Design and performance study of a segmented intelligent isolation bearing

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ABSTRACT

In this paper, a novel type of isolator, named segmented intelligent isolation bearing (SIIB), is designed and manufactured, which can meet the requirements of seismic fortification under three seismic intensities, i.e. frequent intensity, basic intensity, and rare intensity. A theoretical formula for the output of the SIIB is established to provide a basis for the determination of the size of the SIIB. MRE and STMP used in SIIB were prepared, of which the changes of shear storage modulus and damping factor with the magnetic field under different strain are analyzed. The mechanical properties of the SIIB under small displacement, medium displacement, and large displacement are tested, respectively, and the hysteretic characteristics of force–displacement are analyzed. The dynamic mechanical model combining the rheological model, phenomenological model, and bilinear restoring force model is established to represent the behavior of the SIIB. The results showed that the theoretical results agree well with the experimental results, and the model can significantly reflect the dynamic characteristics of SIIB.

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1. Introduction

Vibration control of engineering structures is a new field of vibration resistance of engineering structures. Unlike traditional isolation methods, it resists external excitation by changing dynamic parameters such as stiffness, damping, and natural frequency of isolation structures. As well known, smart materials are kinds of designed materials whose properties are controllable with the application of external stimuli [1,2]. Therefore, numerous researchers have been or are now working on applying smart materials in vibration control; in particular, magnetorheological materials with various stiffness and damping under magnetic field are increasingly favored [3–5].

Among magnetorheological materials, MREs have better flexibility and a certain load carrying capacity, and there is no sealing problem in the presence of magnetorheological fluid (MRF). To date, many researchers have made many achievements theoretically and experimentally for MRE-based isolators. Siddaiah et al [6] presents an experimental investigation on the magnetorheological effect of a new magnetorheological elastomer–based adaptive bridge isolation bearing system. Experimental results demonstrated that the effective stiffness of the adaptive bridge bearings increases with increased applied magnetic field. Bastola et al [7] adopted a new method to develop such an isolator where both a magnetic field and a preload were applied simultaneously. Brancati et al [8] evaluated the possibility of adopting MRE to realize vibration isolators for lightweight structures. The experimental investigations showed a good magnetorheological effect for pads made of MRE. Wahab et al [9] focused on an experimental setup on a laminated magnetorheological elastomer (MRE) isolator under a steady state.
compression test. The experimental results show that the proposed laminated MRE isolator can effectively alter the compression stiffness up to 14.56%. Yu et al. [10] studied the temperature characteristics of a laminated MRE isolator and they found the maximum attenuations of the stiffness and the damping are 26.42% and 34.55%, respectively, with the temperature increasing from 30°C to 80°C. Przybylski et al. [11] outlined the design and test of a controllable multilayered MRE isolator based on a circular dipolar Halbach array, which is a set of magnets that generate a strong and uniform magnetic field. The isolator successfully altered the lateral stiffness and damping force by 81.13% and 148.72%, respectively.

One runs through a pool filled with a mixture of corn starch and water but falls into it when walking slowly or statically, which is a remarkable manifestation of shear thickening. When subjected to increasing shear stress, the viscosity of the shear thickening suspension rises sharply, and this behavior can be utilized in the design of damping and control devices [12–16]. Fischer et al. [17] investigated the integration of shear-thickening fluids (STFs) into composite structures with the aim of tuning part stiffness and damping capacity under dynamic deformation. The results showed that under dynamic bending load, the stiffness and damping can be changed simultaneously with the change of strain and frequency. Zhang et al. [18] presents a study of the rheological properties of STFs and its application as a damper. They also developed a mathematical model to investigate working mechanisms of STF-based devices. Zhou et al. [19] fabricated a novel prototype shear thickening fluid damper and investigated its dynamic characteristics experimentally. It was observed that the output force of shear thickening fluid damper sharply increased as soon as an external stimulus was imposed. Syarakos et al. [20] simulated the flow inside a fluid damper where a piston reciprocates sinusoidally inside an outer casing containing high-viscosity silicone oil. Despite these studies on shear thickening for vibration control, few reports have been reported on shear thickening for seismic isolation in civil engineering.

