combining horizontal seismic isolation with vertical vibration isolation—has attracted growing attention.

To simultaneously mitigate horizontal seismic motion and vertical vibration, several researchers have proposed combined three-dimensional isolation systems in which a vertical vibration isolation unit is connected in series with a traditional horizontal isolation bearing. Fukasawa T [5] proposed a three-dimensional bearing consisting of a rubber isolation bearing combined with a metal spring, which improved the vertical damping performance of the system. Shimada et al. [6] connected a laminated rubber bearing in series with an air-spring-based vertical isolation unit, reducing the vertical natural period of the isolated structure to approximately 1 s. Cao [7] further combined disk springs with a single-curved friction pendulum to form a three-dimensional isolation system capable of reducing the superstructure response induced by vertical metro vibration. Although such combined systems usually exhibit high load-bearing capacity, they also suffer from obvious disadvantages, including structural complexity, large dimensions, and high manufacturing cost, which limit their practical application. In this context, thick-layer rubber bearings, owing to their simple configuration and relatively low cost, have attracted increasing research interest.

Previous studies have shown that thick-layer rubber bearings can provide improved vertical vibration isolation compared with traditional laminated rubber bearings. Kanazawa [8] confirmed through scaled shaking-table tests that thick-layer rubber bearings were more effective in mitigating environmental vibration. Yabana [9] developed a new type of thick laminated rubber bearing that showed favorable control performance for environmental vibration around 10 Hz, and scaled tests verified its applicability in three-dimensional isolation systems. Zhu [10] experimentally investigated the mechanical properties of thick-layer rubber bearings, showing that the vertical stiffness decreases with increasing rubber thickness, and proposed a modified calculation method for vertical stiffness. Pan [11] further demonstrated through scaled tests that thick laminated rubber three-dimensional bearings could effectively reduce metro-induced vertical vibration. Nevertheless, reducing vertical stiffness also lowers the load-bearing and stability capacity of the bearing. Therefore, a key challenge is how to achieve sufficient vertical stiffness reduction while maintaining reliable support for the superstructure.

However, the dynamic performance of elastomeric isolation components is not governed solely by static stiffness, but is also strongly affected by viscoelastic damping, nonlinear constitutive behavior, and vibration transmissibility characteristics under service excitation. Zhao Zhangda [12] investigated the dynamic characteristics of low-frequency high-stiffness viscoelastic damping structures and showed that the elastic modulus distribution of the damping layer significantly influences both stiffness and energy dissipation under harmonic excitation. Cheng Zhongyi [13] proposed a parallel polyurea method to enhance the damping performance of metal lattice vibration-isolation structures, and their experimental results demonstrated that the introduction of a viscoelastic damping component could significantly reduce the transmissibility peak while improving shock attenuation capability. Zhu Guanghong [14] further developed a nonlinear fractional-order constitutive model for soft magnetorheological elastomers and found that amplitude-dependent modulus and nonlinear viscoelastic behavior have a pronounced influence on the dynamic response and vibration-isolation performance of elastomer-based systems. These studies indicate that the evaluation of rubber isolation bearings should not be limited to stiffness reduction alone, but should also incorporate elastomer mechanics, viscoelastic damping, and transmissibility-based dynamic analysis.

At present, rubber isolation bearings have been widely used in seismic mitigation and vibration reduction in buildings, bridges and rail transit structures. However, the mechanical properties of rubber bearings are easily affected by environmental factors, fatigue loads and temperature changes during long-term service. Cezary Kraśkiewicz [15]

tested the fatigue performance of under ballast mats based on EN 17282 [16] and found that cyclic load led to obvious changes in the static and dynamic stiffness of rubber mats, which directly reduced the vibration isolation effect. Chamindi Jayasuriya [17] pointed out that under sleeper pads with appropriate stiffness can effectively reduce ballast deformation and particle breakage, and improve the long-term stability of rail tracks.

However, most studies focus on ordinary laminated rubber bearings, and there is a lack of systematic research on the durability of stiffness-reduced rubber isolation bearings under complex environments. Yanmin Li [18] confirmed that the alternation of aging and seawater erosion would significantly increase the hardness and stiffness of rubber materials for lead-rubber bearings, and reduce the elongation at break and tensile strength.

In addition, temperature has a significant influence on the mechanical properties of rubber bearings. Cezary Kraśkiewicz [19] tested the resistance of under sleeper pads to severe environments such as water, freeze–thaw and high temperature based on EN 16730 [20], and proved that styrene–butadiene rubber-based pads had better environmental durability.

Based on the above considerations, this study proposes a new type of isolation bearing—a stiffness-reduced rubber isolation bearing. The specific structure is shown in Figure 1. Through an innovative design, this bearing combines thick-layer rubber bearings and laminated rubber bearings in parallel, making full use of the low stiffness characteristics of thick-layer rubber to effectively reduce the impact of vertical earthquakes and environmental vibration caused by metro on the superstructure. Meanwhile, it can avoid the buckling instability phenomenon of thick-layer rubber. Additionally, the horizontal and vertical stiffness of the bearing can be adjusted by changing the ratio of the inner thick-layer rubber diameter to the outer diameter of the bearing.

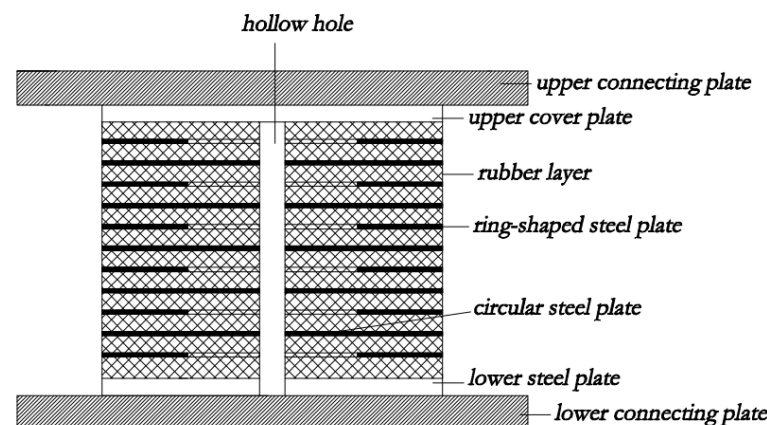


Figure 1. Structure diagram of stiffness-reduced rubber isolation bearing.

This new type of bearing can not only solve the comfort problem caused by vibration from metro operation but also meet the seismic performance requirements of the upper cover structure. Under ideal conditions, the inner thick-layer rubber bearing and the outer laminated rubber bearing work in parallel to achieve vertical vibration reduction in the vertical direction, while they work in series to realize horizontal isolation in the horizontal direction. Compared with common “seismic and vibration dual control” bearings available on the market, the new bearing has the advantages of simple structure, controllable cost, and reasonable working mechanism, thus possessing high engineering application value.

For the proposed new isolation bearing, this study establishes the theoretical formulas for horizontal and vertical stiffness. Through experimental tests and finite element simulation, the horizontal and vertical performance of the stiffness-reduced rubber isolation bearing under vertical compressive stress is analyzed, and the results are compared with

the theoretical calculation values to verify the engineering application feasibility and the accuracy of the theoretical model.

2. Stiffness Calculation Model of Stiffness-Reduced Isolation Bearing

As shown in Figure 2, the stiffness-reduced rubber isolation bearing can be regarded as a combined isolation bearing composed of a traditional laminated rubber bearing and a thick-layer rubber bearing in parallel, which jointly undertake vertical load-bearing. Due to the different stiffness of the two bearings and their parallel load-bearing mode, based on the deformation coordination principle, it is necessary to separately calculate the vertical stiffness of the inner and outer bearings, and then obtain the total vertical stiffness of the bearing through parallel combination.

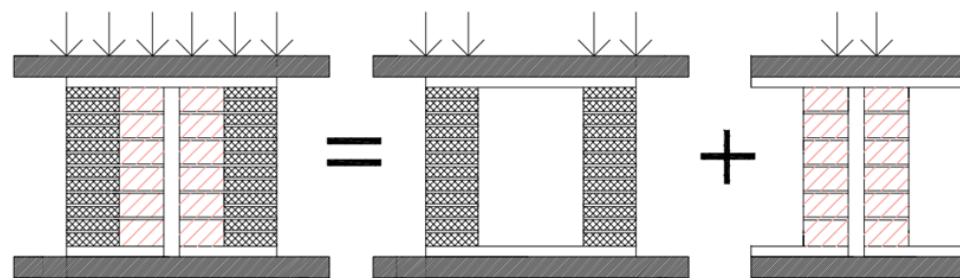


Figure 2. Vertical bearing diagram of stiffness-reduced rubber isolation bearing.

2.1. Vertical Stiffness Calculation of Inner Thick-Layer Rubber Bearing

Compared with traditional rubber bearings, the first shape factor of thick-layer rubber bearings is significantly reduced due to the increased thickness of the rubber layer. According to Article 5.2 of the “Rubber isolation bearings for buildings” (JG/T118-2018) [21], the first shape factor of rubber isolation bearings should not be less than 15. Therefore, the code formulas are not applicable to the vertical stiffness calculation of thick-layer rubber bearings, and the original stiffness calculation formula needs to be modified.

