

# Finite Element Simulation-Based Investigation of Mechanical Properties in High-Damping Seismic Isolation Rubber Bearings

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**Abstract.** Seismic isolation bearing technology serves as a critical method for enhancing the seismic performance of building structures and possesses significant application value. This study focuses on Natural Rubber Bearings (NRB) and High-Damping Rubber Bearings (HDRB). Using the Abaqus finite element simulation platform, detailed numerical models of the bearings were developed, with the hyperelastic behavior of the rubber material characterized by the Mooney-Rivlin constitutive model. The accuracy of the models was validated through comparison with experimental data, showing a deviation in vertical stiffness of less than 1%. Building on this validation, the research comprehensively analyzes the hysteretic behavior of HDRB under shear loading, its force-displacement characteristics under compressive stress, and its dynamic response under seismic excitation. Results demonstrate that HDRB retains the advantageous elastic recovery capacity and durability inherent to NRB, while significantly improving energy dissipation efficiency through the incorporation of damping compounds, making it particularly suitable for high seismic demand scenarios. This study provides a theoretical foundation and numerical reference for the optimized design of isolation bearings. It also suggests directions for future research, including material enhancements and investigations into performance across varied environmental conditions.

**Keywords:** High-damping rubber isolators; finite element modeling; hysteresis performance; isolation technology.

## 1. Introduction

In recent years, with the frequent occurrence of global seismic disasters, the seismic performance of building structures has become a research focus in the engineering community. As an effective passive energy dissipation technology, seismic isolation bearings reduce structural damage by prolonging the natural vibration period and dissipating seismic energy[1]. They have been widely implemented in bridges, buildings, and critical infrastructure. Since the 1970s, various types of seismic isolation devices have been developed, which fall into two main categories: rubber-based systems, such as laminated rubber bearings and lead rubber bearings, and friction-based systems, represented by friction pendulum bearings. Today, these two types of isolation systems are well-established technical solutions for mitigating seismic risk in structural engineering [2].

Among rubber-based bearings, Natural Rubber Bearings (NRB) are widely used due to their excellent elastic recovery, stable mechanical properties, and high durability[3, 4]. High-Damping Rubber Bearings (HDRB) are manufactured by incorporating carbon black, resins, or other damping compounds into NRB [5, 6]. As a result, HDRB retains the advantages of NRB—such as structural simplicity—while exhibiting greater energy dissipation capacity and superior hysteretic performance [7, 8]. These characteristics make HDRB particularly suitable for applications in buildings and bridges where recentering capability is essential. However, the mechanical properties of HDRB can be influenced by environmental conditions such as low temperatures [9] and aging [10], which necessitates further investigation.

In recent years, high-fidelity digital modeling and simulation have significantly improved the reliability and efficiency of predicting complex mechanical behaviors, optimizing performance, and supporting seismic design of isolation bearings [11]. For example, in a study on seismic isolation of curved girder bridges, Xie Wenhui et al [12]. employed a simplified model based on bidirectional

nonlinear springs to simulate HDRB and demonstrated its effectiveness in reducing seismic response. However, such simplified models often fail to accurately capture the complex hyperelastic and viscoelastic behavior of rubber materials under large deformations, nor can they adequately represent the performance of bearings under combined compression-shear loading [13, 14].

To address these limitations, this study employs Abaqus-based finite element simulations to establish more accurate constitutive models and material characterizations. A systematic analysis of the mechanical properties of isolation bearings is conducted, with particular emphasis on the seismic performance of High-Damping Rubber Bearings. The research aims to provide more reliable modeling support and theoretical foundations for the optimization and engineering application of isolation technologies, while also suggesting directions for future investigations.