Yang et al. [21] further studied its field related stiffness/damping characteristics and carried out a series of experimental tests, and then, a new model that can reproduce the unique dynamic behavior of MRE isolator is proposed. Behrooz M et al. [22] studied the contribution of the magnetostrictive effect of MR material to stiffness in isolation and vibration reduction bearing.

It can be seen from the above literature review that the effectiveness of magnetorheological elastomers and shear thickening materials for vibration isolation has been confirmed. However, it is rare to combine magneto-rheological materials with shear-thickening materials for seismic isolation in engineering. The purpose of the research is to comprehensively utilize the stiffness function of MRE and the damping function of STFs. Therefore, based on the characteristics of the magnetorheological elastomer and shear thickening liquid, the shear-thickening magnetorheological plastomer (STMP) was prepared in this paper, and a new type of segmented intelligent isolation bearing (SIIB) was designed based on MRE and STMP. The paper is presented by the following orders. In section 2, we presented the structure model of SIIB and, with some details, the working principle. Section 3 prepared MRE and STMP used in the designed isolator. Section 4 analyzed feasibility of its magnetic field design. Section 5 tested the performance of the SIIB, and its dynamic mechanical model was built in section 6. Section 7 contains the conclusion.
2. Design of the SIIB

2.1. Structural design

Figure 1 shows structural design of SIIB. Compared with other intelligent isolators, the most innovative part of the SIIB is that the SIIB are designed in parallel with three parts, from top to bottom, rubber layer, MRE layer and arc-shell layer, representing medium displacements (34 mm), small displacements (6 mm), and large displacements (58 mm), respectively, which can meet the requirements of seismic fortification under three seismic intensities that are frequent intensity, basic intensity, and rare intensity, respectively.

As shown in Figure 1, the rubber layer is composed of an upper-plate, limit circular column, polytetrafluoroethy (PTFE) slider, supporting column, rubber, and annular steel plate. The overlapping design of the annular steel plate and rubber is to ensure not only the horizontal shear force of rubber but also the vertical bearing capacity of the SIIB. The shear force $F_1$ generated by the rubber layer is represented by the following equation:

$$ F_1 = K_1 \varepsilon = \frac{G_1 A_1}{T_1} \varepsilon $$  \hspace{1cm} (1)

where $K_1$ and $G_1$ are stiffness and shear modulus of rubber, respectively, $A_1$ and $T_1$ are cross-sectional area and thickness of rubber, respectively, and $\varepsilon$ is displacement of the SIIB.

The MRE layer is composed of a cylindrical baffle, limit circular column, PTFE slider, supporting column, coils, steel plate, and MRE. Following the shear force of rubber, the shear force of the MRE layer is shown as Equation (2).

$$ F_2 = K_2 \varepsilon = \frac{G_2 A_2}{T_2} \varepsilon $$  \hspace{1cm} (2)

where $K_1$ and $G_1$ are stiffness and shear modulus of MRE, respectively, and $A_1$ and $T_1$ are cross-sectional area and thickness of MRE, respectively. One writes [23,24], with the increase of magnetic field, the shear modulus of MRE increases, which can be calculated as
ΔG = \frac{36\phi\mu_f\mu_0\beta^2H_0^2}{\epsilon}\left(R_2^2\right)^3\zeta

where ΔG is the increased modulus of MRE in the presence of magnetic field, ϕ is the volume fraction of iron particles in MRE, \mu_f and \mu_0 are vacuum permeability and the relative permeability of the iron particles, respectively, and \mu_0 is the intensity of the applied magnetic field. According to references [23,24], taking \frac{d}{R} = 2.5, \beta = (\mu_p - \mu_f)/(\mu_p + 2\mu_f) \approx 1 and \zeta = \sum_{k=1}^{\infty} \frac{1}{k^3} \approx 1.202. Therefore, Equation (2) can be expressed as

\begin{equation}
F_2 = K_2\epsilon = \frac{G_2A_2}{T_2}\epsilon = \frac{(G_0 + 36\phi\mu_f\mu_0\beta^2H_0^2/\epsilon)^3\zeta}A_2\epsilon \end{equation}

where \G_0 is the shear modulus of MRE without external magnetic field.

