Simulation for a low-rise masonry house using seismic isolator with and without S-shaped steel dampers

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Abstract. In the recent years, due to the limitations of common isolation systems, there are new hybrid base isolation systems proposed, for instance, the hybrid system consisting of unbonded fiber reinforced elastomeric isolator and shape memory alloy wires, hybrid fraction yielding elastomeric bearing and rubber bearing with slit damper devices. In this paper, to improve the dissipative energy capacity of isolation devices and decrease the displacement of the superstructure, the novel hybrid seismic system including seismic isolator connected with S-shaped steel dampers (SSSDs) is investigated, and a simplified model of that system is proposed. The numerical model of a low-rise masonry house using the simplified model of the novel system is established in ABAQUS. The simulations and the comparisons of a low-rise masonry house with and without the novel system are investigated under the earthquake action based on finite element method. The novel hybrid seismic system applied in a low-rise masonry house has more effective protection by adding SSSDs. It can be adopted as a reference to improve the mechanical capacity of the isolation system and supple the practical application in the engineering.

Keywords: Isolation device, Steel damper, Dissipative energy capacity, Finite element method.

1 Introduction

A large number of historical masonry structures in the world are vulnerable to damage and collapse in earthquake, especially churches in Italy. Base isolation which is recognized as a promising alternative has been widely accepted as an effective method for the protection of structures against seismic actions but remain limited. [1]

The common types of commercial isolators are natural rubber (NR), high damping rubber (HDRB), lead rubber bearing (LRB) and fiber reinforced elastomeric isolator (FREI) including unbonded (UFREI) or bonded (BFREI). [2]

Low-cost unbonded fiber reinforced elastomeric seismic isolation systems in new masonry buildings is investigated the seismic performance, and 3D model of a single UFREI substituted by a nonlinear spring and a damper decreases the computational coasts of the nonlinear dynamic analysis taking into account the two horizontal components of the seismic action. [3]

Moreover, unbonded fiber reinforced elastomeric isolator can require no expensive thick steel plates and reduce the seismic demand. A simple UFREI model is implemented in an ABAQUS user element (UEL) taking into account multiple DOFs to reduce the computational efforts of analyses, especially being suitable for complex base isolated structures. [4]

There is the new hybrid seismic base isolation system proposed which combines UFREIs and shaped memory alloy (SMA) wires to increase the energy dissipation capacity of the historical masonry church. [5] Based on Abaqus user element (UEL) the 3D behavior of the isolation system is represented to evaluate the seismic response of a historical masonry in different base isolation systems under nonlinear dynamic time history analyses. [5]

The isolator is made of high damping rubber and an external Ethylene Propylene Diene Monomer ring, and a detailed 3D finite element modelling of isolators in low-rise masonry building has been investigated in unbonded boundary conditions to reduce production costs and allow its applicability. [6]

However, the applications of isolators in historical masonry structures are limited in practices. Seismic isolators are low in energy dissipation capacity and in the horizontal load carrying capacity. Steel damper has advantages in dissipative energy capacity and damping ratio. In this paper, the traditional and novel hybrid seismic isolation systems including seismic isolator with and without S-shaped steel dampers (SSSDs) are simulated and investigated in a low-rise masonry house to supply the practical application in the field of civil engineering.

2 Theoretical analysis

There are two main factors of seismic isolator, such as shape factor in Eq. (1) and aspect ratio in Eq. (2). [7] In the practical project, seismic isolator is usually considered to be loaded in compression and shear in Fig. 1.

$$S = \frac{a}{4t} \tag{1}$$

$$R = \frac{a}{h} \tag{2}$$

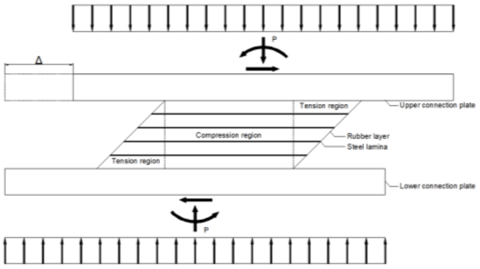


Fig. 1. Seismic isolator loading in compression and shear.