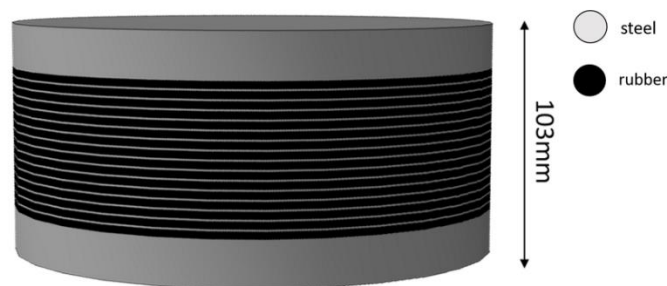
## 2. Research Methodology

This chapter employs Abaqus numerical software to develop a model of rubber bearings, aiming to investigate the force-displacement curves of high-damping rubber under static loading conditions and its hysteretic behavior under cyclic shear loading.

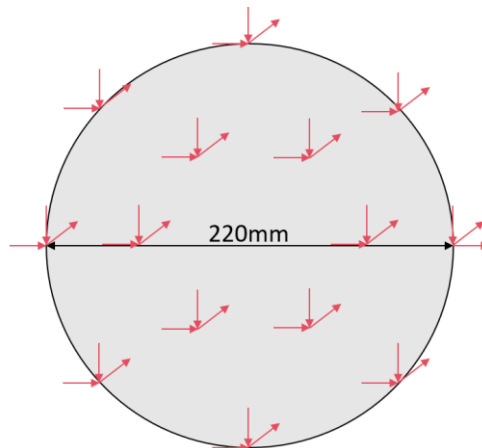
### 2.1. Research Methodology

The rubber bearing (Fig 1) consists of two 20 mm-thick end plates, fifteen 1 mm-thick steel shims, and sixteen 3 mm-thick rubber layers. The bearing has a diameter of 220 mm and a total height of 103 mm. The rubber material is composed of either natural rubber or high-damping rubber, while the intermediate steel shims and end plates are made of Q235 steel, with material parameters provided in Table 1.

In the finite element model, the rubber components were discretized using C3D8H elements (8-node linear hybrid brick elements), and the steel layers were modeled with C3D8R elements (8-node reduced integration elements). The entire model contains a total of 44,280 elements. The bottom of the bearing is fully fixed, with all three translational degrees of constraint applied to the solid elements (Fig 2).



**Fig 1.** rubber bearings



**Fig 2.** Fully constrained at the bottom.

**Table 1. Material Parameters**

	G	E	v	Density	C <sub>01</sub>	C <sub>10</sub>	β
Steel Plate	/	2.1E5	0.3	7.85E-9	/	/	/
Natural Rubber	0.392	/	/	1.1E-9	0.014	0.081	0.001
High-Damping Rubber	0.392	/	/	1.2E-9	0.0182	0.1053	0.008

## 2.2. Mooney-Rivlin Constitutive Model

The Mooney-Rivlin model is capable of simulating most mechanical behaviors of rubber; however, it exhibits significant errors when modeling rubber under multiaxial stress states or filled with carbon black. The strain energy function for the polynomial form of the hyperelastic model is given by:

$$W = \sum_{i,j=0}^N C_{ij}(I_1 - 3)^i(I_2 - 3)^j + \sum_{i=1}^N \frac{1}{D_i}(J - 1)^{2i} \quad (1)$$

where N is the order of the polynomial model,  $I_1$  and  $I_2$  are the first and second invariants of the deformation tensor, and J is the volume ratio. When  $D_i=0$ , the material is treated as fully incompressible. In practical simulations,  $D_i$  can be derived EQ.(2):

$$D_i = \frac{2}{E_\infty} \quad (2)$$

where  $E_\infty$  denotes the bulk modulus. Under the assumption of incompressibility ( $I_3=1$ ), the two-parameter Mooney-Rivlin model is obtained, expressed as(3):

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (3)$$

Here,  $C_{01}$  and  $C_{10}$  are the Rivlin coefficients. The ratio  $C_{01}/C_{10}$  typically ranges between 0.1 and 0.3. Assuming  $C_{01}=0.25C_{10}$ , the initial elastic modulus  $E_0$  and shear modulus G can be calculated as:

$$E_0 = 6(C_{01} + C_{10}) \quad (4)$$

$$G = 2(C_{01} + C_{10}) \quad (5)$$

## 2.3. Working Condition Settings

### 2.3.1. Vertical Static Loading

A downward displacement of 1 mm was applied to the rubber bearing, while the base was fully fixed. The analysis was performed using a Static, General step with the geometric nonlinearity option enabled.