The deformation of a single thick rubber layer under compression is shown in Figure 3. Assuming the boundary deformation follows a parabolic form [22], and considering the incompressibility of rubber while neglecting the change in the inner hole diameter D_1 , the relationship between the maximum expansion deformation P of the rubber under compression and the vertical displacement d is expressed as Equation (1).

$$P = \frac{3D_0d}{4(t_r - d)} \quad (1)$$

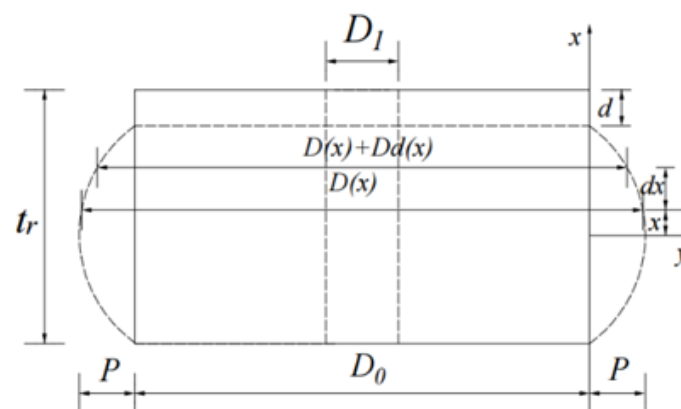


Figure 3. Compression deformation diagram of thick rubber.

Based on this, the parabolic formula for rubber compressive deformation is derived as follows:

$$y = -\frac{3D_0d}{(t_r-d)^3}x^2 + \frac{3D_0d}{4(t_r-d)}y \quad (2)$$

Thus, the diameter of the rubber layer at any height can be obtained:

$$D(x) = D_0 - \frac{6D_0d}{(t_r-d)^3}x^2 + \frac{3D_0d}{2(t_r-d)}y \quad (3)$$

Dividing the single-layer thick rubber into numerous serially connected rubber layers with thickness dx , the reciprocal of the stiffness of the single-layer rubber is equal to the sum of the reciprocals of the stiffness of each sub-layer, as shown in Equation (4):

$$\frac{1}{K_{V,1}(d)} = \int_{-\frac{t_r-d}{2}}^{\frac{t_r-d}{2}} \frac{1}{E'_c A(x)} dx = \int_{-\frac{t_r-d}{2}}^{\frac{t_r-d}{2}} \frac{4}{\pi E'_c (D(x)^2 - D_1^2)} dx \quad (4)$$

In the formula, D_0 , D_1 , and t_r have the same meanings as defined earlier; P is the maximum expansion deformation of the rubber layer; d is the vertical displacement; and E'_c is the new compression modulus, which is calculated by the new first shape factor S'_1 considering the influence of bearing deformation, as shown in Equation (5):

$$S'_1 = \frac{D_0 - D_1}{4(t_r - d)} \quad (5)$$

From the article [23], for multi-layer rubber in series, neglecting the stiffness of the interlayer steel plates, the total stiffness of the thick-layer rubber bearing is the series stiffness of each rubber layer, as expressed in Equation (6):

$$K_V = \frac{K_{V,1}}{n} \quad (6)$$

2.2. Vertical Stiffness Calculation of the Outer Laminated Rubber Bearing

Using the theoretical formula for vertical stiffness in the “Rubber isolation bearings for buildings” (JG/T118-2018) [21] to calculate the vertical stiffness of the outer laminated rubber bearing will result in significant errors. This is because the inner diameter of the hollow hole of the outer laminated rubber bearing reaches half of the bearing radius, leading to its 1st shape factor S_1 being much less than 15. Therefore, the theoretical formula in the code cannot be used, and the theoretical formula needs to be modified.

The outer laminated rubber bearing can be regarded as a laminated rubber bearing with the inner part “hollowed out”. When the laminated rubber bearing is compressed, the compressive displacement δ is uniform everywhere. According to the deformation coordination principle:

$$\delta = \delta_1 = \delta_2 \quad (7)$$

$$k = \frac{F}{\delta} = \frac{EA}{L} \quad (8)$$

Since $\delta_1 = \delta_2$ and $\frac{F_1 L_1}{E_1 A_1} = \frac{F_2 L_2}{E_2 A_2}$, and the heights of the two bearings are the same:

$$\frac{F_1}{F_2} = \frac{E_1 A_1}{E_2 A_2} = \frac{k_1}{k_2} \quad (9)$$

The stiffness ratio of the “hollowed-out” laminated rubber bearing can be derived as:

$$\frac{k_2}{k_1} = \frac{A_2}{A_1} \quad (10)$$

In the formula, k_2 and A_2 are the stiffness and area of the outer laminated rubber bearing, respectively; k_1 and A_1 are the stiffness and area of the traditional laminated rubber bearing, respectively. Then, $K_{V,2}$ can be obtained by the following formula:

$$K_{V,2} = \frac{A_2}{A_1} \times K_{V,1} = \left(\frac{D_0^2 - D_1^2}{D_0^2} \right) \times K_{V,1} \quad (11)$$

2.3. Vertical Stiffness Calculation Model of the Stiffness-Reduced Isolation Bearing

After the inner and outer rubber bearings are connected in parallel, they can be regarded as a parallel compression model. Due to compression, the compressive displacement is uniform everywhere, and the stiffness calculation model is as follows:

$$K_V = \frac{F}{\delta} = \frac{K_{V,1} \times \delta + K_{V,2} \times \delta}{\delta} = K_{V,1} + K_{V,2} \quad (12)$$

2.4. Horizontal Stiffness Calculation Model of the Stiffness-Reduced

Due to the different thicknesses of the inner and outer rubber layers of the bearing, the outer annular steel plates constrain the inner thick rubber layer, resulting in different shear deformations between the outer rubber layer and the inner rubber layer [24], as shown in Figure 4. Therefore, the traditional parallel model is not applicable to the stiffness calculation of the new bearing, and a new modification is required.

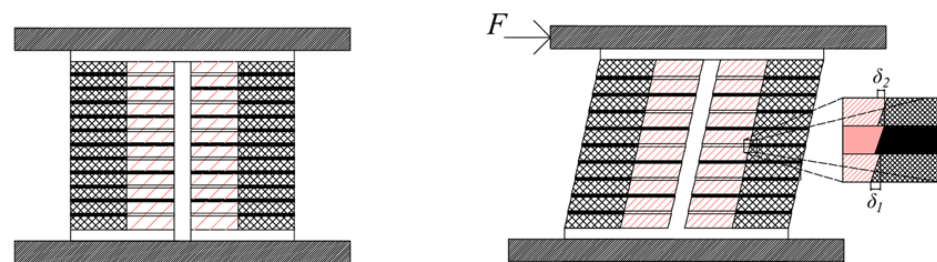


Figure 4. Horizontal deformation diagram of isolation bearing.

Taking the unit rubber layer on the right side of Figure 4 as an example, the bearing is divided into several shear units. In each shear unit, the rubber layers on both sides are first connected in parallel and then in series with the middle rubber layer. Therefore, a shear unit can be regarded as a series-parallel model. For n shear units, the following formulas are derived:

$$K_{H1} = \frac{GA_1}{T_{R1}} \quad (13)$$

$$K_{H2} = \frac{GA_2}{T_{R2}} \quad (14)$$

$$K_{H0} = \frac{(K_{H1} + K_{H1})K_{H2}}{K_{H1} + K_{H1} + K_{H2}} \quad (15)$$

$$K_H = nK_{H0} = n \frac{(K_{H1} + K_{H1})K_{H2}}{K_{H1} + K_{H1} + K_{H2}} \quad (16)$$

In the formula, K_{H1} and K_{H2} are the horizontal stiffness of the inner and outer ring rubber, respectively; A_1 and A_2 are the areas of the single-layer rubber of the inner and outer rings, respectively; T_{R1} and T_{R2} are the thicknesses of the single-layer rubber of the inner and outer rings, respectively; K_{H0} is the horizontal stiffness of a single shear unit; and K_H is the horizontal stiffness of the bearing.

3. Experimental Study and Analysis

3.1. Experiment Overview

To verify the above theoretical derivation, a 25,000 kN dynamic compression-shear testing machine was used in this experiment, as shown in Figure 5, with a maximum horizontal shear force of 2000 kN and a horizontal displacement of 600 mm. Vertical loading was controlled by load, and horizontal loading was controlled by displacement. The bearing test is shown in Figure 6. The horizontal shear deformation diagram is shown in Figure 7.

Based on the principle of constant outer diameter and variable inner diameter of the annular steel plates inside the bearing, two types of bearings were designed and fabricated. Bearing (a) is a traditional laminated rubber bearing (SJ-1), and bearing (b) is a stiffness-reduced rubber isolation bearing (SJ-2) with the inner diameter of the annular steel plate being 50% of the outer diameter. The specimens are shown in Figure 8, and the specific parameters are listed in Table 1.

As shown in Figure 8a, two small holes are drilled on both sides of the hollow hole of the stiffness-reduced rubber isolation bearing, which is the junction between the inner thick-layer rubber bearing and the outer laminated rubber bearing. Drilling these holes facilitates the fabrication of the new bearing.



Figure 5. Loading devices.



Figure 6. Experimental setup for compressive loading test of the rubber isolation bearing.



