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SHAPE MEMORY ALLOY (SMA)-BASED SUPERELASTICITY-ASSISTED SLIDER (SSS)

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ABSTRACT

The objective of this paper is to introduce an innovative Isolation System (IS) based on friction and superelasticity. The proposed IS is referred to as Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS), derived from a practical combination of Flat Sliding Bearings (FSBs) allowing isolation displacements and austenitic SMA wire ropes properly providing self-centering capability.

SSS is characterized for its configurations in both the traditional and industrial forms of application, with and without Isolation Units (IUs). A simplified numerical modeling is carried out to obtain an initial view on the mechanical behaviors and dynamic properties. Seismic performances are evaluated using a new phenomenologicalmacroscopic model. The effectiveness of SSS is examined and compared to that of other practical ISs, such as friction pendulum system and high damping laminated rubber bearing. SSS seems to be effective for the earthquake protection of structural and non-structural elements. The practical implementation is detailed with a 1/5-scale model IU. Numerical outcomes are validated by experimental results.

INTRODUCTION

Aseismic Base Isolation (ABI) is the most effective demand reducing technique for earthquake protection of structures. ABI prevents earthquake ground motions being transmitted into the structure above. This mainly requires an isolation interface between the structure and its foundation. Nothing must interfere and obstruct movements in isolation level and all elements or services crossing the isolation plane should be flexible. The main advantages of ABI apart from eliminating or at least greatly reducing earthquake casualties are the few repairs needed after an earthquake, no interruption of building functionality and protection of contents.

The concept of ABI seems to be more than 25 century old. Its first application dates back to the years 540-530 BC, when the sliding isolation effect of smoothed surfaces of stones in the base level was used by Achaemenid engineers to build the mausoleum of Cyrus the Great in Pasargadae, Iran (Botis and Harbich, 2012). A similar application can also be considered for the Parthenon temple of Athenian Acropolis between 447-432 BC (Bayraktar et al., 2012). The other example of ancient application is known as the utilization of boiled glutinous rice and lime in the foundation of former emperor palace of ancient China (Izumi, 1998) in the Forbidden City of Beijing between the years 1406-1420 AD. Later in Peru, the Incas built Dry-stone walls of Machu Picchu Temple of the Sun as a sample of seismic isolation technology around the year 1450 AD (Monfared et al., 2013). Aseismic isolation has become a practical reality after 1980 with the development of elastomeric bearings. Other systems have then been developed as typical modifications of the sliding approach. Although rubber isolators have widely been used in practice, sliding isolators have attracted much interest of researchers and structural designers. This interest mainly arises from the advantages of sliding isolation systems with respect to improvement of seismic performances. The most attractive features of sliding isolators are: (i) further elongation of the natural period, (ii) insensitivity to the frequency content of excitation, and (iii) lower transmission of the ground motion accelerations into the superstructure. Flat Sliding

Bearings (FSBs) are known as the simplest sliders. FSBs, however, require a proper restoring mechanism. The problem has typically been solved by geometry, using Friction Pendulum System (FPS). FPS has become a well-known practical Isolation System (IS). There are, at the same time, some limitations with the FPS. Shape Memory Alloy (SMA)-based recentering is a relatively modern approach in order to provide an alternative restoring mechanism for FSBs. Superelasticity with large strain plateau, acceptable energy dissipation capacity through flag-shaped hysteretic loops, high fatigue and corrosion resistances are the most favorable characteristics of austenitic SMAs for using in aseismic ISs. To date, various SMA-based sliding ISs have been proposed by different researchers including Dolce et al. (2000), Wild et al. (2000), Khan and Lagoudas (2002), Cardone et al. (2003), Casciati et al. (2007), Attanasi et al. (2008), Cardone et al. (2009), Khodaverdian et al. (2012), and Ozbulut and Silwal (2014). The idea behind the system proposed by Cardone et al. (2009) was indeed based on the IS studied by Dolce et al. (2000). It was referred to as Smart Restorable Sliding Base Isolation System (SRSBIS). SRSBIS was detailed by Jalali et al. (2011) and Cardone et al. (2011). The simple working principle of this kind of application, which is essential compared to the complicated behaviors of both FSBs and SMAs, together with continuing researches on SMA-based aseismic isolation encouraged us to investigate practical issues for its implementation. Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS) has been introduced in this regard (Narjabadifam and Eradat, 2013). This article deals with the pilot investigations of SSS.