Based on the theory [8,9], it is to estimate the mechanical capacities of the novel hybrid system. There are the formulas of mechanical property as followed in Eqs. (3)-(7), which can represent the main characters of the novel hybrid system. The theoretical data of seismic isolator without SSSDs is shown in Table 1.

$$T = 2\pi\sqrt{\frac{p}{g}\cdot\frac{t_r}{G}} \tag{3}$$

$$K_{h,eff} = \frac{(F_{h,max}-F_{h,min})}{(\Delta_{h,max}-\Delta_{h,min})} \tag{4}$$

$$\xi = \frac{W_d}{4\pi W_s} \tag{5}$$

$$W_s = \frac{1}{2}K_{h,eff}\Delta_{h,ave}^2 \tag{6}$$

$$\Delta_{h,ave} = \frac{1}{2}\left(\left|\Delta_{h,max}\right| + \left|\Delta_{h,min}\right|\right) \tag{7}$$

Table 1. Theoretical calculation for seismic isolator.

Total thickness of rubber layer (mm)	Total thickness of steel laminae (mm)	Shear modulus (MPa)	Steel damper thickness (mm)	Shape factor	Aspect ratio	Pressure (MPa)	Horizontal period (s)
50	2	0.8	2	3.75	2.88	3	0.869

3 Finite element analysis

In this research, the novel hybrid system in Fig. 2(b) consists of two main types of materials, rubber and steel. Seismic isolator in Fig. 2(a) is made of standard rubber and reinforcing steel, and S-shaped steel damper (SSSD) also made of common steel.

Using standard rubber [10], it is to analysis the mechanical properties of seismic isolators made of standard rubber. The steel dampers of the device are made of common steel, Q345, with tensile strength about 470 MPa and has the value of Young’s Modulus and Poisson’s ratio, 206 GPa and 0.3, respectively.

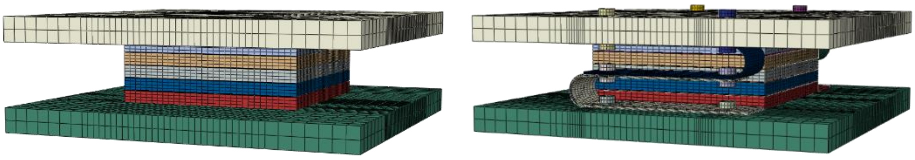
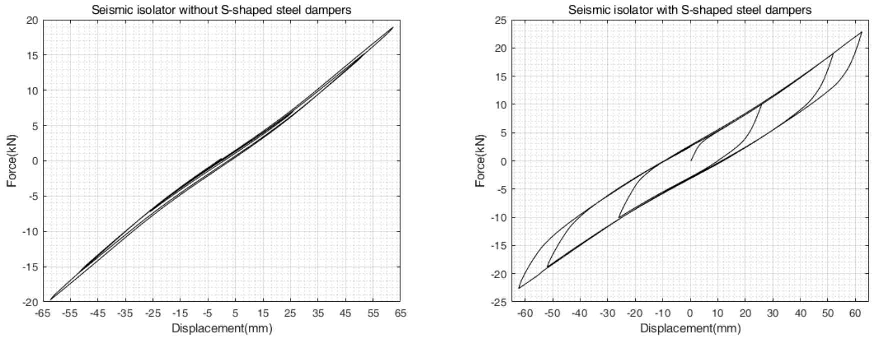

(a) (b)

Fig. 2. FE models of seismic isolator without (a) and with (b) SSSDs.

In Fig. 2(b), the model of the novel seismic device is established in ABAQUS. [11] Rubber pads are welded with steel laminas with dimensions 150×150×52mm^3. The S-shaped steel damper (SSSD) consists of four straight parts and two semicircle parts, which are realized with bolted U-shaped steel elements. S-shaped steel dampers of the novel hybrid system are bolted between upper and lower connection plates.

Comparing seismic isolators with and without SSSDs and simplified models of them, the cyclic tests in Fig. 3 are performed in ABAQUS under the amplitudes of 50%h, 100%h and 120%h (26mm, 52mm, 62.4mm, respectively) and a constant vertical pressure of 3 MPa. In Figs. 3(a) and 3(b), the force displacement curves of seismic isolator without and with SSSDs.



(a) (b)

Fig. 3. The force displacement curves of seismic isolator without (a) and with (b) SSSDs.

