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Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS): an engineering solution for practical aseismic isolation with advanced materials

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Abstract. Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS) is proposed as an engineering solution to practically exploit the well-accepted advantages of both sliding isolation and SMA-based recentering. Self-centering capability in SSS is provided by austenitic SMA cables (or wire ropes), recently attracting a lot of interest and attention in earthquake engineering and seismic isolation. The cables are arranged in various novel and conventional configurations to make SSS versatile for aseismic design and retrofit of structures. All the configurations are detailed with thorough technical drawings. It is shown that SSS is applicable without the need for Isolation Units (IUs). IUs, at the same time, are devised for industrialized applications. The proof-of-concept study is carried out through the examination of mechanical behavior in all the alternative configurations. Force-displacement relations are determined. Isolation capabilities are predicted based on the decreases in seismic demands, estimated by the increases in effective periods and equivalent damping ratios. Restoring forces normalized relative to resisting forces are assessed as the criteria for self-centering capabilities. Lengths of SMA cables required in each configuration are calculated to assess the cost and practicality. Practical implementation is realized by setting up a small-scale IU. The effectiveness of SSS under seismic actions is evaluated using an innovative computer model and compared to those of well-known Isolation Systems (ISs) protecting a reference building. Comparisons show that SSS seems to be an effective IS and suitable for earthquake protection of both structural and non-structural elements. Further research aimed at additional validation of the system are outlined.

Keywords: shape memory alloy; superelasticity; sliding bearing; earthquake protection; aseismic base isolation

1. Introduction

Structural earthquake engineering is aimed at earthquake protection of structures. This goal can be achieved in different ways, classified into two major categories known as capacity increasing and demand reducing strategies. Increasing the capacity against earthquakes is the strategy of mostly used aseismic methods that follow the same approach being applied for service loads. The effectiveness of these methods in reducing structural damage is well accepted. Capacity increase, however, leads to higher transmission of accelerations (if the stiffness is increased) and non-reversible deformations (if the ductility is allowed within the structure), while better performances are needed in practice. It is also not practical to continue to increase the stiffness, nor is it cost-effective or easy to increase the ductility. Moreover, since the inherent nature and structural effects of earthquake excitations are different than those of service loads, a different strategy should rationally be adopted against earthquakes. Demand reduction is the proper alternative strategy that may result in improved seismic performances. Base isolation is known as the most effective demand reducing technique for seismic protection of structures, both in earthquake-resistant design and anti-seismic retrofit.

The concept of isolation for aseismic control of structures seems to be more than 40 centuries old. According to the most recent archeological findings, aseismic isolation has first been applied around 2000 BC in ancient Crete, Greece, where the Palace of Knossos was constructed on a layer of sand and gravel to produce a filtering action against earthquakes (Dickson 2016, Alberti 2018). Something like 500 years later, Troy Walls in Turkey were also constructed using the similar method (Failla 2017). The most remarkable application, however, dates to

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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 (Bek *et al*. 2013). A similar application can also be considered for the Parthenon temple of Athenian Acropolis between 447-432 BC (Bayraktar *et al*. 2012). Another 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 in the Forbidden City of Beijing between the years 1406-1420 AD (Izumi 1998). Later, in Peru, the Incas built Dry-stone walls of Machu Picchu Temple of the Sun around the year 1450 AD (Monfared *et al*. 2013).

Aseismic isolation has become a practical reality after 1980s (Kaptan 2013) with the development of Laminated Rubber Bearings (LRBs) made by vulcanization bonding of rubber sheets to thin steel plates in order to overcome the drawbacks of un-reinforced rubber isolators put in practice since 1960s (Ahmadi 2013) following previous applications of rolling and sliding isolators (Naeim and Kelly 1999). Modifications of elastomeric, sliding, and other types of bearings have then been developed in many of projects (Mostaghel and Khodaverdian 1987, Villaverde 2017) as the examples of the oldest and the most recent studies.

