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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF A NOVEL HYBRID SEISMIC ISOLATION SYSTEM

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Abstract

This study explores a novel hybrid seismic isolation system that combines a steel-reinforced elastomeric isolator with S-shaped steel dampers (SSSDs). The integration of SSSDs significantly enhances the system's damping properties, offering a practical alternative to conventional solutions like high-damping or lead-plug elastomeric isolators, with added benefits in terms of manufacturing cost, durability, environmental impact, and deformation capacity. The paper first introduces the experimental characterization of the elastomeric isolator with and without SSSDs, assessed through cyclic shear tests. Following this, it presents a simplified finite element model to support the application of the hybrid isolation system in structural contexts, with calibration and validation grounded in the experimental data. Experimental findings indicate that this hybrid isolation system, with its enhanced damping and practical advantages, holds considerable promise for advancing resilient and cost-effective seismic protection in modern structural engineering. Instead, numerical results demonstrate that the simplified model effectively captures the lateral behavior of the hybrid system, highlighting its potential for efficient use in broader numerical structural applications.

Keywords: S-shaped steel damper; Elastomeric isolator; Hybrid seismic isolation system; Experimental investigation; Finite element analysis.

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1 INTRODUCTION

Base isolation has become an effective strategy to reduce structural vulnerability and provides a highly reliable and efficient retrofitting solution. Among the various isolation technologies, steel reinforced elastomeric isolator (SREI) is the method of seismic isolation that is commonly used in practical engineering [1]. In regions with high seismic risk, the hysteretic steel dampers have widely been applied in both bridge and building structures. Recently, the design approaches integrate these energy dissipation steel dampers with commercial rubber bearings [2–4], forming hybrid isolation systems that significantly enhance energy dissipation capacity while effectively controlling maximum displacement demands. The field of passive energy dissipation devices in seismic engineering has experienced significant advancements in seismic engineering applications [5,6]. The combination of hysteresis steel dampers with seismic isolators has been introduced as an alternative to traditional high-damping isolators or lead rubber isolators [7,8], demonstrating improved seismic performance characteristics.

The propose of U-shaped steel dampers in structures was first suggested by Kelly et al. [6], and subsequent tests showed these dampers to be flexible within their elastic range and capable of handling large displacements with significant damping in the inelastic range. Notably, U-shaped steel dampers (USSDs) have shown a stable hysteretic response even at high displacement levels, as highlighted in studies by Suzuki et al. [9] and Oh et al. [4]. Oh et al. further developed a base isolation system combining laminated-rubber bearings and U-shaped hysteretic (UH) dampers made from high-toughness steel (HTS), which proved effective in reducing seismic demands by lengthening structural periods and concentrating displacements in the isolation layer. Haeri et al. [10] introduced a hybrid isolator, combining frictional, yielding, and elastomeric components, demonstrating improved performance over traditional lead rubber bearings (LRB)[11–15] in terms of stability and energy absorption across various shear strains. Other advancements include the integration of high-toughness steel ring dampers (HTSRDs) with natural rubber bearings (NRB), as explored by Sheikhi et al. [16], which enhances damping and stiffness, particularly at higher shear strains. Using low yielding dampers in reducing structural response during large earthquakes support the effectiveness of such devices in managing seismic responses in concrete bridges and railway systems by enhancing damping ability and reducing structural displacements during seismic events.

This study has a comprehensive investigation considering about the effects of different vertical pressures and shape factors of seismic isolator with SSSDs, and tests three rubber compounds with distinct shear modulus to achieve a detailed characterization. Moreover, in the numerical research, a simplified Finite Element (FE) model [17] is developed to support structural applications of novel hybrid isolation systems. This simplified model simulates the proposed SREI+SSSD system adopting nonlinear springs and dashpots arranged in parallel, where each pair represents a principal element of the system: one SREI and two SSSDs. Compared to previous methodologies [8,12,18], a modular modeling approach is proposed, minimizing the need for experimental testing of the entire system by focusing on tests of individual components only.