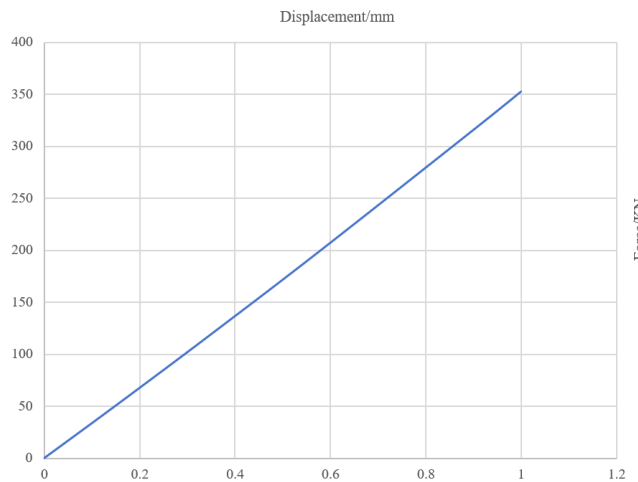
### 2.3.2. Vertical Static Loading

Under a constant vertical displacement of 1 mm, a horizontal sinusoidal displacement with an amplitude of 30 mm and a period of 1 s was applied. The simulation used a Dynamic, Implicit step with geometric nonlinearity activated.

### 3. Structural Analysis

#### 3.1. Validation of Model Accuracy

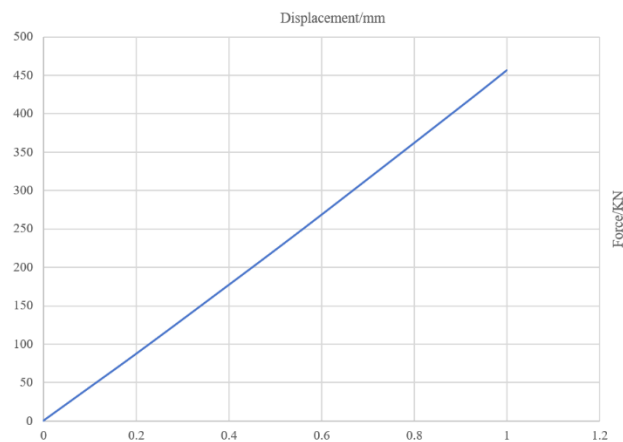
According to referenced literature, the designed vertical compression stiffness of the natural rubber isolation bearing is 359.556 kN/mm, while the experimental value is 337.17 kN/mm[4]. The force-displacement curve obtained from the simulation of the natural rubber bearing is shown in Figure 3. At a displacement of  $-0.1$  mm, the reaction force is approximately 33.6 kN. The simulated vertical stiffness is calculated to be approximately 336 kN/mm, which deviates from the experimental value by only 0.3% — well below the 1% threshold. This result confirms the high accuracy of the finite element model.



**Fig 3.** Vertical Force-Displacement Curve of Natural Rubber Bearing

#### 3.2. Comparative Analysis of Vertical Stiffness

A vertical static loading test was performed on the high-damping rubber isolation bearing. The simulation results are presented in Figure 4. At a displacement of 0.1 mm, the reaction force is approximately 43.4 kN, yielding a simulated vertical stiffness of approximately 434 kN/mm. These results indicate that for seismic isolation bearings with identical shear modulus  $G$ , the use of high-damping rubber leads to a higher vertical stiffness compared to natural rubber.

