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BASE ISOLATOR WITH VARIABLE STIFFNESS AND DAMPING: DESIGN, EXPERIMENTAL TESTING AND MODELLING

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ABSTRACT

Vulnerability in base isolation system of civil structures originated from passive nature of the rubber material raises the urgency of developing smart base isolation system with adaptive and controllable properties, i.e. variable stiffness and damping. To address this issue, this paper presents comprehensive investigations on a novel adaptive base isolator, including design, experimental testing and dynamic modelling. Smart rubber with field-dependent modulus and damping property is incorporated into the laminated base isolator design. Experimental testing is conducted utilising an advanced shake table facility to examine its performance under cycling loading. Results show that the adaptive base isolator possesses a stiffness increase of more than 16 times and damping ratio between 10% and 27%. With such features, it can be developed into a smart base isolation system to protect civil structures against any type of earthquake. Results also show that this device has high nonlinear hysteresis, i.e. shear stiffening behaviour. A mechanical model is thus required to describe the complex behaviour of new adaptive base isolator. A new strain stiffening element is proposed for this purpose. Comparison between the model and the experimental data verifies the fidelity and effectiveness of the proposed model.

KEYWORDS

Base isolation, variable stiffness, magnetorheological elastomer, strain stiffening, mechanical model.

INTRODUCTION

Traditional rubber-made base isolators form the critical component in the base isolation systems for civil structures. In recently days, they have been challenged by vulnerability during unexpected earthquake (Li et al. 2012). Main reason for this is that base isolator made of rubbers possesses fixed stiffness property and can only work well for a narrow band of frequency range. Out of this range the isolator is likely leading to failure of the system and thus damage to the building and contents. To solve this problem, a quest has been recognised to develop base isolator with adaptive stiffness (Li et al. 2012). As such, the base isolation system can work adaptively to protect the building from seismic vibrations.

There have been efforts from researchers in pursuing variable stiffness mechanism in base isolation system. For example, Nagarajaiah and Sahasrabudhe (2006) proposed a semi-active independently variable stiffness mechanism to be used in seismic response control of smart sliding isolated buildings. Beside this, another way to develop variable stiffness base isolator is to incorporate smart rubber material into the design of base isolator. Capable of changing its modulus and damping property, magnetorheological (MR) elastomer is a natural candidate for this purpose. MR elastomer is a composite material with magnetic-sensitive particles suspended or arranged within non-magnetic elastomer matrix (Li et al. 2013a). With presence of magnetic field, MR effect offers the material with field-dependent material property, i.e. controllable modulus and damping. This is a result from chain structure of iron particles under action of magnetic field. While in absence of magnetic field, the material reclaims its original property. Physical status of the material can be tuned between soft elastomer and semi-solid, depending on the external magnetic field applied to the material (Li et al. 2013b).

In this paper, design of variable stiffness and damping (VSD) base isolator with MR elastomer is investigated. A base isolator prototype inheriting classic laminated elastomer and steel structure has been designed. Experimental testing is conducted to investigate its behavior under cycling motions. To characterize the behavior of the VSD base isolator, a phenomenological model is established for its future application in control design. Comparison between the numerical modeling and experimental testing showed that the proposed model can well capture the dynamics of the variable stiffness and damping base isolator.

DESIGN OF THE VARIABLE STIFFNESS AND DAMPING BASE ISOLATOR

To serve in base isolation system of civil structure, base isolator is required to have large vertical loading capacity and low lateral stiffness. Large vertical loading capacity maintains the stability of the base isolation system to support building structures. While low lateral stiffness allows flexibility during earthquakes thus the dangerous motion can be decoupled to safeguard the building. These two objectives can be achieved through laminated design in which rubber and steel layers are arranged alternatively (Naeim and Kelly 1999).