Figure 7. Experimental setup for the bearing under 100% shear deformation.

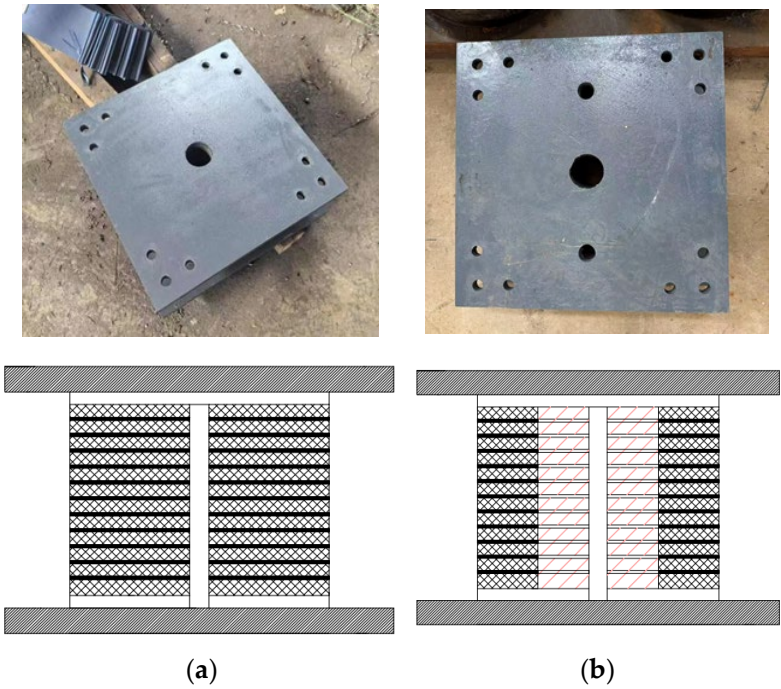


Figure 8. Comparison diagram of rubber bearing. (a) Traditional laminated rubber bearing. (b) Stiffness-reduced rubber isolation bearing.

Table 1. Design parameters of rubber isolation bearings.

Parameters	SJ-1	SJ-2
Rubber layer diameter (mm)	400	400
Inner thick-layer rubber diameter (mm)	0	200
Outer rubber layer parameters ($t_r \times n$)	5.25×16	5.25×16
Inner rubber layer parameters ($t_r \times n$)	0×0	13.25×8
Steel plate thickness (mm)	2.75	2.75
Hollow hole diameter (mm)	65	65

3.2. Test Procedures and Experimental Parameters

To ensure the reproducibility of the experimental results and clarify the nature of the compression-shear tests on the rubber isolation bearings. All tests were carried out in accordance with the Test Methods for “Rubber isolation bearings for buildings” (JG/T118-2018) [21], “Standard for seismic isolation design of building” (GB/T 51408-2021) [25] and the “Rubber bearings—Part 1: Seismic-protection isolators test methods” (GB/T 20688.1-2007) [26], which conform to the standard test requirements for rubber isolation bearings in civil engineering.

3.2.1. Test Preparation Procedures

As shown in Specimen Installation: The bearing specimens (SJ-1 and SJ-2) were horizontally centered and fixed on the lower loading plate of the 25,000 kN dynamic compression-shear testing machine (Figure 5), and the upper loading plate was aligned with the center of the bearing to ensure uniform stress on the bearing during loading and avoid eccentric compression.

Zero Calibration: After installation, the testing machine was calibrated for load and displacement zero, and the initial contact load was applied to eliminate the gap between the bearing and the loading plates.

Preloading: Preloading was performed under a vertical compressive stress of 6 MPa (the minimum vertical load in the test) with 3 cycles of small-amplitude horizontal shear deformation ($\pm 20\%$ shear strain) to make the bearing reach a stable stress state and verify the normal operation of the testing system.

3.2.2. Formal Test Procedures

To test the mechanical properties of the stiffness-reduced rubber isolation bearing and the traditional laminated rubber bearing under the same parameters but different structures, horizontal shear and vertical compression tests were conducted on the two bearings, respectively. The test loading conditions are shown in Table 2.

Table 2. Test loading conditions.

Working Condition	Vertical Load (MPa)	Loading Frequency (Hz)	Loading Rate	Number of Cyclic Loading	Shear Strain	Experimental Purpose
1	8	0.05	5 mm/s (displacement)	3	50%	Horizontal performance
2					100%	
3					150%	
4					200%	
5	6	0.05	2 kN/s (load)	4	0%	Vertical performance
6	8					
7	10					

(1) Horizontal Shear Test (Working Conditions 1–4)

In accordance with Clause 4.6.3 of the “Standard for seismic isolation design of building” (GB/T 51408-2021) [25], the compressive stress limit for key protected buildings and special protective structures should not exceed 10 MPa. Furthermore, when the 2nd shape factor of the rubber isolation bearing—defined as the ratio of the effective diameter to the total thickness of the rubber—is less than 5.0, the average compressive stress limit is required to be reduced. Based on a simple calculation using the geometric parameters presented in Section 2, the 2nd shape factor of the stiffness-reduced rubber isolation bearing was determined to be 4.76. Consequently, a 20% reduction in the compressive stress limit was applied, yielding a vertical compressive stress of 8 MPa for the tests.

The loading frequency was selected as 0.05 Hz, which complies with the requirements specified in “Rubber bearings—Part 1: Seismic-protection isolators test methods” (GB/T 20688.1-2007) [26]. This frequency was adopted to obtain the fundamental hysteretic characteristics and equivalent stiffness parameters of the bearings while minimizing the inertial effects of the loading system.

For the horizontal shear performance test under the vertical compressive stress of 8 MPa, the load-control mode was adopted for vertical loading, and the vertical stress was stably maintained at 8 MPa throughout the test. The horizontal loading adopted the displacement-control mode, and the shear strain was gradually increased from 50% to 100%, 150% and 200% (corresponding to the horizontal displacement of ± 42 mm, ± 84 mm, ± 126 mm and ± 168 mm for the two bearings). The loading rates were set according to those specified in Table 2, and three cyclic loading sequences were performed, and the horizontal force-displacement data were collected in real time by the testing machine’s data acquisition system until the hysteretic curve was stable.

(2) Vertical Compression Test (Working Conditions 5–7)

For the vertical compression performance test under 0% shear strain, the horizontal displacement of the bearing was fixed at the initial position (no horizontal shear deformation), and a load-controlled mode was employed for vertical cyclic loading, as detailed in Table 2. The vertical loading sequence was applied as follows: 0- P_0 - P_2 - P_0 - P_1 (first cycle), P_1 - P_0 - P_2 - P_0 - P_1 (second cycle), and P_1 - P_0 - P_2 - P_0 - P_1 (third cycle). Here, P_2 and P_1 are defined as 1.3 P_0 and 0.7 P_0 , respectively, with P_0 corresponding to vertical compressive stresses of 6 MPa, 8 MPa, and 10 MPa. The loading frequency was set to 0.5 Hz. A total of four loading cycles were conducted, and the load-displacement curve obtained from the third cycle was adopted for analysis.

3.3. Horizontal Performance Test

Horizontal shear tests were performed on the stiffness-reduced rubber isolation bearing and the traditional laminated rubber bearing, respectively, as shown in Figure 7, under working conditions 1–4. Figure 9 shows the horizontal shear hysteretic curves of the two bearings under the same compressive stress but different shear strains. The following conclusions are drawn:

- (1) Under the same compressive stress, in the small displacement stage (horizontal displacement: 0 mm~ ± 100 mm), the horizontal force values of the stiffness-reduced rubber isolation bearing under different shear strains are relatively close, and the hysteretic loops are more “compact”. This indicates that the force response difference under different shear deformations is small in the small displacement stage, and the relatively small area of the hysteretic loops implies weak energy dissipation capacity. In contrast, the horizontal force difference in the traditional laminated rubber bearing is more obvious in the small displacement stage, and the larger area of the hysteretic loops indicates stronger energy dissipation capacity.
- (2) Under the same compressive stress, in the large displacement stage (horizontal displacement: ± 100 mm~ ± 200 mm), the horizontal force of the stiffness-reduced rubber isolation bearing increases relatively gently, while that of the traditional laminated rubber bearing increases more steeply. This shows that the ductility of the stiffness-reduced rubber isolation bearing is relatively weaker than that of the traditional laminated rubber bearing.
- (3) Under different shear deformations, the curves of the stiffness-reduced rubber isolation bearing have a higher fitting degree in the entire displacement range, indicating that the structure has lower sensitivity to the amplitude of shear deformation and more uniform mechanical performance. For the traditional laminated rubber bear-

ing, the curves under different shear deformations are more scattered, especially the force growth difference is significant in the large deformation stage, reflecting higher sensitivity to shear deformation amplitude and more prominent differentiation of mechanical performance under large deformation.

- (4) Meanwhile, the stiffness-reduced bearing showed greater energy dissipation capacity and a higher equivalent viscous damping ratio, with a dissipated energy per cycle $\xi_{eq} = 7.23\%$. By contrast, the traditional bearing yielded corresponding values of 4.58%. In terms of cyclic degradation, the traditional laminated rubber bearing showed no obvious stiffness degradation, and its secant stiffness remained nearly stable over the identified cycles. By contrast, the stiffness-reduced rubber isolation bearing exhibited a stiffness reduction of about 5.25% between the extracted stable cycles, indicating a certain degree of softening under repeated loading. Nevertheless, the bearing still maintained a relatively high compressive resistance and stable cyclic response within the tested loading range.