The arc-shell layer mainly consists of upper and lower magnetic shells, upper and lower non-magnetic shells, STMP, lower plate, supporting column, coils, and sliding shaft. It can be seen from Figure 1 that STMP is filled between the arc shells and is sealed with rubber on both sides. For the arc-shell layer, STMP mainly performs energy dissipation, and the horizontal shearing force is mainly provided by the arc shell. The upper part of the shell is fixed on the middle plate, and the lower part is embedded in the lower plate through a sliding shaft. Therefore, the two ends of the arc shell can be regarded as the rigid joint and hinge point. The simplified model is shown in Figure 2.

The simplified model is a quadratic statically indeterminate structure. In the actual project, the SIIB moves horizontally in the X_2 direction, and the unknown force X_2 can be solved by the structural force method. The basic system and the unknown force are shown in Figure 2(b). The typical equation of force method is

\begin{equation}
\begin{cases}
\delta_{11}X_1 + \delta_{12}X_2 + \Delta_{1c} = 0 \\
\delta_{21}X_1 + \delta_{22}X_2 + \Delta_{2c} = 0
\end{cases}
\end{equation}

where
2.2. Working principle

In order to meet the seismic deformation requirements of the earthquake under different seismic intensity, the horizontal displacement in three stages of the SIIB is designed according to the Code for seismic design of buildings (GB 50011–2010) of National Standards of the People’s Republic of China. The performances of the SIIB can be summarized as the following three stages.

- **Stage 1 (X1 = 1)**: The moment borne by the SIIB is 1% of its bending moment capacity when the shear force is 1% of the SIIB’s shear capacity.
- **Stage 2 (X2 = 1)**: The moment borne by the SIIB is 10% of its bending moment capacity when the shear force is 10% of the SIIB’s shear capacity.
- **Stage 3 (X3 = 1)**: The moment borne by the SIIB is 100% of its bending moment capacity when the shear force is 100% of the SIIB’s shear capacity.

The calculations of the bending moment and shear force capacity of the SIIB are based on the design parameters given in Table 1.

### Table 1. Parameters of the SIIB.

| Layer                              | Values   | MRE layer   | Values   | Arc shell layer | Values |
|------------------------------------|----------|-------------|----------|----------------|--------|
| Thickness of rubber                | 8 mm     | Thickness of MRE | 4 mm | Thickness of single arc shell | 5 mm   |
| Thickness of annular steel plate   | 8 mm     | Thickness of steel plate | 18 mm | Radius of inner shell | 20 mm  |
| External diameter of rubber        | 320 mm   | Thickness of MRE | 50 mm | Thickness of STMP | 1.5 mm |
| Internal diameter of rubber        | 200 mm   | Turns of coils | 705 | Turns of coils | 2964   |
Standards of the People’s Republic of China. The elastic stiffness of the MRE layer is designed to be smaller than the elastic stiffness of the rubber layer according to Equations (1) and (2). In addition, one knows that the elastic stiffness of the arc shell is larger than those of MRE and rubber layer.