In the cyclic loading test, shown in Figs. 3(a) and 3(b), the force-displacement curve area of S-shaped steel damper is much larger than that of seismic isolator, which is that S-shaped steel damper has more advantages than seismic isolator without SSSDs in aspect of energy dissipation capacity.

Comparing with seismic isolator without SSSDs in Fig. 3(a), it is evidently to increase the area of force-displacement in Fig. 3(b) by adding S-shaped steel dampers, and the novel hybrid system can have more energy dissipation capacity than traditional isolation system because S-shaped steel damper work effectively.

4 Simplified spring-damper analysis

Using detailed model of isolators in the nonlinear finite element analysis is somehow computationally expensive. Thus, in this study, to research the performance of the seismic isolation system with and without SSSDs applied in a small masonry house under nonlinear time history analysis, the simplified models are proposed, as shown in Fig. 4.

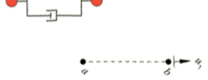
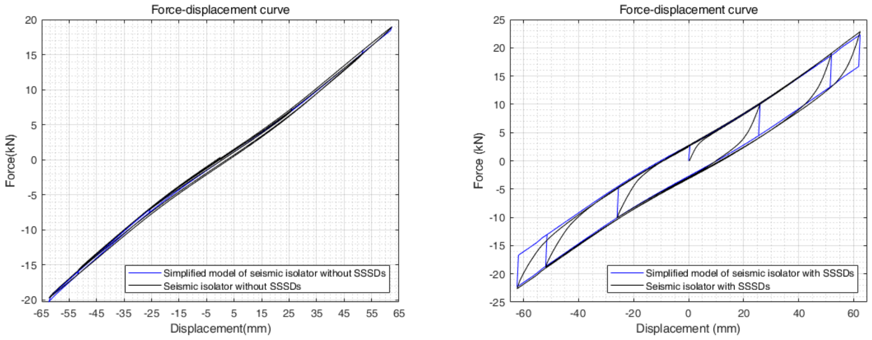


Fig. 4. Simplified spring-damper model

The comparisons of the force displacement curves of seismic isolator without and with SSSDs and simplified models of them are in Figs. 5(a) and 5(b).



(a) (b)

Fig. 5. Comparisons of simplified models of seismic isolator without (a) and with (b) SSSDs

In Table 2, it is investigated the parameters of seismic isolator with and without SSSDs and simplified models of them, such as structural period and damping ratio. Corresponding to seismic isolator with and without SSSDs, the nonlinear horizontal stiffness, structural period and damping ratio of simplified models are very close in Table 2 so that using the simplified models can reliably represent for seismic isolator with and without SSSDs.

Table 2. The comparative data of different isolation models.

Model type	Effective horizontal stiffness (N/mm)	Structural period (s)	Damping ratio
Seismic isolator without SSSDs	310.282	0.936	0.013
Seismic isolator with SSSDs	364.604	0.864	0.131
Simplified model of seismic isolator without SSSDs	314.616	0.930	0.016
Simplified model of seismic isolator with SSSDs	357.747	0.872	0.162

5 Dynamic analysis

In dynamic analysis, the models of a single-story masonry house without and with proposed isolators and SSSDs are subjected to L’ Aquila ground motion (PGA=0.43g), as shown in in Fig. 6. The density and Young’s modulus of masonry brick are 1800 kg/m^3 and 1600 MPa, respectively. A plastic damage behavior of the masonry material by means of the Concrete Damage Plasticity model (CDP) in ABAQUS is adopted to determine the nonlinear stress strain behavior of masonry, and the main modeling parameters are presented and described in Table 3. [11,12]

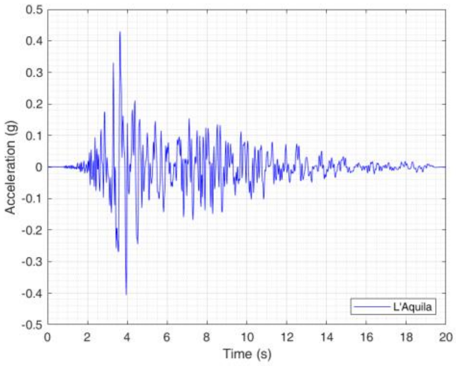
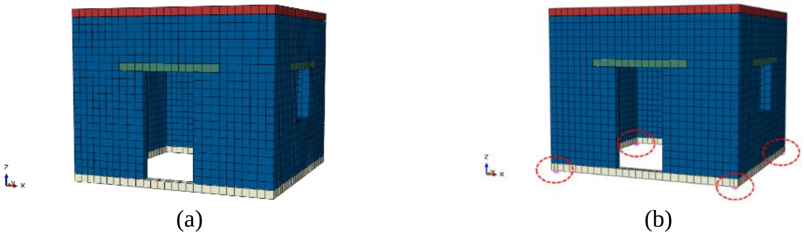


Fig. 6. L'Aquila earthquake accelerogram.