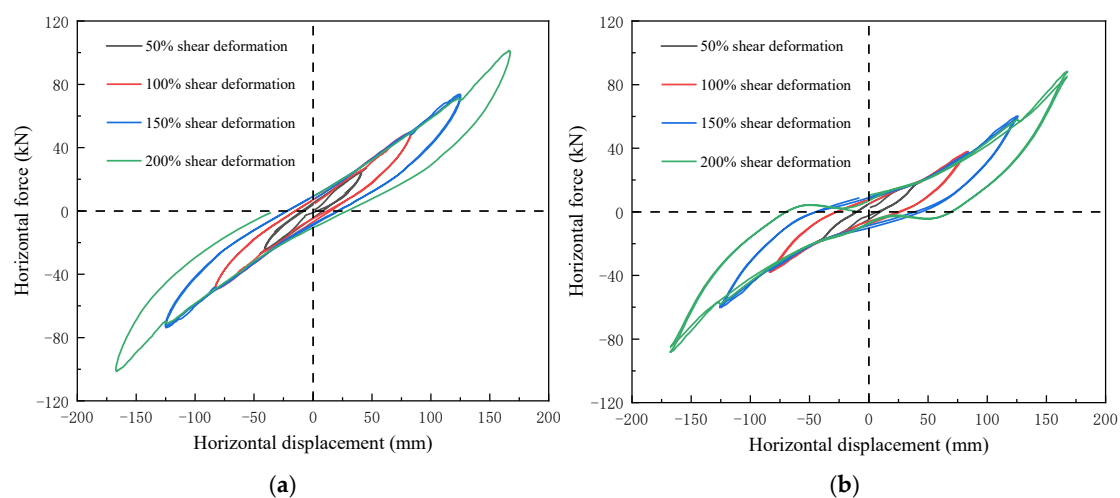


Figure 9. Horizontal shear hysteresis curve. (a) Traditional laminated rubber bearing. (b) Stiffness-reduced rubber isolation bearing.

A buckling instability analysis was performed for both types of bearings under a vertical load of 8 MPa and a shear strain of 200%. The calculation formula is as follows [27]:

$$SF_b(\gamma) = \frac{P_{cr}(\gamma)}{P_{test}} \quad (17)$$

In the formula, $P_{cr}(\gamma)$ represents the critical buckling load at a shear strain, γ and P_{test} denotes the vertical load applied during the test.

In practical engineering applications, P_{cr} is commonly calculated using the following formula:

$$P_{cr} = G \cdot S_1 \cdot S_2 \cdot A \quad (18)$$

It should be noted that the formula above calculates the critical buckling load of the bearing in the absence of horizontal displacement. When the bearing undergoes significant horizontal shear deformation, its effective compression area decreases, leading to a substantial reduction in the critical buckling load. In such cases, the correction is typically performed using the effective compression area method. The critical load P_{cr} decreases with increasing horizontal displacement, and this relationship can be approximately expressed as:

$$P_{cr}(\gamma) = P_{cr} \cdot \frac{A_e}{A} \quad (19)$$

In the formula, A_e represents the effective compression area under a horizontal displacement γ .

Omitting the calculation procedure, the resulting safety factor against buckling is obtained as $SF_b(\gamma) = 5.56 \geq 3.0$, indicating a significant overall buckling stability reserve under the considered loading condition.

To directly assess whether 200% shear deformation caused macroscopic damage, post-test photographs of the specimens are provided in Figure 10. No visible macroscopic cracking, tearing, or rubber–steel debonding was observed under 8 MPa axial stress and 200% shear strain in either specimen, indicating adequate large-deformation capacity.



Figure 10. Post-test appearance of specimens after 200% shear strain under 8 MPa. (a) Traditional laminated rubber bearing. (b) Stiffness-reduced rubber isolation bearing.

3.4. Vertical Performance Test

Vertical compression tests were conducted on the stiffness-reduced rubber isolation bearing and the traditional laminated rubber bearing under working conditions 5–7. Figure 11 shows the vertical compression hysteretic curves of the stiffness-reduced rubber isolation bearing. The test results show:

- (1) Compared with the traditional laminated rubber bearing, the vertical stiffness of the stiffness-reduced rubber isolation bearing is smaller, with an average reduction of 35.8%. Based on the calculation of the vertical equivalent viscous damping ratios of the two types of bearings, the average vertical equivalent viscous damping ratio of the traditional laminated rubber bearing is 4.58%, while that of the stiffness-reduced rubber isolation bearing is 8.19%. Furthermore, after multiple loading cycles, neither type of bearing exhibited significant stiffness degradation.
- (2) Due to the characteristics of the inner thick-layer rubber, the hysteretic curves of the stiffness-reduced rubber isolation bearing are fuller under the same compressive stress, showing stronger energy dissipation capacity and better ductility. It can maintain a stable stress state even under large deformation.
- (3) Compared with the traditional laminated rubber bearing, the latter “ring-on-ring” shape of the stiffness-reduced rubber isolation bearing indicates that the structure undergoes a certain degree of stiffness degradation in the large deformation stage, but it can still maintain high load-bearing capacity, with better deformation stability and deformation resistance.

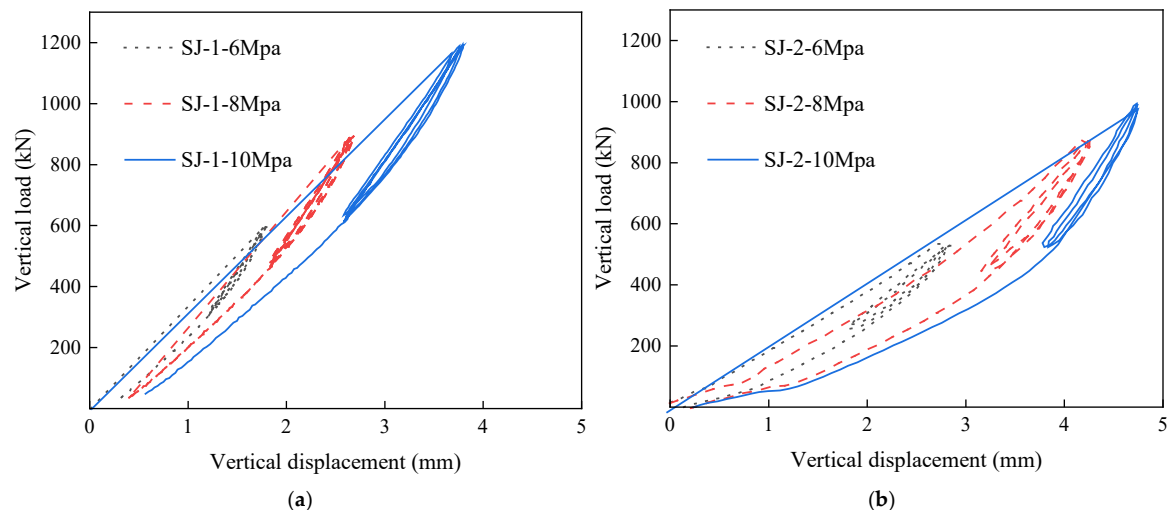


Figure 11. Vertical compression hysteresis curve. (a) Traditional laminated rubber bearing. (b) Stiffness-reduced rubber isolation bearing.

4. Numerical Simulation of Mechanical Properties of the Stiffness-Reduced Rubber Isolation Bearing

This section presents the finite element simulation analysis of the stiffness-reduced rubber isolation bearing, which is not a preliminary theoretical prediction for the subsequent experiment, but a supplementary and extended analysis based on the experimental results. The core objective of the present study is to verify the feasibility of the proposed bearing prototype and the accuracy of the stiffness calculation model through laboratory experiments. On this basis, the finite element method is used to expand the simulation to bearings with different inner/outer diameter ratios (0%, 25%, 50%, 75%, 100%), which can further explore the stiffness evolution law of the bearing with structural parameters and provide more comprehensive data support for its engineering design. The structural arrangement of the paper—experiment preceding simulation—is consistent with the research logic of “prototype validation to parametric expansion” adopted in this study.

4.1. Establishment of Finite Element Model

Considering the costs associated with experimental testing, the finite element software Abaqus/CAE 2021 was employed to conduct numerical simulations to validate the theoretical model. Subsequently, a comparative analysis was performed among the theoretical predictions, experimental results, and numerical simulation data.

In this simulation, the rubber material was modeled using the Yeoh model. The material parameters of the Yeoh model were calibrated based on the rubber tensile test data provided by the manufacturer. The parameters and tensile test data of the rubber specimen were all provided by the rubber bearing manufacturer. The tensile test data of the rubber specimen is shown in Figure 12 and the rubber was defined as an incompressible material with a Poisson’s ratio of 0.499, which is consistent with the physical properties of natural rubber used in engineering practice for isolation bearings.