The basic working principle of the SIIB is as follows. Under the small displacement condition, due to the low stiffness of the MRE, the SIIB is mainly works in the MRE layer. One knows the MRE possess very different modulus than stiffness in the presence of magnetic field. By adjusting the current $I_1$ through the coils of MRE layer, the stiffness force of SIIB under a small displacement condition can be intelligently controlled. After reaching the limit displacement of the MRE layer, the rubber isolation layer continues to work, responsible for the load under large displacement conditions. Due to the parallel design, the shear forces between layers are equal. Therefore, after the rubber layer reaches the limit displacement, the arc shell layer enters the plastic phase to bear larger load. Simultaneously, more seismic energy will be dissipated since the damping of the STMP increases with the increase in the current $I_2$ through the coils of the arc shell layer.

In short, by controlling the current magnitude, the two excitation coils can be controlled to generate a controllable magnetic field, thereby controlling the stiffness and damping of the MRE and STMP and realizing the intelligent isolation control of the SIIB.

3. Prepartion and testing of MRE and STMP

3.1. Prepartion and testing of MRE

MRE is made by dispersing ferromagnetic particles (carbonyl iron powder, nickel powder, etc.) in the matrix (natural rubber, silicone rubber, etc.). The preparation process of MRE is mainly divided into four steps, i.e. matrix plasticizing, component mixing, pre-structuring, and curing. Polyether polyurethane glue was used as the matrix in the matrix plasticizing, and it is plasticized for about 8 minutes. Component mixing is a process of mixing ferromagnetic particles with various additives to obtain a mixed plastomer. In the pre-structuring process, a prefabricated mold, as shown in Figure 3, is used and heated to 80°C to soften the matrix, and the ferromagnetic particles are more easily chained in the direction of the magnetic field without pre-vulcanization. The pre-structuring lasted for 15 minutes under magnetic field of 1.2 T. The solidification molding is to vulcanize the rubber compound, and the rubber linear macromolecule is transformed into a threedimensional network structure to obtain MRE, which is presented in Figure 4. The vulcanization temperature and time were 140°C and 10 min, respectively.

In this paper, the dynamic performance of MRE is tested with a rheometer MCR51. Figure 5 shows curves of shear storage modulus and loss factor versus magnetic field under different strains. It can be seen from Figure 5(a) that the shear storage modulus of the MRE increases with the strengthening of the magnetic induction intensity, and the shear storage modulus of the MRE increases greatly when strain is small by 2.581 Mpa with the strain of 0.1%; however, this increases smaller when strain is large. This is due to the larger distance of ferromagnetic particles in MRE under large strain, the smaller magnetic force between particles and the weaker interaction between particles, resulting
Figure 3. Mold of MRE.

Figure 4. MRE sample.
in the decrease of the shear storage modulus. One observes that the loss factor of MRE increases with the increase of strain and decreases with the strengthen of magnetic field intensity from Figure 5(b).

3.2. Prepartion and testing of STMP

The STMP prepared in this paper is a new type of intelligent material, which is a multi-functional material with both magnetic sensitivity and rate sensitivity. The STMP mainly includes the preparation of matrix with rate-sensitive properties and mixing of ferromagnetic particles with the matrix. A certain amount of boric acid was weighed in the beaker and heated continuously in the vacuum drying box at 160°C for 2 hours to dehydrate to obtain pyroborbic acid; a certain mass fraction of dimethylsilicone oil, pyroborbic acid, and anhydrous ethanol was weighed, stirred by a high-speed mixer for 15 minutes, and then stirred uniformly and placed in the vacuum drying box at 210°C for 1 hour; and the mixture was taken out of the vacuum drying box, and then obtained matrix with rate-sensitive property after cooling. The carbonyl iron powder and crosslinking agent were dispersed into the matrix to obtain a uniform mixture. After homogeneous mixing, the plastics obtained by mixing were vulcanized in vacuum drying box at 140°C for 40 minutes. After cooling, the STMP were obtained. Figures 6 and 7 show the vacuum drying box used and STMP sample prepared.