CONFIGURATION

The layout of SSS is schematically depicted in Figure 1. The practical application of SSS is possible directly or by means of space-saving Isolation Units (IUs), being also suitable for retrofitting purposes.

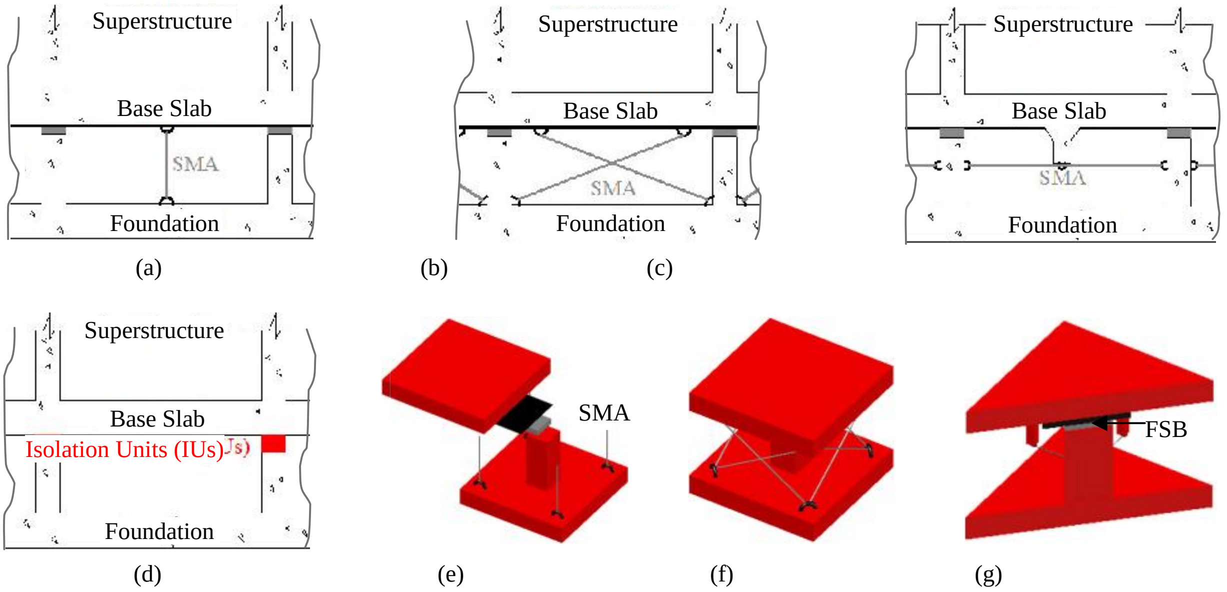


Figure 1. SSS: (a) vertically arranged SMAs, SSS-v; (b) diagonally arranged SMAs, SSS-d; (c) horizontally arranged SMAs, SSS-h; (d) SSS-IUs: (e) SSS, IU-v; (f) SSS, IU-d; (g) SSS, IU-h

As shown in Figure 1, three alternative configurations can also be considered based on the vertical, diagonal or horizontal arrangement of SMA wire ropes (Reedleen et al., 2013). Another configuration can be considered as the application of continuous wire ropes, such as that case studied by Ozbulut and Silwal (2014) using SMA wires instead of recently introduced SMA wire ropes.

FORCE-DISPLACEMENT BEHAVIOR

Figure 2 shows the force-displacement behaviors expected for SSS, obtained from simplified numerical modeling. The system is assumed to be made up of highly polished stainless steel (SUS) plates faced with polytetrafluoroethylene (PTFE) pads as the FSBs accompanied by superelastic NiTi SMA wire ropes with the wires manufactured by “nimesis technology” (a leading French company).