In the preprocessing stage, a structured mesh was adopted for all components to ensure the calculation accuracy. The rubber layers were meshed with C3D8RH elements with a mesh size of 5 mm, and the steel plates and loading plates were meshed with C3D8R elements with a mesh size of 10 mm. A mesh convergence analysis was conducted to verify the mesh independence of the simulation results, which are presented in Table 3. Considering both computational time and accuracy, the mesh scheme adopted for Group

M2 was selected, i.e., a mesh size of 5 mm for the rubber layers and 10 mm for the steel plates and loading plates.

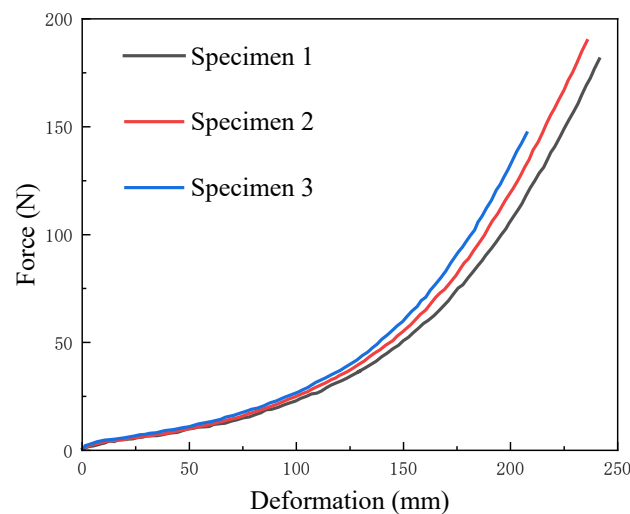


Figure 12. Tensile test data curve of rubber material (provided by the rubber bearing manufacturer).

Table 3. Mesh convergence study of the finite element model.

Mesh Scheme	Rubber Mesh Size (mm)	Steel Mesh Size (mm)	Calculated Horizontal Stiffness (kN·mm ^{−1})	Difference
M1	8	12	0.569	3.3%
M2	5	10	0.551	/
M3	3	8	0.545	1.1%

(Note: The calculated horizontal stiffness values in the table represent the horizontal stiffness of the traditional laminated rubber bearing under 8 MPa vertical stress and 200% shear strain. The ‘difference’ refers to the percentage decrease or increase in each group relative to group M2).

All finite element simulations were carried out using the Abaqus Standard solver, which is suitable for static compression-shear analysis of rubber bearings with large deformation. Geometric nonlinearity was enabled in all simulation models to account for the large shear and compressive deformation of the rubber layers under the test conditions, which is a key setting to ensure the consistency between the simulation results and the actual mechanical behavior of the bearing.

To verify the correctness of the calculation model of the stiffness-reduced rubber isolation bearing, the radius of the inner thick-layer rubber was changed while keeping the outer diameter of the bearing constant, making it 0%, 25%, 50%, 75%, and 100% of the outer diameter, respectively. The bearings with ratios of 0% and 100% are the traditional laminated rubber bearing and the thick-layer rubber bearing, which serve as the control groups. Simulation analysis was performed on the five models. The finite element model diagram is shown in Figure 13.

The connection property between the steel plate layers and rubber layers is set to “Tie” to simulate the actual connection between the steel plate layers and rubber layers of laminated rubber bearings in engineering practice. Meanwhile, it should be noted that for the stiffness-reduced rubber isolation bearing, the thin-layer rubber must be further tied to the annular steel plate to conform to the actual situation; otherwise, the thin-layer rubber may embed into the annular steel plate in the subsequent finite element simulation, leading to inaccurate simulation data.

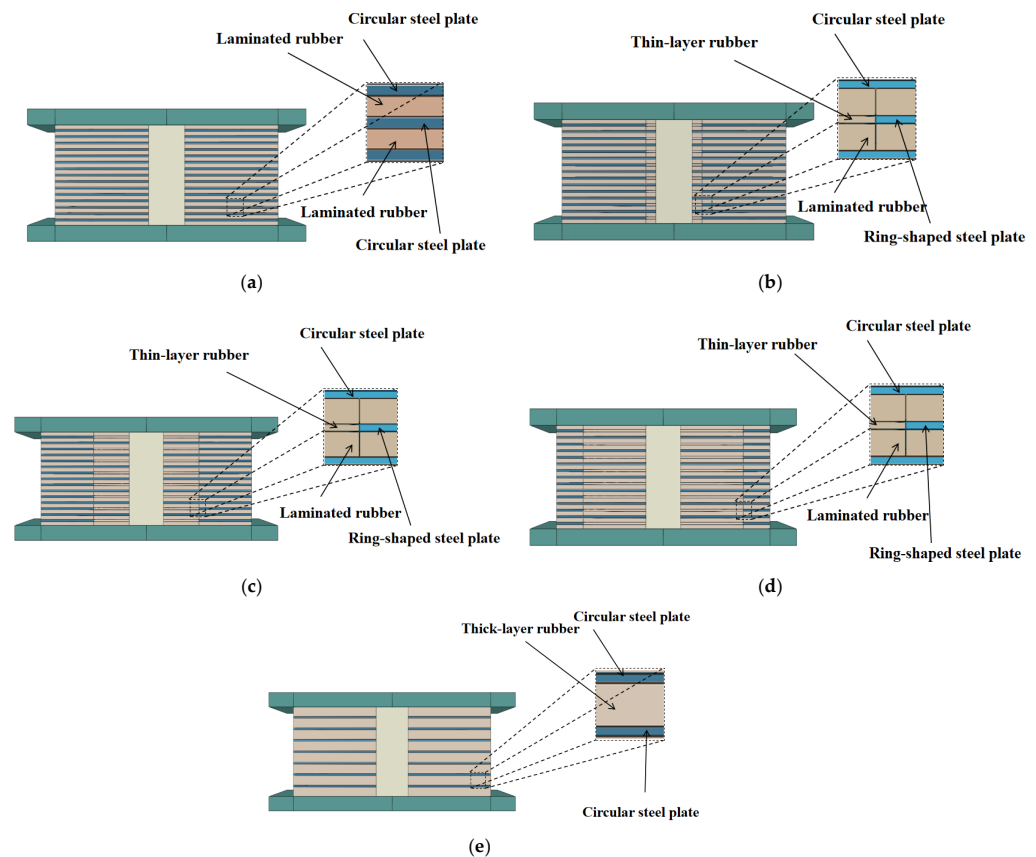


Figure 13. Construction diagram of stiffness-reduced rubber isolation bearing. (a) Traditional laminated rubber bearing, (b) 25% stiffness-reduced rubber isolation bearing; (c) 50% stiffness-reduced rubber isolation bearing; (d) 75% stiffness-reduced rubber isolation bearing; (e) thick-layer rubber bearing.

4.2. Analysis of Calculation Results

After applying an axial pressure of 8 MPa and a horizontal shear deformation of 200% to each bearing, by observing the maximum stress value and deformation of each bearing section in the finite element simulation, as shown in Figure 14. It is found that the maximum stress of the bearing always occurs in the fourth circular steel plate from the bottom to the top. Among the above five bearings, the maximum stress value appears in the 75% stiffness-reduced rubber isolation bearing, which is 213 MPa. No plastic strain occurred. For the rubber layers, the maximum strain occurred in the rubber layer in contact with the cover plate. The maximum deformation value also occurs in the 75% stiffness-reduced rubber isolation bearing, and the maximum stress values of the other bearings are shown in Table 4 below.

Table 4. Maximum stress and maximum displacement of each bearing under 8 MPa and 200% shear strain.

Inner Diameter/Outer Diameter	Maximum Stress (MPa)	Maximum Vertical Displacement (mm)
0% (SJ-1)	207	2.741
25%	109	3.372
50% (SJ-2)	164	3.925
75%	213	4.589
100%	166	5.309