Figure 8(a) shows the relationship between shear storage modulus of STMP and magnetic flux density under different strain. Under different strain conditions, the shear storage modulus of the STMP increases with the increase of magnetic induction intensity, reflecting the magnetic sensitivity, i.e. magnetorheological effect. The relationship between the damping factor and the angular frequency of STMP under different magnetic field is presented in Figure 8(b). The damping factor decreases with the increase of angular frequency, reflecting the rate sensitivity, i.e. shear thickening effect. At the same time, as the magnetic induction intensity increases, the variation of the damping factor with the angular frequency also decreases. It is because the magnetic particles inside the
STMP are magnetized under the action of a magnetic field, which results in the increase of the interaction force between ferromagnetic particles and the restriction of the movement between particles, thus making the deformation more difficult.

Figure 6. Vacuum drying box.

Figure 7. STMP sample.
Figure 8. Curves of (a) shear storage modulus versus magnetic flux density and (b) loss factor versus angular frequency.

Figure 9. Magnetic circuit design of SIIB. (a) Magnetic circuit diagram of SIIB. (b) Equivalent magnetic circuit.

4. Magnetic field analysis of the SIIB

As an important part of SIIB, the design of the magnetic circuit structure will directly affect the performance of isolation bearing. The design magnetic circuit of the SIIB is shown in. According to the relationship between magnetic potential and magnetic flux, the equivalent magnetic circuit can be obtained as shown in . In , is the magnetic potential generated by the excitation coils in the MRE layer; is the magnetic potential generated by the excitation coils in the arc shell layer; and are the magnetic flux and magnetoresistance of MRE; and are the magnetic flux and magnetoresistance of STMP; and are magnetic flux and magnetoresistance at position A, B, and C, respectively. According to Ohm’s law of magnetic circuit, the reluctance everywhere can be expressed by the following equation. The parameter is shown in.

\[
R_A = \frac{h_a}{\mu_0 \pi (\frac{h}{2})^2}, R_B = \frac{h_b}{\mu_0 \pi (\frac{h}{2})^2}, R_C = \frac{4h_c}{\mu_0 (\frac{h_c}{2}) H}, R_1 = \frac{32h_1}{\mu_1 \pi (\frac{h_1}{2}) H}, R_2 = \frac{4h_2}{\mu_2 (\frac{h_2}{2}) H} \tag{10}
\]
Table 2. Reluctance calculation results.

| Position | $R_a$ | $R_b$ | $R_c$ | $R_1$ | $R_2$ |
|----------|-------|-------|-------|-------|-------|
| Reluctance ($10^5$H$^{-1}$) | 633   | 101.3 | 562.8 | 3242  | 180   |

Table 3. Results of parameter identification.

| Parameters | $\gamma$ | $\beta$ | $\alpha$ | $\alpha_{ma}$ | $K_0$ | $C_0$ | $K_{ma}$ | $C_{ma}$ | $K_{m0}$ | $C_{m0}$ |
|------------|----------|---------|----------|---------------|-------|-------|----------|---------|----------|----------|
| 6 mm       | -0.75    | 0.25    | -0.3052  | 0.1576        | 0.8033| 0.9492| 0.3181   | 0.8003  | 0.134    | 0.4218   |
| 34 mm      | 4.197    | 3.198   | 10.62    | -4.435        | 3.455 | 0.6446| 2.87     | 3.583   | 0.752    | 0.5505   |

where $\mu_a$ and $\mu_b$ are the permeability of the PTFE slider, $H$ is the lateral length of sliding shaft, and $\mu_c$ is the permeability of air. $\mu_1$ and $\mu_2$ are the relative permeability of MRE and STMP, respectively. In the process of calculation, $\mu_1$ and $\mu_2$ are taken for 4, and $h_a = 1$, $l_a = 40$, $h_b = 1$, $l_b = 100$, $h_c = 1$, $l_c = 20$, $H = 180$, $h_1 = 1$, $l_1 = 50$, $h_2 = 1.5$, $l_2 = 50$, where each unit dimension is millimeter. Figure 9(a) Figure 9(b) The calculation results of the reluctance of each part are shown in Table 2. Tables 3 Figure 9(a) Figure 9(b)