Fundamental of Design

Performances of the VSD base isolator can be achieved by evaluating the stiffness (refers to static stiffness here and later in this paper) of the devices. The lateral stiffness of the VSD base isolator can be expressed as:

$$\boldsymbol{K_s = \frac{GA}{nh}} \tag{1}$$

Where G is the shear modulus of MR elastomer, A and h are the cross-section area and the thickness of a single rubber layer, respectively; n is the number of MR elastomer layers in the device.
The vertical loading capacity of the device can be estimated by:

$$\boldsymbol{W = A'GS\gamma_w} \tag{2}$$

Where A' is the overlap of the bearing top and bottom that is the effective bearing area, figure 1. G is the shear modulus of the rubber; S is the shape factor. γ_w is the allowable shear strain due to weight.

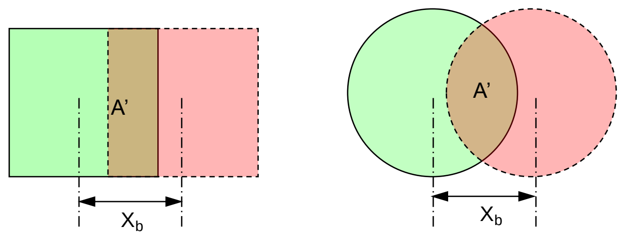


Figure 1. Effective area of the base isolator under displacement

The shape factor is defined as S=(load area)/(force-free area), which is a non-dimensional measure of the aspect ratio of the single layer of the elastomer. For example, in a square pad of width a and with a single-layer thickness t,

$$\boldsymbol{s = \frac{a}{4t}} \tag{3}$$

For a circular pad of diameter Φ and thickness of t,

$$s = \frac{\Phi}{4t} \quad (4)$$

Material Property

Soft MR elastomers are used in this design. Basic compositions in the MR elastomer are silicone rubber (Selleys Pty. LTD), silicone oil, type 378364 (Sigma-Aldrich Pty. LTD) and carbonyl iron particles, type C3518 (Sigma-Aldrich Pty. LTD). The density of silicone rubber, silicone oil and carbonyl iron particles are 1.04 g/cm3, 0.96 g/ml and 7.86 g/cm3, respectively. The iron particles' diameter is between 3 µm and 5 µm. To produce MR elastomer, firstly, 15 g silicone oil was introduced to 15 g silicone rubber in a beaker and stirred by a stirrer for 15 minutes. 70 g carbonyl iron particles were then added to the mixture and stirred for another 30 minutes till all the components were evenly dispersed. A vacuum chamber was used to eliminate the air bubbles for 1 hour and then the mixture was placed in a mold with 1 mm thickness. During the curing, no magnetic field was applied. After curing for 5 days, the isotropic soft MREs were taken out of the mold and ready to use. The sample's volume fraction is 22.9%.

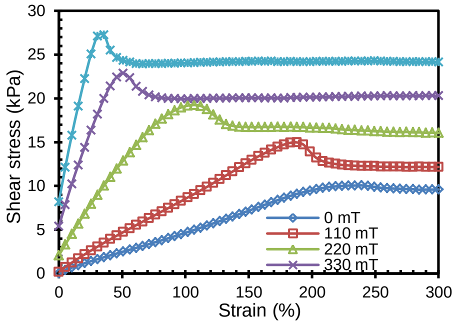
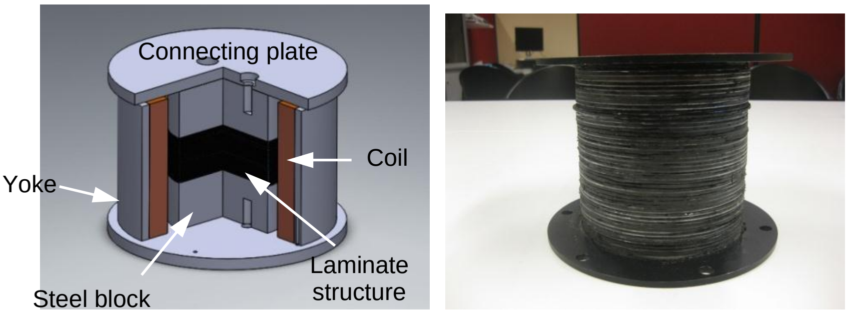