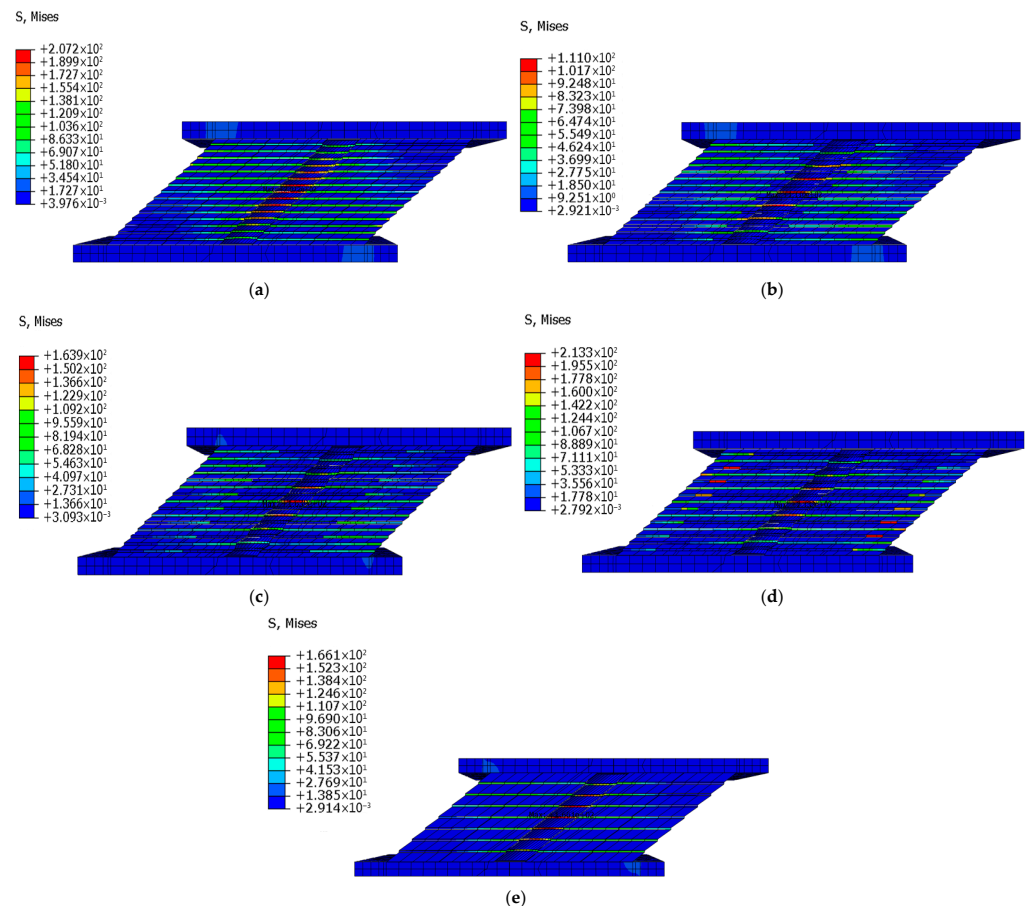


Figure 14. Stress contour plot of each bearing under 8 MPa and 200% shear strain. (a) Traditional laminated rubber bearing; (b) 25% stiffness-reduced rubber isolation bearing; (c) 50% stiffness-reduced rubber isolation bearing; (d) 75% stiffness-reduced rubber isolation bearing; (e) thick-layer rubber bearing.

Based on the finite element results, a comparative analysis was conducted with the theoretical derivation formulas and experimental data. The horizontal and vertical stiffness values of the bearing under a vertical load of 8 MPa were analyzed, and the calculation results are shown in Tables 4–6. The following conclusions are drawn:

- (1) Among all bearings under 8 MPa axial pressure and 200% shear strain, the maximum stress occurs in the 75% stiffness-reduced rubber isolation bearing, reaching 213 MPa, while the minimum maximum stress is observed in the 25% stiffness-reduced rubber isolation bearing, which is 109 MPa. Additionally, the thick-layer rubber at the hollow hole of the stiffness-reduced rubber isolation bearing tends to squeeze inward. The inferred reason is that during horizontal shear deformation, the internal thick-layer rubber begins to deform peripherally under compression; however, the outer laminated rubber and steel plate layers restrict its outward deformation, leading to inward squeezing toward the hollow hole. The maximum vertical displacement appears in the thick-layer rubber bearing, with a value of 5.309 mm, and the minimum vertical displacement occurs in the laminated rubber bearing, which is 2.741 mm. These simulation results are consistent with the experimental findings.
- (2) Under the same vertical load, the equivalent horizontal stiffness of the stiffness-reduced rubber isolation bearing is smaller than that of the laminated rubber bearing. Specifically, for every 25% increase in the inner diameter/outer diameter ratio of the stiffness-reduced rubber isolation bearing, the equivalent horizontal stiffness decreases by an average of 4.18%.

- (3) Under the same vertical load, the vertical stiffness of the stiffness-reduced rubber isolation bearing is smaller than that of the laminated rubber bearing. Specifically, for every 25% increase in the inner diameter/outer diameter ratio of the stiffness-reduced rubber isolation bearing, the vertical stiffness decreases by an average of 17.87%.
- (4) The maximum error between the theoretical value of the equivalent horizontal stiffness and the finite element simulation value is no more than 5.6%, and the maximum error with the experimental value is no more than 3.3%. The maximum error between the theoretical value of the vertical stiffness and the finite element simulation value is no more than 7.9%, and the maximum error with the experimental value is no more than 2.3%. These verify the reliability of the above theoretical model.

Table 5. Comparison of horizontal stiffness calculation results.

Inner Diameter /Outer Diameter	Analytical Value (kN·mm ^{−1})	FEM Simulation Value (kN·mm ^{−1})	Relative Change Rate of Simulation Values	Experimental Value (kN·mm ^{−1})
0% (SJ-1)	0.532	0.551	/	0.544
25%	0.521	0.529	4.16%	/
50% (SJ-2)	0.484	0.511	3.52%	0.500
75%	0.453	0.482	6.02%	/
100%	0.432	0.429	3.03%	/

(Note: Relative change rate of simulation values refers to the proportion of decrease or increase in the latter data set relative to the previous data set. The analytical values are derived from the horizontal stiffness series-parallel calculation model (Equations (13)–(16)) in Section 2; the FEM simulation values are obtained from the Abaqus finite element model; the experimental values are measured from the compression–shear tests of SJ-1 and SJ-2.).

Table 6. Comparison of vertical stiffness calculation results.

Inner Diameter /Outer Diameter	Analytical Value (kN·mm ^{−1})	FEM Simulation Value (kN·mm ^{−1})	Relative Change Rate of Simulation Values	Experimental Value (kN·mm ^{−1})
0% (SJ-1)	313.57	326.03	/	316.58
25%	256.15	265.87	22.63%	/
50% (SJ-2)	211.86	228.55	16.33%	203.22
75%	198.26	195.48	16.92%	/
100%	178.21	169.05	15.63%	/

(Note: The analytical values are derived from the vertical stiffness parallel calculation model (Equations (1)–(12)) in Section 2; the FEM simulation values are obtained from the Abaqus finite element model; the experimental values are measured from the compression-shear tests of SJ-1 and SJ-2.).

5. Analysis of Vibration Isolation Performance

The vertical vibration isolation mechanism of rubber isolation bearings has both similarities and significant differences compared with horizontal seismic isolation. The isolation principle of both is based on the stiffness regulation of bearings, which weakens the dynamic response of the superstructure by dissipating vertical seismic energy. However, bearings must carry the full vertical load of the building; therefore, their stiffness design must be based on meeting the vertical bearing capacity. Insufficient vertical stiffness may lead to instability or even overturning of the bearing, while excessive stiffness may cause resonance between the superstructure and ground motion, resulting in amplified vibration response. In such cases, the isolation bearing cannot achieve the expected vibration reduction effect, but will instead aggravate the seismic risk of the structure.

Under the condition of satisfying vertical bearing capacity, the superstructure is simplified as a single-degree-of-freedom system. Under sinusoidal excitation, the simplified model is shown in Figure 15. The motion differential equation of the isolated structure under vertical vibration is expressed as follows [27].

$$mv(t)'' + cv(t)' + kv(t) = P(t) \quad (20)$$

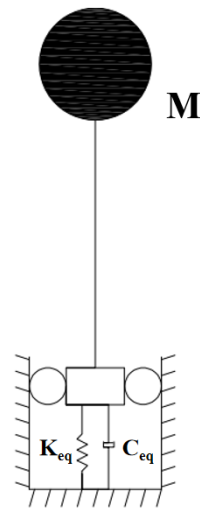


Figure 15. Vertical isolation model of the bearing.

In the formula, $v(t)''$, $v(t)'$, $v(t)$ are the vertical displacement, velocity and acceleration of the superstructure, respectively. Under harmonic excitation, $v_g(t)'' = v_{g0}(t)'' \sin \omega t$, where ω is the excitation frequency. The vibration transmissibility β is derived as:

$$\beta = \frac{v(t)''}{v_{g0}(t)''} = \sqrt{\frac{1 + (2\xi\gamma)^2}{(1 - \gamma^2)^2 + (2\xi\gamma)^2}} \quad (21)$$

In the formula, $\gamma = \frac{\omega}{\omega_n}$ is the frequency ratio between excitation frequency and natural frequency of the superstructure; $\omega_n = \sqrt{\frac{K_v}{m}}$ is the vertical natural frequency of the isolation layer composed of rubber bearings; and ξ is the vertical equivalent damping ratio, which can be regarded as the equivalent damping ratio of the bearing.

Consequently, a reduction in the vertical stiffness of the isolation layer leads to an increase in the frequency ratio γ , which in turn reduces the vibration transmissibility.

5.1. Effects of External Excitation and Damping Ratio on Vertical Vibration Isolation

It can be seen from the above formula that external excitation of environmental vibration directly affects the frequency ratio γ , thereby influencing the vertical vibration transmissibility.

As illustrated in Figure 16. When the external excitation frequency is very low ($\gamma \rightarrow 0$), the transmissibility approaches 1, meaning the vibration response of the superstructure is almost equal to the excitation, and effective isolation is difficult to achieve. When the excitation frequency is close to the natural frequency of the structure ($\gamma \approx 1$), the vertical dynamic response will be greatly amplified due to resonance, which must be avoided by adjusting the vertical stiffness of the isolation bearing. When the excitation frequency is sufficiently high ($\gamma > \sqrt{2}$), such as environmental vibration induced by trains, the response of the superstructure will be smaller than the excitation, which generally does not cause major safety problems but still affects daily comfort.