Table 3. The values of mechanical parameters adopted for the CDP model of masonry house.

Dilatation angle	Eccentricity	σ_{b0}/σ_{c0}	K_c	Viscosity parameter
10	0.1	1.16	0.667	0.0001

The small masonry house in Figs. 7(a) and 7(b) has the dimensions 4×4×3 m^3 (length×width×height) and its wall thickness is 150mm. The total weight of the house is about 17.59t. In the FE simulation of the masonry house, the roof, the lintels and the foundation beam are assumed rigid due to the practical condition of the house prototype in Fig. 8. The other parts of the house model are tied with each other in the model by surface-to-surface constraint.


(a)

(b)

Fig. 7. The model of masonry house without (a) and with (b) simplified models.

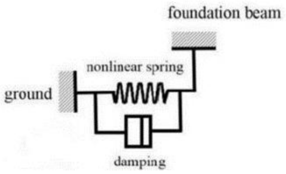


Fig. 8. The simplified spring-damping model connected with ground and foundation beam.

From Fig. 9 to Fig. 11, it is shown that the compressive damage and the tensile damage of masonry house with the simplified models of seismic isolators and SSSDs are more obviously reduced than that of masonry house in fix-based model or with bonded seismic isolators.

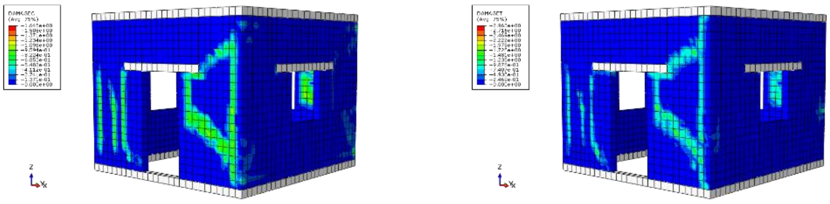

(a) (b)

Fig. 9. The compressive damage (a) and the tensile damage (b) of masonry house without seismic isolators.

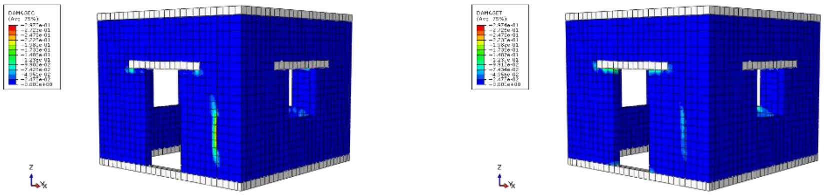

(a) (b)

Fig. 10. The compressive damage (a) and the tensile damage (b) of masonry house with bonded seismic isolators.

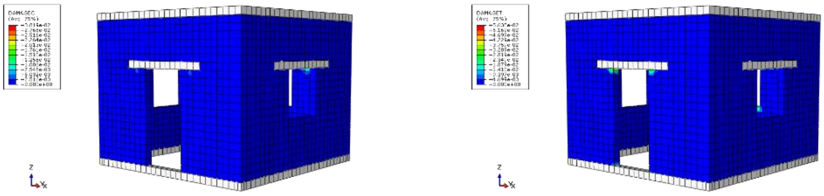

(a) (b)

Fig. 11. The compressive damage (a) and the tensile damage (b) of masonry house with seismic isolators and SSSDs.

In Fig. 12, the top roof acceleration clearly decreases under L’ Aquila earthquake with the application of seismic isolators and SSSDs. The modal response of masonry house is improved, especially in significant increase of structural period, as shown in Table 4. Seismic isolator with SSSDs could be applied in the practical engineering to protect the low-rise masonry house effectively.