Figure 2. Shear stress versus strain curve in steady state test

Figure 2 shows the stress-strain relationships of the soft MR elastomer when several magnetic fluxdensities are applied. The shear modulus of the new MR elastomer clearly exhibits an increasing trend with applied magnetic field. It is observed that the shear yield stress of the MRE increases from 9.95 kPa to 27.09 kPa when the field density increases from 0 to 440 mT, indicating a great MR effect of 13 times increase in shear modulus

Structure of the VSD Base Isolator



(a) (b)
Figure 3. Laminated VSD base isolator: (a) cross section view of MR elastomer base isolator; and (b) laminated MR elastomer and steel structure

The VSD base isolator consists of several important components, i.e. laminated MR elastomer and steel core, electromagnetic coil, cylindrical steel yoke and connecting plates at each side, figure 3. Electromagnetic coil with resistance of 42.3 Ω and 2900 turns is to energize the MR elastomer material in the core with sufficient magnetic field. Top and bottom plates are to connect the device with ground and superstructure. Under horizontal loadings, the laminated core deforms with the limit of gap between itself and the yoke. The isolator contains 25 layers of MR elastomer sheets with thickness of 1mm and diameter of 120 mm.

EXPERIMENTAL TESTING

Comprehensive experimental testing was conducted to evaluate the performance of the VSD base isolator utilizing the experimental set-up, shown in figure 4. In experimental set-up, shake table was used to provide horizontal loadings to the isolator either in the quasi-static mode or in dynamic mode. A load cell was used to measure the lateral load applied to the isolators. A DC power supply (provides DC current to energize the magnetic coil. For cycling tests, various harmonic inputs under displacement control were chosen to load the VSD base isolator. Three amplitudes (2 mm, 4 mm and 8mm) were selected for the tests under various loading frequencies (0.1 Hz, 1 Hz, 2 Hz and 4Hz). For each loading case, four currents (0.0 A, 1.0 A, 2.0 A and 3.0 A) were applied to examine performance of the device under different magnetic fields.

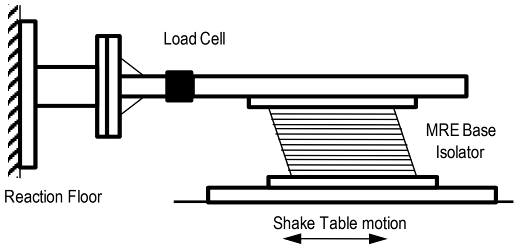


Figure 4. Sketch map of the experimental set-up

Figure 5 shows the force-displacement loops of the VSD base isolator at various sinusoidal loadings of three amplitudes at frequency of 2.0 Hz. For each loading case, force increases with applied currents can be clearly observed. The measured force also increases with increase of the loading amplitude naturally. The stiffness of the VSD base isolator, representing by the slope of the hysteresis loops, has significant increase when currents were applied. Moreover, it is noted that the damping of the VSD isolator, representing by the enclosed areas of the loops, increases when the applied current increases.