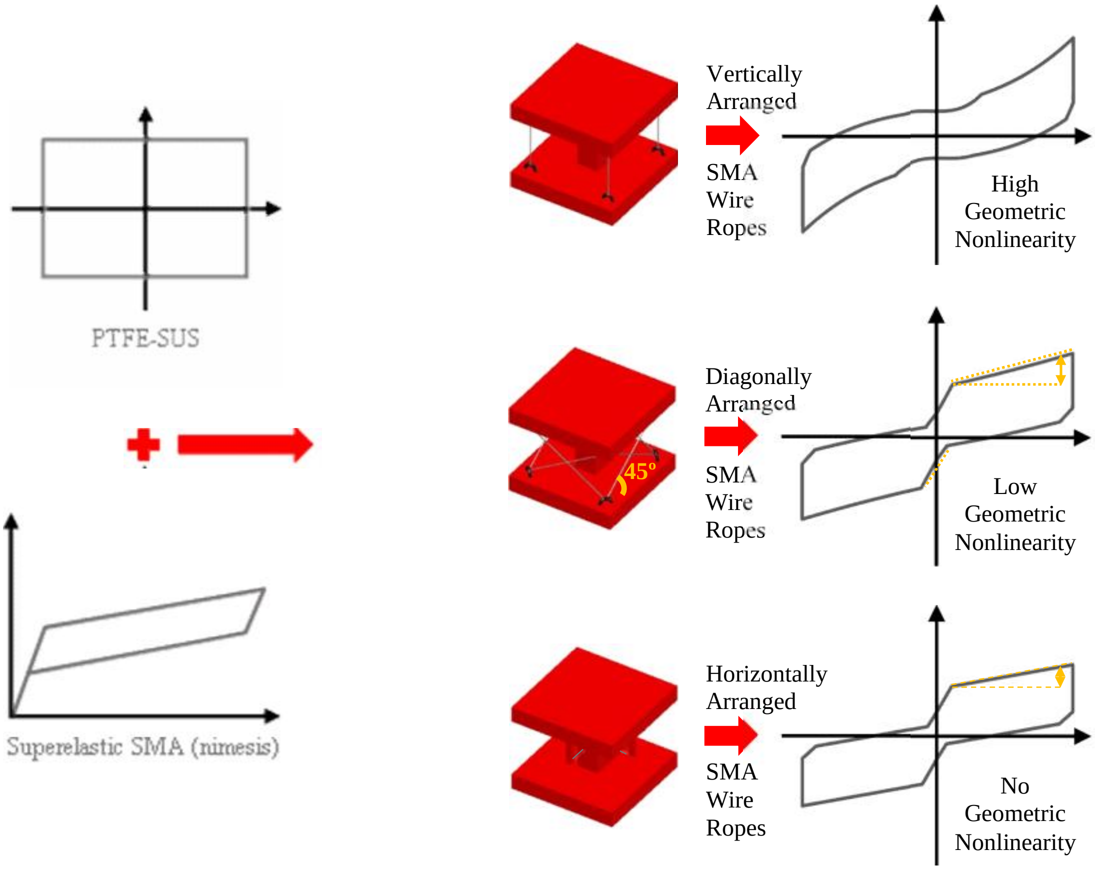


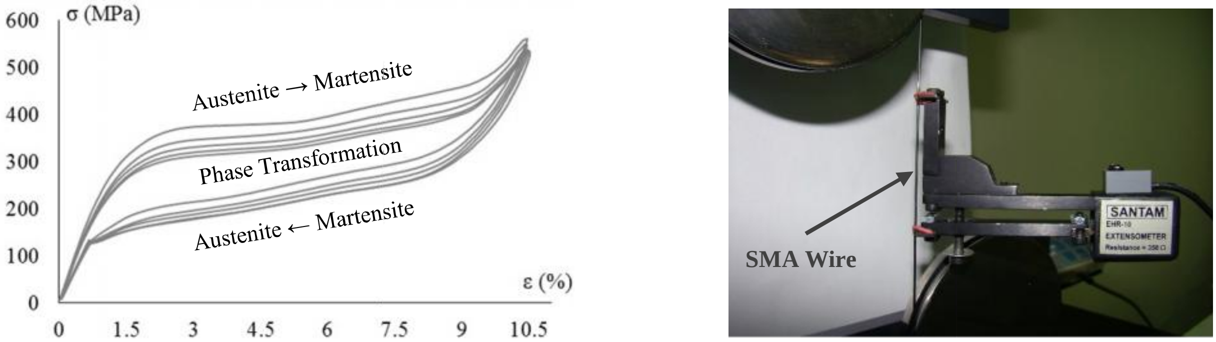
Figure 2. Numerically modelled geometry-dependent mechanical behavior of SSS for the same design parameters (same seismic action, same superstructure, same materials, and same design displacement)