Figure 16 also indicates that when $\gamma \ll 1$, the damping ratio has little influence on vertical vibration transmissibility. When γ is close to 1, increasing the damping ratio can effectively reduce the resonant response. In this sense, damping adjustment is most effective near resonance. For high-frequency vertical vibrations, the effect of damping may change: reducing the vertical damping ratio may become more beneficial for lowering transmissibility. Therefore, the damping ratio in isolation design should be determined according to external excitation and structural characteristics, rather than simply increasing or decreasing.

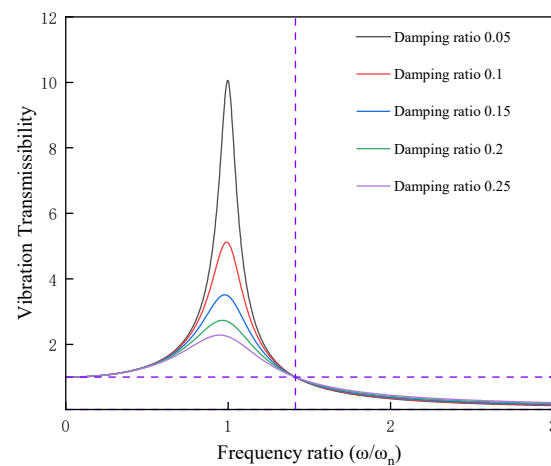


Figure 16. Vibration transmissibility under various damping ratios.

5.2. Simulation of an Engineering Case

A building above a metro station is analyzed. The building is 21.9 m in height, 32.23 m in width, with a height–width ratio of 0.68. ETABS 21 is used for structural modeling and analysis, where the three-dimensional model is shown in Figure 17 and the bearing layout is shown in Figure 18. Key bearing parameters are obtained from the Abaqus/CAE 2021 analyses in the previous section and are summarized in Tables 7 and 8.

Three isolation-layer configurations are investigated: (i) uncontrolled structure, (ii) laminated rubber bearing structure, and (iii) stiffness-reduced rubber isolation bearing structure. The input motions are measured metro-induced vertical vibration measurements of metro traffic, with two representative records selected. Each record was scaled to a peak acceleration of 100 mm/s^2 . Vertical excitation was applied, and the top-story vertical acceleration is computed for each configuration. The two input time histories are shown in Figure 19.

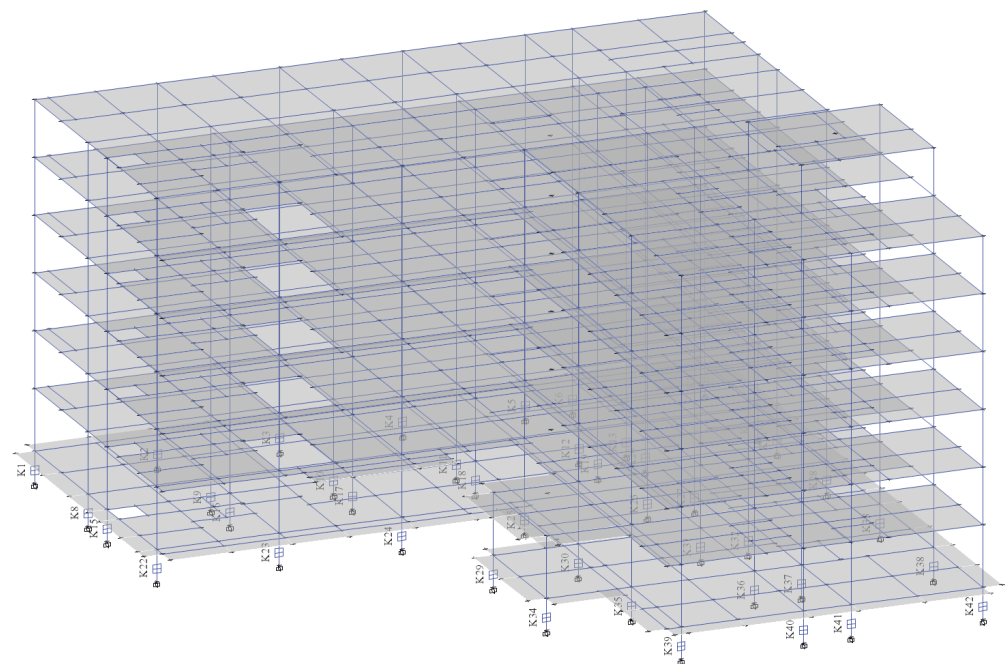


Figure 17. Three-dimensional modeling of the building structure.

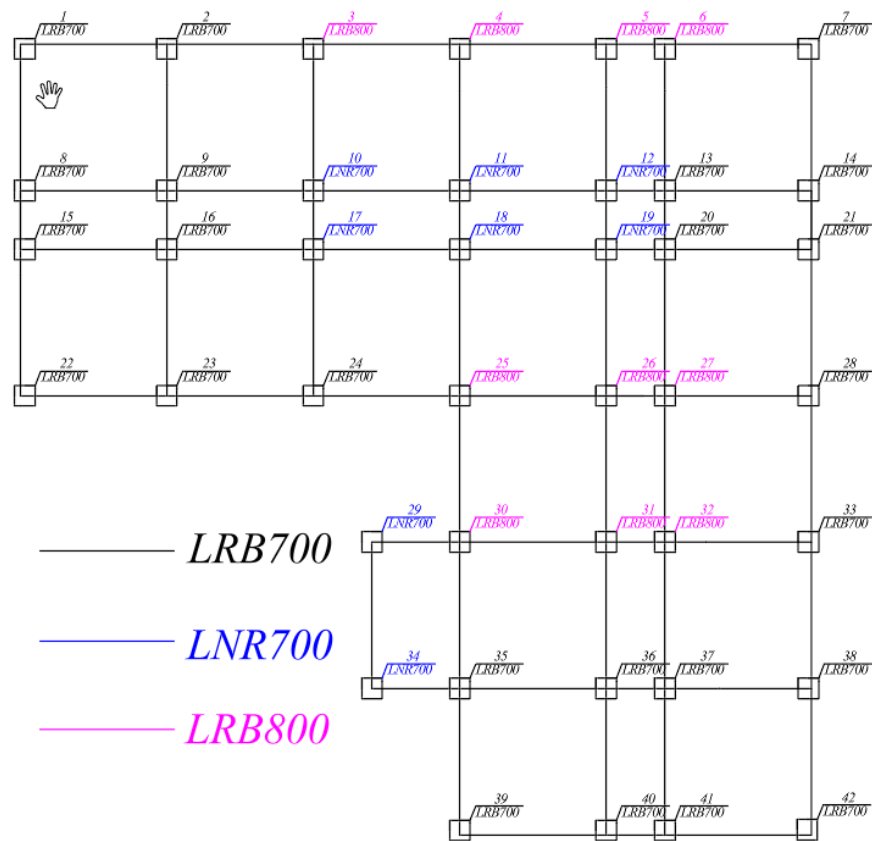


Figure 18. Detailed layout of bearings.

Table 7. Mechanical parameters of traditional laminated rubber bearing.

Item	LRB700-I	LRB800-I	LNR700-I
Quantity used	24	10	8
Vertical Stiffness (kN/mm)	2600	2900	2300
horizontal stiffness (kN/mm)	1.87	2.05	1.17
damping ratio (%)	24	23	/
Pre-yield stiffness (kN/mm)	15.2	17.4	/
Post-yield stiffness (kN/mm)	1.17	1.33	/
Yield force (kN)	90	106	/

Table 8. Mechanical parameters of stiffness-reduced rubber isolation bearing.

Item	LRB700-II	LRB800-II	LNR700-II
Quantity used	24	10	8
Vertical Stiffness (kN/mm)	2600	2900	2300
horizontal stiffness (kN/mm)	1.87	2.05	1.17
damping ratio (%)	24	23	/
Pre-yield stiffness (kN/mm)	15.2	17.4	/
Post-yield stiffness (kN/mm)	1.17	1.33	/
Yield force (kN)	90	106	/

As summarized in Figure 20 and Table 9, for the two measured metro-induced vertical input records with a peak acceleration of 100 mm/s², both the laminated rubber bearing structure and the stiffness-reduced rubber isolation bearing structure exhibit pronounced reductions in the mean absolute peak top-story vertical acceleration compared with the uncontrolled structure. Specifically, the mean absolute peak top-story vertical accelerations

decrease from 6.63 and 4.80 mm/s² (uncontrolled structure) to 0.73 and 0.97 mm/s² (laminated rubber bearing structure), and further to 0.53 and 0.70 mm/s² (stiffness-reduced rubber isolation bearing structure). Relative to the laminated rubber bearing structure, the stiffness-reduced rubber isolation bearing structure achieves an additional reduction of approximately 38.2% in the mean absolute peak top-story vertical acceleration. These results provide preliminary numerical evidence that reducing the vertical stiffness of the isolation layer can be beneficial for mitigating rail-induced vertical vibration in this representative high-rise building scenario.