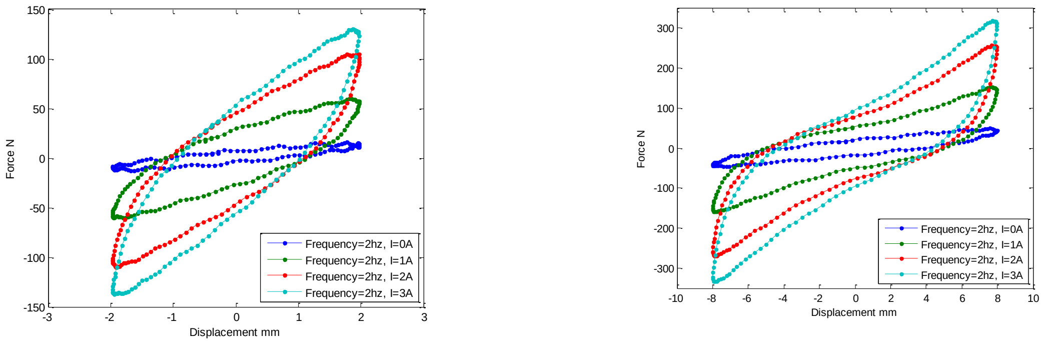


Figure 5. Force-displacement relationships of the VSD base isolator at cycling testing with frequency of 2.0 Hz: (a) 2mm and (b) 8mm

It is also clear that the new MRE base isolator exhibits a stiffening effect when the shear strain becomes large, i.e. strain stiffening. The strain stiffening effect is more obvious for low loading frequency cases, i.e. 0.1Hz. It is also observed that the strain stiffening effect becomes more obvious at high applied current. For the low amplitudes, e.g. at amplitude of 2 mm, the strain stiffening is hardly observed.

Table 1 lists the effective stiffness of the VSD base isolator under various loading conditions. Stiffness of the VSD isolator increases dramatically along applied current. The stiffness increase can be tuned from 531% to 1630% for different loading amplitudes when applying currents. The maximum effective stiffness is 66 kN/m and the maximum increase of the effective stiffness (i.e. when increasing current from 0.0 A to 3.0 A) is 1630% from quasi-static tests. Table 2 lists the normalized equivalent damping coefficients from experimental data. Damping of the VSD isolator decreases along applied current, ranging from 15% to 28%. It is clear that the proposed device possess variable stiffness and damping property when different magnetic fields are applied.

Table 1. Effective stiffness [kN/m] of the MRE base isolator under various loading conditions

Effective stiffness (kN/m)	Δ=2 mm				Δ=4 mm				Δ=8 mm			
	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz
0.0A	3.64	4.96	5.80	6.88	3.63	4.69	5.33	6.43	3.72	4.62	5.24	6.23
1.0 A	25.58	27.13	27.52	27.75	19.35	20.72	20.87	21.07	15.99	17.72	17.81	18.12
2.0A	45.73	52.22	50.64	50.47	33.73	38.15	37.53	37.25	27.32	31.44	31.15	31.30
3.0A	62.98	66.13	65.02	65.26	46.64	48.74	47.88	47.72	36.41	39.31	39.29	39.30
Increase (0A-3A)	1630%	1234 %	1022%	848%	1186%	939%	798%	642%	878%	751%	650%	531%

Table 2. Damping ratio of the MRE base isolator under various loading conditions

Damping Ratio (kN s/m)	Δ=2 mm				Δ=4 mm				Δ=8 mm			
	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz	0.1 Hz	1.0 Hz	2.0 Hz	4.0 Hz
0.0 A	0.151	0.220	0.243	0.258	0.145	0.223	0.249	0.266	0.127	0.205	0.232	0.254
1.0 A	0.214	0.240	0.250	0.276	0.202	0.228	0.244	0.277	0.183	0.204	0.222	0.254
2.0 A	0.207	0.218	0.233	0.252	0.193	0.206	0.220	0.246	0.177	0.188	0.202	0.226
3.0 A	0.183	0.201	0.212	0.229	0.175	0.189	0.201	0.223	0.173	0.179	0.188	0.210

PHENOMENOGOLICAL MODELLING

To characterise the behaviour of the VSD base isolator, a mechanical model (Li and Li 2014) was established as shown in figure 6. The mathematical expression of this model is:

$$\boldsymbol{F = k_1 y + \alpha z^3} \tag{5}$$

$$\boldsymbol{k_1 y = k_0(x - y) + c_0(\dot{x} - \dot{y})} \tag{6}$$

$$\boldsymbol{\alpha z^3 = c_1(\dot{x} - \dot{z})} \tag{7}$$

Where, c_0 and c_1 are the viscous damping coefficients, k_0 and k_1 are the coefficients for elastic stiffness and α is the model parameter to characterize the strain-stiffening behaviour in VSD base isolator. The dashpot element c_1 is to introduce variable transition to strain-stiffening behavior for the MRE base isolator.