2 DESIGN DETAILS

Proposing a novel hybrid seismic isolation device combined double SSSDs with one elastomeric isolator is shown in Figure 1. The elastomeric isolator consists of a steel-reinforced component with a plan area of 150×150 mm ($B \times B$) and a height (H) of 52 mm. Various steel lamina thickness and rubber layer thickness were designed to investigate the influence of shape factor (S), evaluated as the ratio between the plan area and the free lateral area, on the final lateral behavior. So, three elastomeric isolator models (G8B05, G8B10, and G8B15) are designed in Table 1, varying rubber layer thickness from 10 to 9.6 mm, corresponding to the range of steel lamina thickness from 0.5 to 1.5 mm. The results of these three models in terms of shape factor (S) are equal to 3.75, 3.91, and 4.08, respectively. The dimensions of the SSSD have a thickness (t) of 2 mm, a width (w) of 40 mm, a straight length (L) of 10.5 mm, and a radius (R) of the semicircle part of 12 mm.

Additionally, elastomeric isolators have been considered with different rubber compounds. Specifically, three standard rubber compounds with different with different hardness levels, Shore A 40, 45, and 50, were selected, corresponding to shear modulus (G) of 0.4 MPa, 0.6 MPa, and 0.8 MPa, respectively. The hysteretic performance of traditional isolation system coupled with and without SSSDs are experimentally investigated and compared under cyclic shear tests considering with different parameters effects.

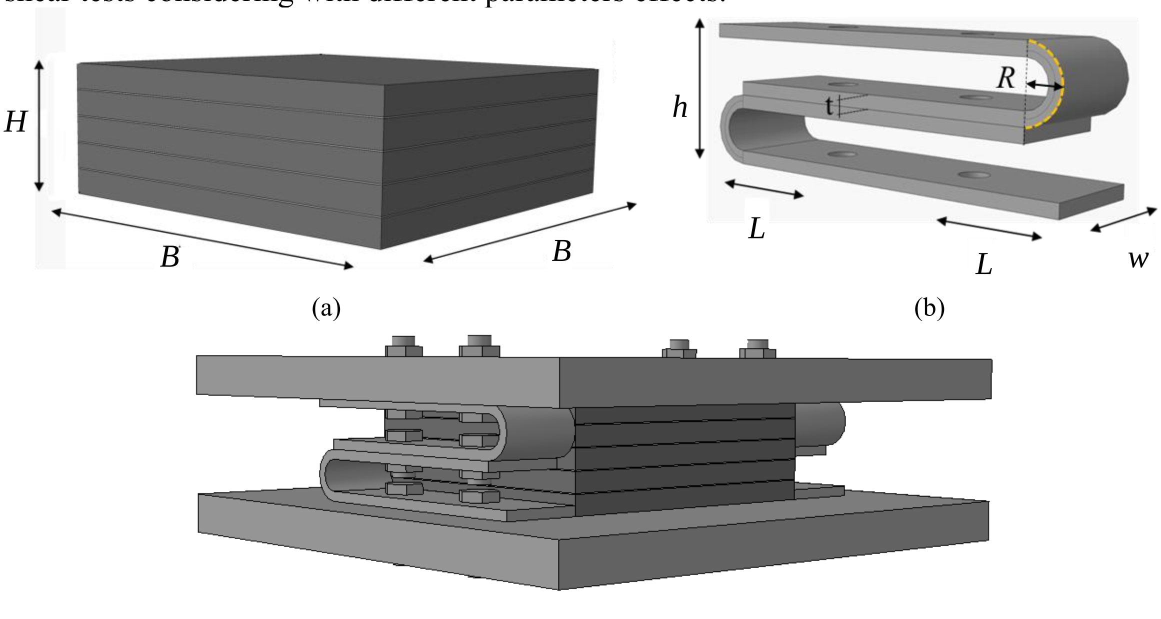


Figure 1: Geometric properties of elastomeric isolator with SSSDs.