Since it is difficult to measure the magnetic field intensity in each working gap by the experimental method after the assembly of the SIIB, the finite element method can be used to simulate the magnetic field in the design and improvement stage of the magnetic circuit structure. The finite element model is established by the general finite element software ANSYS. Because the magnetic circuit of the isolator is symmetrical, the three-dimensional electromagnetic field is transformed into two-dimensional plane for finite element analysis of electromagnetic field, and the element is plane 13. The corresponding magnetic circuit design parameters can be obtained. Due to the symmetry of the magnetic circuit in the SIIB, the three-dimensional electromagnetic field is transformed into a two-dimensional plane for finite element analysis of the electromagnetic field. The finite element model of the SIIB can be observed in Figure 10. In Figure 10(a), A1 is steel 45; A2 is STMP; A3 is air; A4 and A5 are excitation coil in arc shell layer and MRE layer; A6 is stainless steel; and A7 is MRE.

Setting $I_1$ and $I_2$ to 3A, the distribution of magnetic flux lines and magnetic field density of SIIB was obtained, as shown in Figure 11. As shown in Figure 10(b), the average magnetic induction intensities of MRE and STMP working parts are 0.4 T and 0.5 T, respectively, when $I_1$ and $I_2$ are 3A. Figure 12 shows the magnetic induction intensity of

![Figure 10](image_url)  
(a) Material partition  
(b) Finite element meshing  

**Figure 10.** Finite element model of isolation bearing. (a) Material partition. (b) Finite element meshing.
Figure 11. [(a) and (b)] Distribution of magnetic flux lines and magnetic field density (T) of SIIB under different currents.

Figure 12. Magnetic induction intensity of SIIB in different current. (a) Magnetic induction intensity of MRE. (b) Magnetic induction intensity of STMB.

MRE and STMP along X and Y axes, respectively, under different current conditions. It can be seen from Figure 12 that the magnetic induction intensity of the MRE part is uniformly distributed under different current conditions; the magnetic induction intensity of the middle part of the STMP is stable and does not change with the change of current. However, the magnetic induction intensity at both ends strengthens with the increase of current.

SIIB is manufactured on the premise that the size of the structure is continuously adjusted to ensure the normal operation of the magnetic circuit. The physical pictures of main parts and SIIB are presented in Figure 13.

5. Performance testing of the SIIB

This SIIB shear performance testing machine adopts a servo static and dynamic testing machine (SDS-300) provided by the National Mechanics Experimental Center of Hohai University. In order to facilitate the installation of SIIB in the test project, the vertical pressure of SIIB is provided by the reaction frame. In order to reduce the influence of
friction of reaction frame, the PTFE plate is added between SIIB and reaction frame, and silicone grease lubricant of the bridge is filled. The experimental device is shown in Figure 14. Two DC power sources are used to connect excitation coils of MRE layer and arc shell layer. During the experiment, the displacement amplitude of SIIB was controlled and the mechanical properties of SIIB were tested in cases of small displacement, medium displacement and large displacement with different current. The values of current $I_1$ and $I_2$ remain the same during the experiment.

Figure 13. Parts and assembly drawings of segmented anti-shock and isolation bearings.
5.1. **Small displacement analysis**

Under the condition of small displacement, the load–displacement curve of SIIB with different current and frequency is shown in Figure 15.(a–c) The area of force–displacement curve can indicate the energy dissipation capacity. As can be seen from Figure 15,(a–c) SIIB consumes more energy with the increase of current at different excitation frequencies. Figure 15(d) indicated clearly that the equivalent stiffness of SIIB increases linearly with the increase of applied current under small displacement condition, which is due to the increase of shear modulus of MRE under the action of applied current, resulting in the increase of transverse stiffness of MRE layer. However, the change of equivalent stiffness of the SIIB is not obvious under different excitation frequencies.
5.2. Medium displacement analysis