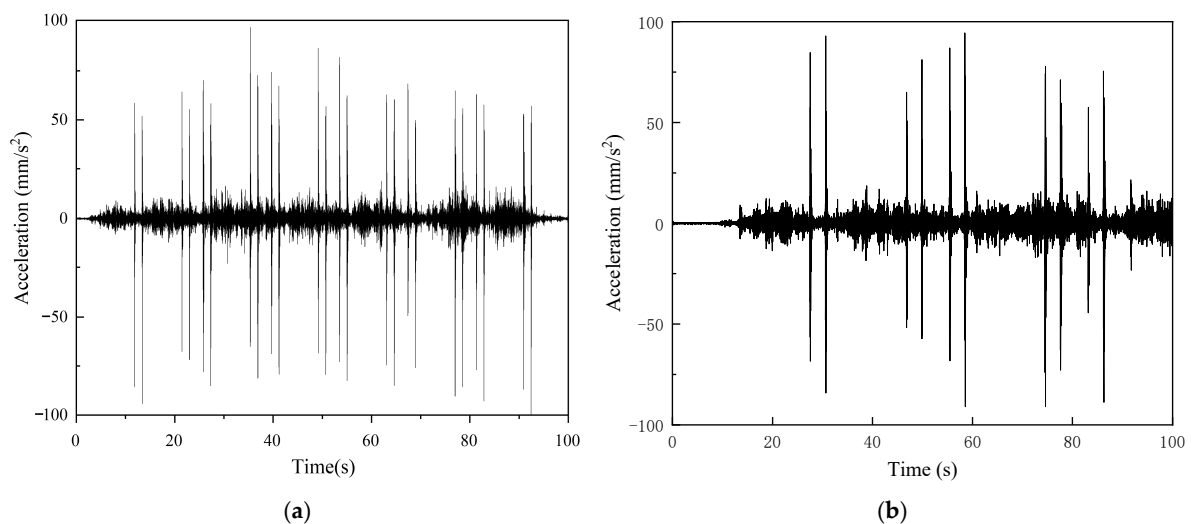


Figure 19. Measured time-history curves of metro traffic. (a) measured record 1. (b) measured record 2.

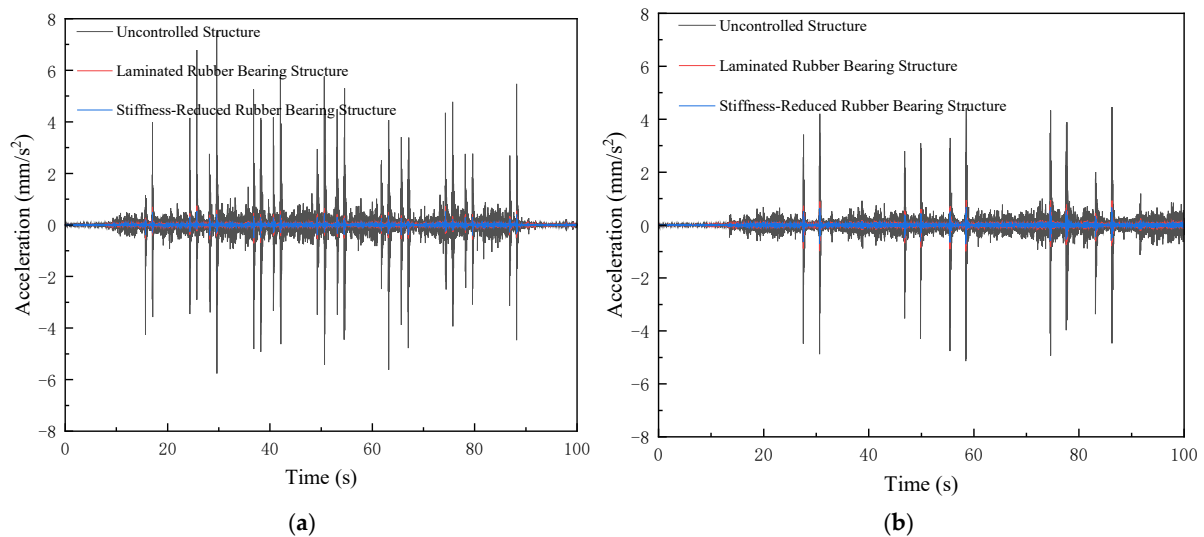


Figure 20. Top-story vertical acceleration time history. (a) measured record 1. (b) measured record 2.

Table 9. Vertical acceleration peak.

	Uncontrolled Structure		Laminated Rubber Bearing Structure		Stiffness-Reduced Rubber Isolation Bearing Structure	
	(a)	(b)	(a)	(b)	(a)	(b)
Positive peak	7.50	4.46	0.75	0.95	0.54	0.68
Negative peak	−5.76	−5.14	−0.71	−0.99	−0.51	0.72
Mean peak (abs.)	6.63	4.80	0.73	0.97	0.53	0.70

6. Conclusions

To address the limitations of traditional laminated rubber bearings in simultaneously achieving horizontal seismic isolation and vertical vibration mitigation, as well as the high cost and low practicality of combined three-dimensional isolation bearings and the insufficient load-bearing capacity of thick-layer rubber bearings, this study proposed a stiffness-reduced rubber isolation bearing. Its stiffness characteristics and mechanical behavior were investigated through theoretical derivation, experimental testing, and finite-element simulation. The main conclusions are summarized as follows.

- (1) Based on the deformation compatibility principle and the incompressibility of thick rubber, the traditional code-based formulas, which are not directly applicable to bearings with low shape factors, were modified. Analytical expressions were established for the vertical stiffness of the inner thick-rubber region, the outer laminated-rubber region, and the overall bearing. In addition, by considering the different shear deformation characteristics of the inner and outer rubber regions, a series-parallel analytical model for horizontal stiffness was derived. Comparison with FEM and test results showed that the maximum error of the analytical horizontal stiffness was within 5.6% relative to FEM and 3.3% relative to experiments, while the maximum error of the analytical vertical stiffness was within 7.9% relative to FEM and 2.3% relative to experiments. These results indicate that the proposed analytical model can reasonably predict the stiffness characteristics of the bearing and may serve as a useful basis for preliminary engineering design.
- (2) In terms of horizontal behavior, the experimental and numerical results showed that the proposed stiffness-reduced bearing maintained stable horizontal load-carrying capability over the tested displacement range. The agreement between FEM and experiment was satisfactory, indicating that the numerical model can reproduce the overall horizontal mechanical response of the bearing. Compared with the traditional laminated rubber bearing, the stiffness-reduced bearing exhibited lower sensitivity to shear deformation amplitude in the small-to-moderate displacement range, whereas under larger horizontal deformation its force increase became more gradual. This suggests that the proposed configuration can preserve horizontal isolation capability, while its large-deformation response characteristics remain different from those of the traditional laminated rubber bearing.
- (3) In terms of vertical behavior, the average vertical stiffness of the stiffness-reduced bearing was reduced by 35.8% compared with that of the traditional laminated rubber bearing. Quantitative hysteretic analysis further showed that the proposed bearing exhibited a softer vertical response together with distinct energy dissipation characteristics under cyclic compression. Although some stiffness degradation was observed under large deformation, the specimen maintained overall integrity and load-carrying capacity within the tested range. These results confirm the effectiveness of the proposed configuration in reducing vertical stiffness while retaining adequate compressive resistance. However, the actual vibration-isolation performance should be evaluated jointly with the frequency ratio and damping characteristics, rather than inferred from stiffness reduction alone.
- (4) When the outer diameter of the bearing was kept constant, increasing the diameter of the inner thick-rubber region led to a monotonic decrease in both horizontal and vertical stiffness. Specifically, for every 25% increase in the inner-diameter-to-outer-diameter ratio, the equivalent horizontal stiffness decreased by an average of 4.18%, while the vertical stiffness decreased by an average of 17.87%. This trend demonstrates that the proposed bearing provides a practical means of stiffness tailoring, whereby

the horizontal and vertical stiffness can be adjusted through geometric design to meet different performance requirements.

- (5) The FEM results showed that the thick-rubber region near the hollow core tended to deform inward during loading. This behavior is attributed to the fact that, under compression–shear deformation, the inner thick rubber tends to expand laterally, while the surrounding laminated rubber and steel shims constrain its outward deformation, resulting in inward squeezing toward the hollow region. This observation identifies the transition region near the hollow core as a critical zone for local deformation concentration. Therefore, in practical design, additional attention should be given to local deformation control and detailing in this region to reduce the risk of local damage at the rubber–steel interface.
- (6) Using ETABS 21 software, the metro vibration time-history curves were imported to analyze the top-story acceleration and displacement of three structural configurations: the uncontrolled structure, the structure isolated with traditional laminated rubber bearings, and the structure isolated with stiffness-reduced rubber bearings. The results indicate that, compared with the structure isolated with traditional laminated rubber bearings, the structure isolated with stiffness-reduced rubber bearings achieves an effective reduction of approximately 38.2% in the mean peak top-story vertical acceleration, thereby improving the structural comfort.
- (7) Overall, the stiffness-reduced rubber isolation bearing proposed in this paper forms a feasible configuration that achieves reduced vertical stiffness while maintaining overall stability by combining an inner thick-layer rubber region and an outer laminated rubber region in parallel. Compared with traditional thick-layer rubber bearings, this design mitigates the risk of instability that may arise from insufficient vertical load-bearing capacity. In contrast to more complex dual-control isolation systems, the proposed bearing features a relatively simple structure and lower manufacturing complexity. Based on a preliminary interpretation using transmissibility theory and a comparative analysis of dynamic responses in a representative engineering case study, the proposed bearing demonstrates the potential to simultaneously achieve vertical vibration control.

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