As seen, a high level of geometric nonlinearity is included in the case of the vertical arrangement of SMA wire ropes, being reduced to a low level in diagonal and eliminated completely in horizontal configurations.

SEISMIC PERFORMANCES

Seismic performances of SSS can practically be evaluated using SAP2000 program, the well-known civilengineering software, including also nonlinear link elements for the other practical ISs. Tothis purpose, appropriate nonlinear link elements should be combined together within a phenomenologicalmodel. The friction isolator link element, which is based on the friction law developed by Constantinou et al. (1990) can be used to model the friction behavior of sliding interfaces. The radius should be put equal to zero forflat surfaces. Friction coefficients at slow and fast velocities and the rate parameters can be derived from theexperimental results, such as those reported by Dolce et al. (2005). The superelastic behavior of SMAs can bemodelled based on the proper combination of multi-linear elastic link element in parallel with Pivot-type MultilinearPlastic (PMP) link element.

The seismic performances of SSS with its alternative configurations are studied based on the abovementioned procedure, regarding a typical 3-story building located on soil type C in an area with high seismicityaccording to EC8, for a set of seven accelerograms being compatible (on average) with the type I (5%-damped)elastic response spectrum of the EC8. Design displacement (D_d) is 0.3m, SMA wires are considered as those characterized in Figure 3 (with the numerical model shown in Figure 2),andfriction coefficient (μ) is assumed as 0.05 in order to take into account the variability offriction with contactpressure, air temperature and status of lubrication of sliding interfaces.



(a) (b)

Figure 3. The phase-dependent hysteretic behavior of 1mm diameter NiTi SMA wires tested for SSS (a) General view of the test setup (b)

Table 1 shows the average responses in terms of residual displacements (δ), maximum displacements (Dmax), and maximum base shears as a fraction of building weight (Vmax / W). Total lengths of required SMA wires (LSMAs) are also reported for each configuration.

Table 1. Seismic performances of the vertical, diagonal, and horizontal configurations of SSS

Configuration	L_{SMAs} (m)	Seismic Performances		
		Δ (cm)	D_{max} (m)	V_{max}/ W
Vertical	3570	4.5	0.300	0.138
Diagonal	7883	2	0.272	0.135
Horizontal	8196	1.5	0.274	0.134

The maximum base shears (reported as Vmax / W) are almost same for all the configurations. The total length of SMA wires required in the vertical configuration is considerably less than the other two configurations. Based on the results obtained from these preliminary analyses, the self-centering capability seems to be stronger in the horizontal and diagonal configurations. However, extensive seismic analyses shows that residual displacements are mostly less than 10% of the maximum displacements, generally recoverable by exploiting the shape memory effect.

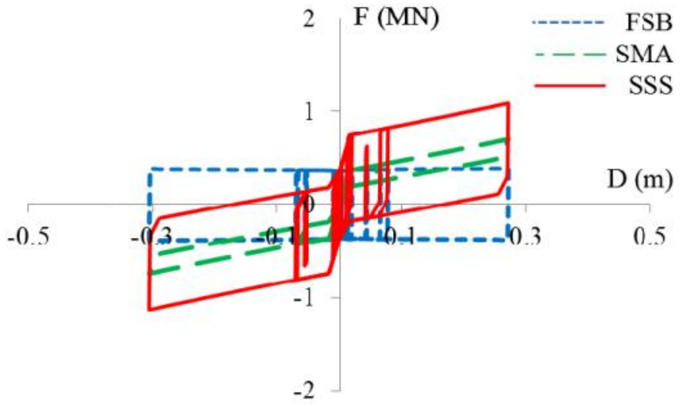


Figure 4. Typical force-displacement diagrams of SSS, for diagonally arranged SMA wire ropes

Force-displacement diagrams of the diagonal configuration are shown in Figure 4 for one of the seven accelerograms considered. The overall behavior of the IS is same as that predicted by the simplified numerical modeling (see Figure 2).