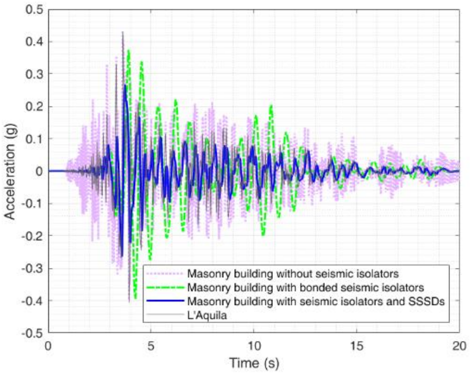


Fig. 12. The top roof acceleration of masonry house with different simplified models.

Table 4. Comparisons of masonry building with different simplified models.

Model type	Structural period (s)
Masonry house without seismic isolators	0.0549
Masonry house with bonded seismic isolators	0.815
Masonry house with seismic isolators and SSSDs	0.813

6 Conclusions

In this paper, the novel hybrid system including seismic isolator and S-shaped steel dampers has more advantages than traditional isolation system (bonded seismic isolator), especially improving in energy dissipation capacity and structural period.

The numerical analysis which is an excellent tool verify that the models of seismic isolator without SSSDs are effective comparing with theoretical calculation, and can develop for improving energy dissipation capacity of seismic isolation system by adding S-shaped steel dampers.

Using the nonlinear horizontal stiffness and damping ratio of seismic isolator with and without SSSDs, the simplified models are very close to the mechanical properties of seismic isolator with and without SSSDs simulated in ABAQUS.

Compared with masonry house with the application of different seismic isolation systems, it is found that the mechanical capacity of masonry house with the simplified model of seismic isolators and SSSDs is more obviously improved under L’ Aquila earthquake than other systems, especially in the top roof acceleration and structural period. The application of seismic isolators and SSSDs could effectively protect the low-rise masonry house under earthquake action.

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References

1. Habieb A B, Valente M, Milani G.: Base seismic isolation of a historical masonry church using fiber reinforced elastomeric isolators. Soil Dynamics and Earthquake Engineer, 120, 127-145(2019).
2. Habieb A B, Milani G, Cerchiaro R, ET AL.: Numerical study on rubber compounds made of reactivated ethylene propylene diene monomer for fiber reinforced elastomeric isolators. Polymer Engineering Science, 61(1), 258-277(2021).
3. Habieb A B, Milani G, Tavio T.: Two-step advanced numerical approach for the design of low-cost unbonded fiber reinforced elastomeric seismic isolation systems in new masonry buildings. Engineering Failure Analysis, 90, 380–96(2018).
4. Habieb A B, Valente M, Milani G.: Implementation of a simple novel Abaqus user element to predict the behavior of unbonded fiber reinforced elastomeric isolators in macro-scale computations. Bulletin of Earthquake Engineering, 17(5), 2741–2766(2019).
5. Habieb A B, Valente M, Milani G.: Hybrid seismic base isolation of a historical masonry church using unbonded fiber reinforced elastomeric isolators and shape memory alloy wires. Engineering Structures, 196, 109281(2019).
6. Pianese G, Torrini D, Milani G, ET AL.: High damping rubber isolators for low-rise masonry buildings. Journal of the International Masonry Society, 34, 2(2022).
7. Soleimanloo H S, Barkhordari M A.: Effect of shape factor and rubber stiffness of fiber-reinforced elastomeric bearings on the vertical stiffness of isolators. Trends Applied Sciences Research, **8**(1), 14-25(2013).
8. Kelly J M.: The current status of seismic isolation technology in the United States. International Atomic Energy Agency (IAEA), 87, 89-111(1992).
9. Tsai H C, Kelly J M.: Stiffness analysis of fiber-reinforced rectangular seismic isolators. Journal of Engineering Mechanics, 128(4), 462–70(2002).
10. Habieb A B, Formisano A, Milani G, Pianese G.: Seismic performance of Unbonded Fiber-Reinforced Elastomeric Isolators (UFREI) made by recycled rubber. Influence of suboptimal crosslinking. Engineering Structures, 256, 114038(2022).
11. Abaqus/Standard User’s Manual, Version 6.14.
12. Habieb A B, Milani G, Tavio T, ET AL.: Low cost frictional seismic base isolation of residential new masonry building in developing countries: a small masonry house case study. The Open Civil Engineering Journal, 11, ,1026-1035(2017).