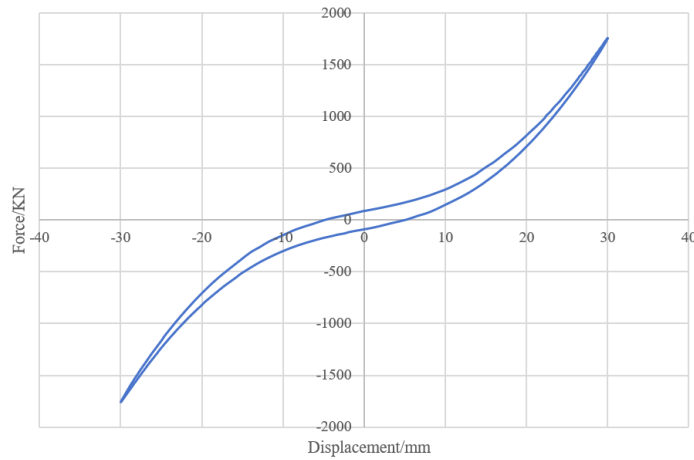


**Fig 4.** Vertical Force-Displacement Curve of High-Damping Rubber Bearing

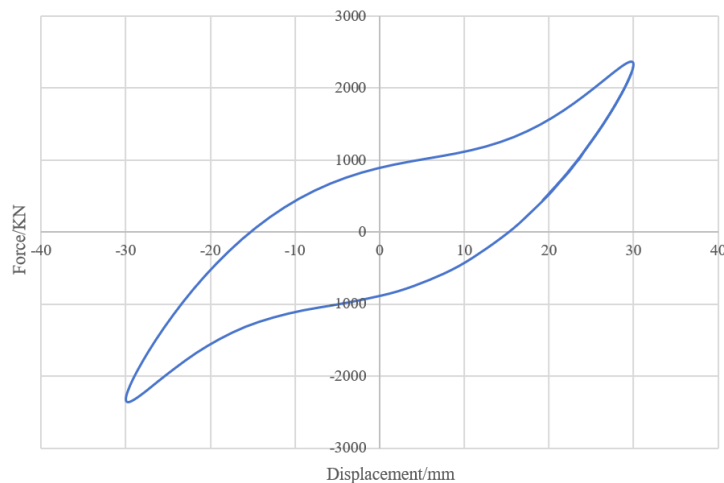
#### 3.3. Comparative Analysis of Hysteresis Curves

Cyclic horizontal loading was applied to both the natural rubber bearing and the high-damping rubber bearing under a constant vertical displacement of 1 mm. The resulting hysteresis curves are shown in Figures 5 and Figure 6.

The hysteresis loop of the natural rubber bearing (Figure 5) exhibits a narrow, spindle-like shape, indicating a damping ratio of 2.25%. In contrast, the hysteresis loop of the high-damping rubber bearing (Figure 6) is significantly fuller, reflecting a higher energy dissipation capacity and a damping ratio of 13.6%.



**Fig 5.** Horizontal Force-Displacement Curve of Natural Rubber Bearing



**Fig 6.** Horizontal Force-Displacement Curve of High-Damping Rubber Bearing

#### 4. Conclusions

This study systematically investigated the mechanical properties of Natural Rubber Bearings (NRB) and High-Damping Rubber Bearings (HDRB) using finite element simulations in Abaqus. The main conclusions are as follows:

- (1) The developed finite element model of NRB demonstrated high accuracy and reliability, with a deviation of less than 1% compared to experimental data. This validates the modeling approach and provides a credible numerical basis for subsequent studies on HDRB.
- (2) HDRB retained the excellent elastic recovery capability of NRB while exhibiting significantly improved hysteretic behavior and energy dissipation capacity. The equivalent damping ratio was substantially higher, indicating greater effectiveness in reducing structural seismic responses.
- (3) Simulation results confirmed the stable mechanical performance of HDRB under combined shear deformation and compressive stress, demonstrating its suitability for seismic isolation applications in high-intensity earthquake regions.
- (4) Future research will focus on optimizing the finite element model of HDRB using artificial intelligence techniques. Machine learning algorithms will be employed to analyze extensive

simulation and experimental data, automatically adjust model parameters, improve simulation efficiency and accuracy, and shorten the product development cycle.

(5) Further investigations will explore the synergistic mechanisms between HDRB and other energy dissipation devices, such as dampers and viscous dampers. Studies on the integrated seismic performance under complex loading conditions will be conducted to enhance the overall seismic safety of building structures.

### Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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