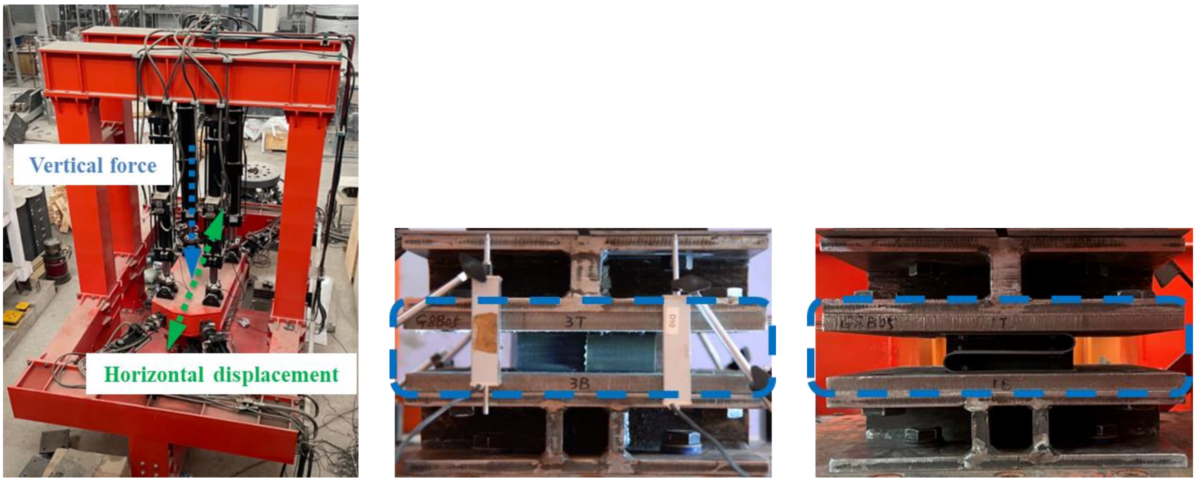
Model	Elastomeric isolator						S-Shaped Steel damper			
[-]	t_s [mm]	t_r [mm]	H [mm]	B [mm]	S [-]	G [MPa]	t [mm]	w [mm]	h [mm]	L [mm]
G8B05	0.5	10			3.75	0.8	-	-	-	-
G8B10	1.0	9.6			3.91	0.8	-	-	-	-
G8B15	1.5	9.2	52	150	4.08	0.8	-	-	-	-
G6B05	0.5	10			3.75	0.6	-	-	-	-
G4B05	0.5	10			3.75	0.4	-	-	-	-
G8B05S	0.5	10			3.75	0.8				
G8B10S	1.0	9.6			3.91	0.8				
G8B15S	1.5	9.2	52	150	4.08	0.8	2	40	52	10.5
G6B05S	0.5	10			3.75	0.6				
G4B05S	0.5	10			3.75	0.4				

Table 1: Designed details of seismic isolator.

3 EXPERIMENTAL INVESTIGATION

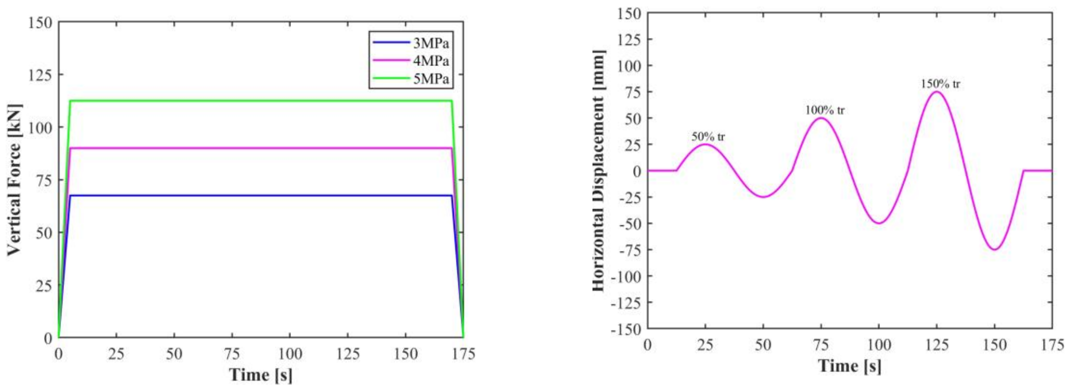
3.1 Test protocol

The specimens of seismic isolator with and without SSSDs in Figure 2(b) and 2(c) have been performed in compressive shear testing setup in Figure 2(a), where the device is subjected to a constant vertical load and cyclic horizontal displacement namely shown in Figure 3(a) and 3(b). The loading displacement rates for the test protocol have been all set at 0.02 Hz, performing quasi-static cyclic shear tests of seismic isolator with and without SSSDs.



(a) (b) (c)

Figure 2: Cyclic shear test: loading setup (a), seismic isolator without (b, d) and with (c, e) SSSDs.



(a) (b)

Figure 3: Loading scheme of shear tests: vertical load (a) and horizontal displacement (b).