For long-period impulse ground motion, the moving speed is very slow, mainly relying on displacement to transmit seismic energy. Therefore, in the case of medium displacement and large displacement, we only test the output performance of SIIB with different currents at 0.1 Hz. Figure 16 reports curves of force versus displacement of SIIB in 1A, 2A and 3A, respectively. Obvious sudden change of stiffness occurs in Figure 16(a,b), in that the stiffness of SIIB changes from MRE layer to rubber layer when the small displacement limit is reached, while the stiffness of MRE is smaller when the current is small. This is why the force-displacement curve in Figure 16(c) is fairly smooth. In addition, the shear force of rubber layer is achieved by the deformation of rubber, which is independent of current. Therefore, the isolation bearing SIIB has the same shape of hysteresis curve and the same maximum force in the range of small displacement to medium displacement. When the rubber layer reaches the limit, the shear force can reach 115 kN.
Figure 16. (a)–(c) Load–displacement behaviors of SIIB under medium displacement.

5.3. Large displacement analysis

Figure 17 shows the load-displacement curves of SIIB under large displacement conditions with different currents. The observation of results from Figure 17 leads to a clear conclusion that in the case of large displacement conditions, the force-displacement hysteresis curves of SIIB are smooth and the stiffness varies uniformly, which is because the rubber layer supplements the force gap between the MRE layer and the output of the arc shell layer. Since the SIIB is a parallel design of the rubber layer, MRE layer, and arc shell layer, the arc shell layer has entered the plastic deformation stage when the rubber layer reaches the limit position of the medium displacement. Therefore, there is no sudden change in stiffness, and the force–displacement curve changes uniformly and continuously. Besides, with the increase of input current, the shear force of SIIB increases slightly, which is due to the increase of viscosity of STMP, contributing part of the output. The output of SIIB can be as high as 227.3 kN when the current is 3A.
6. Modeling and parameter identification

In order to accurately describe the dynamic mechanical properties of SIIB, its mathematical model was established. Rubber and MRE are used as viscoelastic materials under small and medium displacement conditions. Therefore, when the displacement is less than 34 mm, the rheological model and phenomenological model can be used to build the mechanical model of the SIIB. The dynamic mechanical model is shown in Figure 18. In Figure 18, $K_1$, $K_0$, and $C_0$ constitute a three-parameter standard solid-state model, which combines the characteristics of Kelvin model and Maxwell model and reflects the characteristics of polymer materials in isolation bearings; $K_{m1}$ and $C_{m1}$ represent the magneto-stiffness element and the magneto-damping element, respectively, which reflect the magneto-induced effect of SIIB, in which $K_{m1}$ and $C_{m1}$ are related to the magnitude of

Figure 17. (a)–(c) Load–displacement behaviors of AIIB under large displacement.
Figure 18. Dynamic mechanical model of SIIB under small and medium displacement.

current, and $K_{m1} = K_{m10} + K_{m1a}^2$, $C_{m1} = C_{m10} + C_{m1a}^2$, where $K_{m10}$ is the stiffness without applied current and $K_{m1a}$ is the change of stiffness when unit current was applied. Likewise, $C_{m10}$ is the damping without applied current and $C_{m1a}$ is the change of the damping when unit current was applied; Bonc–Wen model reflects the hysteretic characteristics of SIIB. $x$ is the relative displacement between the upper and lower cover plates.