As far as the comparison with the other practical ISs is concerned, the seismic performances of SSS in aseismic isolation of a typical 4-story moment resisting reinforced concrete frame building are compared to those of FPS and HD-LRB (High Damping- Laminated Rubber Bearing) under the same design assumptions. Table 2 summarizes the results in terms of base shears (V), maximum story accelerations (aimax) and maximum story drifts (dijmax). SSS seems to be effective for the purpose of aseismic control of structures.

Table 2. Seismic performances of SSS with vertically arranged SMA wire ropes compared to those of FPS and HD-LRB

IS	Seismic Performances		
	V (kN)	a_i^{max} (m/s^2)	d_{ij}^{max} (%)
SSS	1713	3	0.23
FPS	2074	2.9	0.26
HD-LRB	2245	3.4	0.69

EXPERIMENTAL EVALUATION

For the purpose of experimental evaluation of the performances predicted by the simplified numerical modeling and then simulated through the computer analyses, shaking table tests are programmed to be executed on the IU shown in Figure 5.

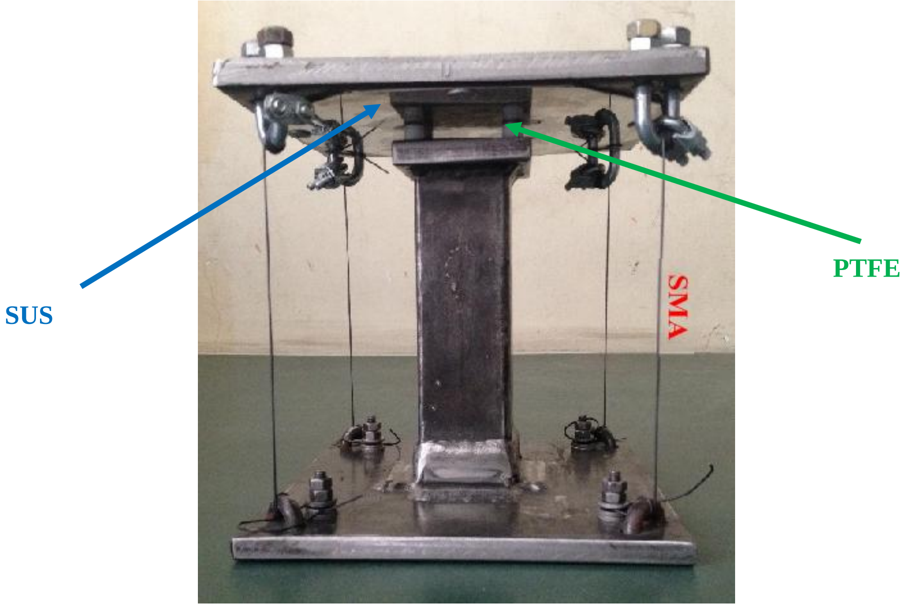


Figure 5. The 1/5-scale model IU with vertically arranged SMAs

The testing model has been set up as a 1/5-scale SSS-IUv with $\mu = 0.095$ and $Dd = 0.33m$ in the prototype carrying a weight of 28.1kN under a structure with very high importance located on soil type D in an area with very high seismicity according to EC8. As shown in Figure 6, the configuration can also be changed to a 1/10-scale model of SSS-IUb with the same design parameters for a prototype weight of 74.5kN. The testing machine is the one-directional shake table available at the central laboratory of the University of Bonab, being able to apply 50kN maximum force with a stroke of ±150mm. The experimental tests have been scheduled to be performed next year. The results will be reported later, after the detailed reports for the study of materials, design procedure, computer simulation, seismic performances, and the recentering capability. However, since the structural mechanism of SSS with vertically arranged SMA wires is same as that of so-called SRSBIS investigated experimentally by Cardone et al. (2011), in first approximation, reference to the experimental results of previous tests can be made for a preliminary comparison with the numerical response of the proposed SMA-based IU obtained with SAP2000 using PMP link elements. Figure 7 compares the experimental force-displacement behavior to that of computer simulation based on the PMP model for a typical design. As expected, the results are acceptably compatible.