3.2 Theoretical analysis

The data of seismic isolator with and without SSSDs subjected to compressive shear test have been evaluated from the hysteresis loop in terms of effective horizontal stiffness (K_h) and damping ratio (ξ) according to the following equations (1)-(3):

$$K_h = \frac{\left(F_{h,\max} - F_{h,\min}\right)}{\left(\Delta_{h,\max} - \Delta_{h,\min}\right)} \tag{1}$$

$$\xi = \frac{1}{2\pi} \cdot \frac{W_d}{K_h \cdot \Delta_{h,ave}^2} \tag{2}$$

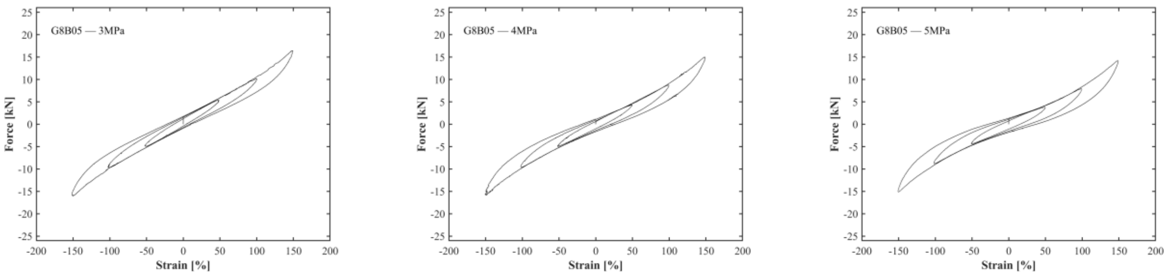
$$\Delta_{h,ave} = \frac{1}{2}\left(\left|\Delta_{h,\max}\right| + \left|\Delta_{h,\min}\right|\right) \tag{3}$$

where K_h is the effective horizontal stiffness; $F_{h,\max}$ and $F_{h,\min}$ are the maximum and minimum horizontal forces obtained under each side of the loading cycle, respectively; $\Delta_{h,\max}$ and $\Delta_{h,\min}$ are the maximum and minimum horizontal displacements obtained under each side of the loading cycle, respectively; W_d is the dissipated energy in each cycle, which is equal to the area inside the force-displacement hysteresis curve; W_s is stored energy. In Equation 3, $\Delta_{h,ave}$ is equal to the average of absolute value displacement of $\Delta_{h,\max}$ and $\Delta_{h,\min}$. Note that the evaluation has been conducted for each cycle of each shear strain.

3.3 Comparative analysis

For the effect of the shape factor *S*, the increasing of shape factor leads to a decrease in the damping ability of seismic isolation system and an increase in the effective horizontal stiffness of seismic isolation system. And it is investigated that the shear modulus *G* of rubber importantly affects the effective horizontal stiffness of the isolation system.

Considering about the vertical loading pressure, the increase of this parameter leads to a positive increase in damping ratio and a decrease in effective horizontal stiffness for all the specimens of the isolation system presented in Figure 4. However, if the shear strain increases, all models show a decrease in damping ratio. On the contrary, the effective horizontal stiffness shows a reduction at 100% of shear strain and, an increase at 150% because of the hardening behavior of the SSSDs.



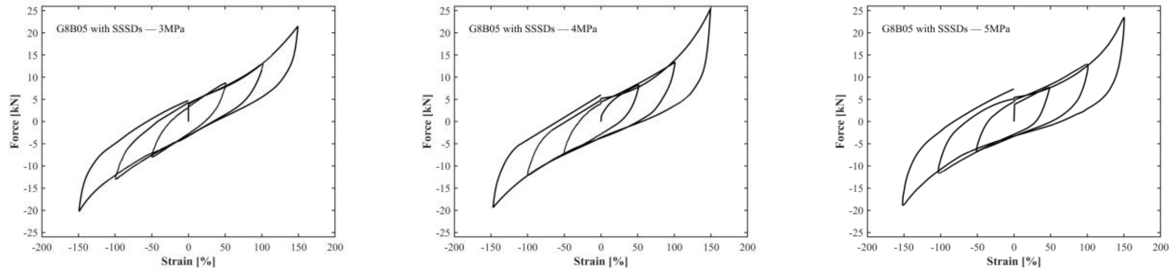
(a) (b) (c)

Figure 4: Typical loop curves for elastomeric seismic isolator without SSSDs under different vertical pressures.