Under the condition of large displacement, the plate and shell have obvious plastic and elastic stages, so the bilinear restoring force model is used for mathematical model. To sum up, the mathematical model expression of SIIB is as follows:

$$F(x) = \begin{cases} 
\text{sgn}(x) \times ((-K_{m2}(x \text{sgn}(\dot{x}) - x_3)) + K_{m3}(x_3 - D - x_2) + F_0) - x_3 \leq x \text{sgn}\dot{x} \leq D - x_3 \\
-x \text{sgn}(x) \times (K_{m4}(x \text{sgn}(\dot{x}) + x_2) - F_0)D - x_3 \leq x \text{sgn}\dot{x} \leq -x_2 \\
\alpha z + K_{m0}x + C_{m0}\dot{x} + K_{m1}\dot{x} + C_{m1}x - x_2 \leq x \leq x_2 \\
\text{sgn}(x) \times (F_0 + K_{m4}(x \text{sgn}(\dot{x}) - x_2))x_2 \leq x \text{sgn}\dot{x} \leq x_3 
\end{cases}$$

(11)

where $x_2$ is the limit of medium displacement (34 mm) and $x_3$ is the limit of large displacement (58 mm). When the absolute value of $x$ is less than $x_2$, $z$ is nonlinear restoring force, there is $\dot{z} = A\dot{x} - (y \text{sgn}(xz) + \beta)|z|^n\dot{x}$, where the parameters $A$, $y$, $\beta$, and $n$ are related to the shape of hysteresis curve, and take $A = 1$, $n = 1$ for convenience of calculation. $\alpha=a_{m0} + a_{ma}\dot{x}^2$ represents hysteretic characteristics of the SIIB. In the case of large displacement, the output of the arc shell occupies the main part, and the STMP is mainly responsible for energy dissipation. Therefore, the current has little effect on the damping force under large displacement. There are $K_{m2} = K_{m20} + K_{m2a}$, $K_{m3} = K_{m30} + K_{m3a}$, and $K_{m4} = K_{m40} + K_{m4a}$, where $K_{m20}$, $K_{m30}$, and $K_{m40}$ are stiffness without applied current; $K_{m2a}$, $K_{m3a}$, and $K_{m4a}$ are stiffness changes when current was applied; $K_{m2}$ reflects elastic stiffness of arc shell; $K_{m3}$ reflects overall stiffness of SIIB and $K_{m4}$ reflects plastic stiffness of arc shell. $F_0$ is the maximum output of rubber layer and $D$ is the yield displacement of arc shell. Figure 19 is a comparison between the experimental results and the theory of small displacement, medium displacement and large displacement at 0.1 Hz. It can be seen from Figure 19 that the established dynamic model can well
describe the force-displacement hysteresis curve of the SIIB. The least squares method [25] is used to determine each parameter in the proposed model and Table 4 give the identification results of each parameter.

7. Conclusion

In the paper, a new type isolator, i.e. SIIB, was developed based on the actual engineering problems, which can meet the seismic fortification requirements under three seismic intensities of multiple intensity, basic intensity, and rare intensity. Dynamic mechanical performance tests were carried out, and a mechanical model suitable for the SIIB was established. Certain meaningful conclusion can be summarized. The SIIB has the characteristics of controlling stiffness and damping and can achieve the effect of isolation and

Table 4. Results of parameter identification.

| Parameters | $k_{m20}$ | $k_{m2a}$ | $k_{m30}$ | $k_{m3a}$ | $k_{m40}$ | $k_{m4a}$ |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 58 mm      | 52.921    | 1.89      | 0.954     | 0.636     | 0.495     | 1.512     |
vibration reduction under different displacement. The maximum force can reach 227.3 kN. In addition, the proposed mechanical model agrees well with experimental results, which proves that it can describe the behavior of the SIIB.

The shearing thickening magnetic rheuroid plastic body is a new type of intelligent material, the working principle is complex, there is not much research on it, and there is no available theoretical model; when a large current is passed into the excitation coil during operation, a higher temperature is produced, and the temperature has a great influence on the dynamic properties of the magnetic rheumatic elastomer and shear thickening magnetic rheumatic plastic, so in later studies, it is necessary to consider the effect of temperature on the dynamic performance of the shock-absorbing mount.

In the future work, we will propose a vibration control system using the SIIB for civil structural. Due to the presence of hysteresis, a force tracking control method of the SIIB based on the inverse Bouc–Wen model given by Equation (11) will be adopted to precisely control the SIIB.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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