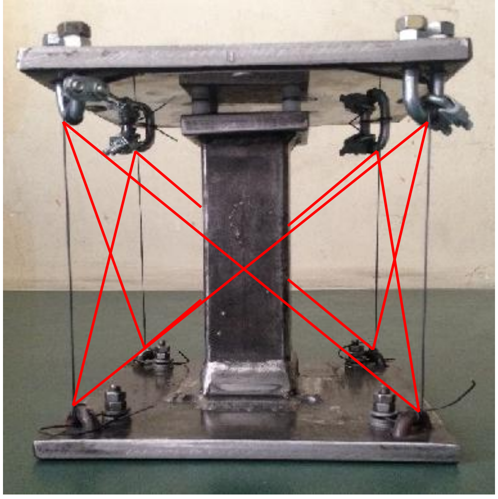


Figure 6. The schematic upgrade of 1/5-scale SSS-IUv into the 1/10-scale SSS-IUb

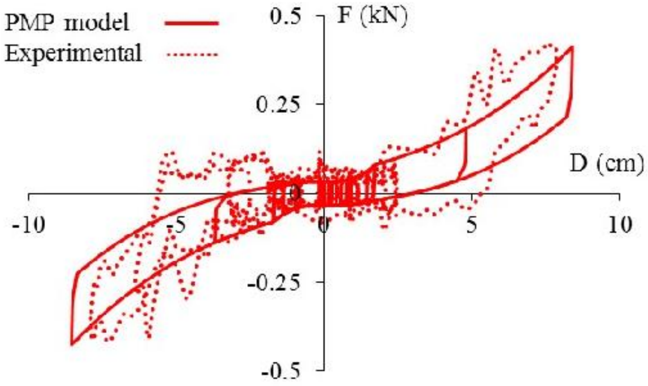


Figure 7. The PMP-based numerically simulated force-displacement diagram compared to the experimental behavior for a typical design of the IS with vertically arranged SMAs

CONCLUSIONS

The practical application of Shape Memory Alloy (SMA) wire ropes within seismic isolation technique has been approached by the SMA-based Superelasticity-assisted Slider (SSS).

It has been illustrated that, SSS can be applied without and with Isolation Units (IUs). Alternative configurations have been detailed based on specific arrangements of SMA wire ropes.

A simplified numerical model has been defined to describe the mechanical behavior of the proposed configurations. A high level of geometric nonlinearity is included in the case of the vertical arrangement of SMA wire ropes, being reduced to a low level in diagonal and eliminated completely in horizontal configurations. The length required for the SMA wires has been addressed as a practical limit in the case of the horizontal arrangement.

For the purpose of computer simulations, for all the forms of application, a phenomenological model has been developed using Pivot-type Multi-linear Plastic (PMP) link element of the SAP2000 program, known as the practical structural engineering software. Seismic performances have been evaluated through the computer simulations and compared together, showing an acceptable compatibility with those predicted by the simplified numerical analyses. Comparison has also been made between the seismic performances of SSS, FPS (Friction Pendulum System), and HD-LRB (High Damping- Laminated Rubber Bearing) under the same design assumptions.

Details for the experimental evaluations have been defined and the behavior of the model has been verified by the experimental behavior available for the combination of vertically arranged SMAs with flat sliding bearings.

SSS seems to be effective for the purpose of aseismic control of structures. Further investigations including detailed study of materials, complete structural design, advanced computer simulation, and precise performance evaluation should be carried out to make the system practical.

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