After completing the tests on the elastomeric isolators alone, the tests were repeated for the devices coupled with the SSSDs. The same test protocol has been followed, and the results have been evaluated and compared in terms of horizontal stiffness and damping ratio obtained from the hysteresis loops in Figure 5.

The results obtained show how the coupling of the elastomeric device with the SSSDs has both positive and negative effects on the overall lateral behavior. In terms of the damping ratio, there is a significant improvement, with an increase in damping capacity of +100/+150%, with respect to the device without SSSDs. As for horizontal stiffness, there is also an increase due to the parallel operation of the two devices. Since these devices function in parallel, the overall horizontal stiffness is calculated by the sum of the individual stiffnesses, leading to an increase of +50/+100% compared to the device without SSSDs.

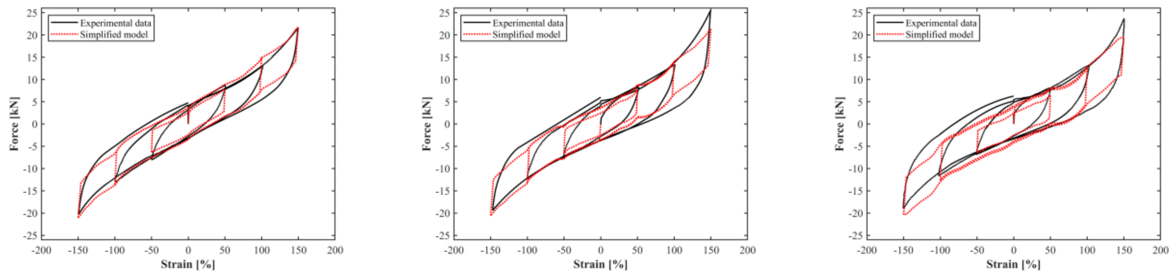
Though the vertical pressure has a negative contribution of the SSSDs, the increasing in effective horizontal stiffness has noted at higher vertical pressure, and the damping ratio has the decreasing influence. For the new combined devices, it can be found that the effective horizontal stiffness has not significant influence on geometric properties and the damping ability has been shown the similar results.



(a) (b) (c)

Figure 5: Typical loop curves of seismic isolator coupled with SSSDs under different vertical pressures.

Numerical simplified models of the novel isolation device have been established in ABAQUS software, adopting nonlinear springs and dashpots connected with upper and lower rigid bodies to represent seismic isolator and S-shaped steel dampers. The hysteretic curves of the models under different pressures have been simulated and compared with experimental data shown in Figure 6. The numerical and experimental results have strong agreement under different vertical pressures of 3MPa, 4MPa and 5MPa. As the pressure increases, the effective horizontal stiffness decreases, while the damping ratio has the increasing influence.



(a) (b) (c)

Figure 6: Typical comparative analysis of seismic isolator coupled with SSSDs under different vertical pressures of 3MPa (a), 4MPa (b) and 5MPa (c).

4 CONCLUSIONS

In this study, it presents an experimental and numerical investigation of a novel seismic isolation system connected seismic isolators with S-shaped steel dampers (SSSDs). Considering about the parameters of geometric properties and shear modulus, experimental data indicates that the novel hybrid isolation system with the application of the SSSDs obviously have superior damping ability and sustain lower effective horizontal stiffness. Under the larger vertical pressure, seismic isolator with SSSDs has greater damping ability and lower effective horizontal stiffness. However, the steel dampers have the opposite behavior as the pressure increases. The novel isolation device with lower shear modulus exhibits more effective horizontal stiffness and similar damping ratio comparing with other isolation devices. For the shape factor of seismic isolator, it has no effect on mechanical properties of the novel isolation system.

The FE models consisting of nonlinear springs and dashpots have been simulated under cyclic shear tests. The numerical results have strong agreements with experimental data. The simplified models representing mechanical performances of elastomeric isolator and the SSSDs have been developed and validated to enable efficient analysis of the novel isolation system in structural applications.

In this research, the novel isolation system coupling seismic isolator with SSSDs has both the advantages of seismic isolator and steel damper, especially improving the capacity for higher damping while maintaining a lower effective horizontal stiffness. It provides an advanced isolation device to probably apply in engineering project, contributing to the development of more efficient and resilient seismic isolation solutions.

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