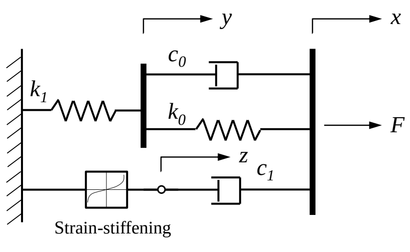
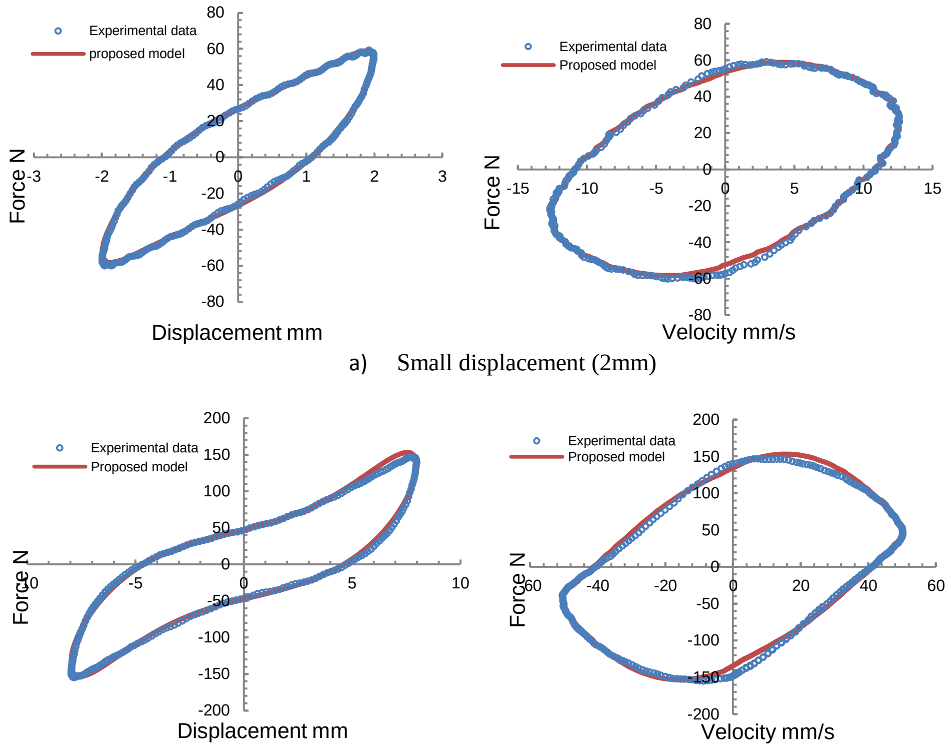


Figure 6. Strain-stiffening models for VSD base isolator

Figure 7 shows the comparison between the experimental data and the proposed model. Both force-displacement and force-velocity relationships are presented in the figure. The results show that the proposed model can well describe the behavior of the adaptive base isolator for both force-displacement and force-velocity loops. It should also be noted that the proposed model can also reproduce the stiffness stiffening behavior of the base isolator when the shear displacement is over the critical shear strain.



a) Small displacement (2mm)

b) Large displacement (8mm)

Figure 7. Comparison between the experimental data and model prediction

CONCLUSIONS

This paper presents the design, testing and modelling of a base isolator with variable stiffness and damping to be used for base isolation system of civil structures. The novel VSD base isolator utilises MR elastomer to replace traditional rubber in the base isolator design. A magnetic coil is used to provide magnetic field to energise the MR elastomer. Experimental testing shows that the VSD base isolator exhibits a maximum stiffness increase of over 16 times while the damping ratio is around 15% to 28%. Finally, a new model was developed to describe the complex behaviour of the device and the model performs well.

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