Sliding isolators have attracted growing interest of researchers, even though rubber isolators have widely been used in practice (Fallah and Zamiri 2013, JSSI 2016). The increasing interest on sliding Isolation Systems (ISs) mainly arises from the advantages of sliders 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, (iii) lower transmission of the ground motion accelerations into the superstructure, and (iv) stronger stability due to the separate functions of carrying weight and providing isolation (Constantinou *et al*. 1990, Panchal and Jangid 2008). Flat Sliding Bearings (FSBs) are the simplest sliders. FSBs, however, require a proper restoring mechanism. The problem has typically been solved by combination of FSBs with LRBs and/or through geometry by using Friction Pendulum System (FPS). FPS has become a well-known practical IS. There are, at the same time, some limitations with FPS (Calafell *et al*. 2010, Calvi *et al*. 2017). The application of Shape Memory Alloy (SMA) materials (Van Humbeeck 1999, Saadat *et al*. 2002, DesRoches *et al*. 2004, Torra *et al*. 2007, 2009, 2014, 2015, Casciati and Van der Eijk 2008, Casciati and Marzi 2010, Carreras *et al*. 2011, Casciati *et al*. 2017, Casciati 2019) to provide an alternative restoring mechanism for FSBs is a relatively modern approach. Superelasticity with large strain plateaus, acceptable energy dissipation capacity through flag-shaped hysteretic loops, and high fatigue and corrosion resistances are the most favorable characteristics of austenitic SMAs for using in ISs (Wilde *et al*. 1997, Dolce and Cardone 2001, Motavalli *et al*. 2009, Sherif and Ozbulut 2018, Liu *et al*. 2019).

To date, various SMA-based sliding ISs and SMA-based devices that can be used in sliding ISs have been proposed by different researchers including Krumme and Hodgson (1998), Dolce *et al*. (2000), Davoodi *et al*. (2001), Khan and Lagoudas (2002), Cardone *et al*. (2003), Casciati *et al*. (2007), Attanasi *et al*. (2008), Cardone *et al*. (2009), Khodaverdian *et al*. (2012), Ozbulut and Silwal (2014, 2016), Narjabadifam (2015), Fang *et al*. (2015), Zheng and Dong (2017), and Wang and Zhu (2018). Krumme and Hodgson (1998) have invented various configurations for SMA-based energy dissipation. Dolce *et al*. (2000) have originated the application of SMAs in sliding ISs. Davoodi *et al*. (2001) have patented the SMA-based building system. Khan and Lagoudas (2002) have tried the isolation by SMA springs. A model IS with mechanically activated bundles of SMA wires has been tested by Cardone *et al*. (2003). Application of SMA bars has been studied by Casciati *et al*. (2007). An IS including SMA springs has been proposed by Attanasi *et al*. (2008), further studied by Attanasi *et al*. (2009) and Attanasi and Auricchio (2011). Arrangement of SMA wires in vertical and bracing configurations has been introduced by Cardone *et al*. (2009), further studied by Jalali *et al*. (2011) and Cardone *et al*. (2011). Aseismic isolation with horizontally arranged SMAs has been investigated by Khodaverdian *et al*. (2012) for bridges. Closed-loop arrangement of SMA wire bundles has been studied by Ozbulut and Silwal (2014). Application of SMA cables in ISs has been introduced by Narjabadifam (2015). SMA-based ring spring, which can be used in ISs, have been proposed by Fang *et al*. (2015). Application of SMA cables in the closed-loop arrangement has been investigated by Ozbulut and Silwal (2016). A SMA-cable-based sliding bearing that includes also elastomeric pad has been introduced by Zheng and Dong (2017) for earthquake protection of bridges, further studied by Zheng *et al*. (2018) and Zheng *et al*. (2019). U-shaped SMA damper with the capability of being used in ISs has been proposed by Wang and Zhu (2018).

For practical application, however, some major problems remain unsolved. First is the high price of SMA material, second is the complicated behavior of the system due to the combination of SMA-based superelasticity with friction-type nonlinearity, and third is the feasibility of implementation in construction industry and the versatility of the system. The high price of SMA is expected to not be a problem soon because of significant continuous decrease in price due to improving metallurgical technologies and/or the possibility of applying low-price high-performance Iron-based or other superelastic alloys (Beltran *et al*. 2011, Cladera *et al*. 2014, Wen *et al*. 2014, Sakon 2018). The problem with complicated behaviors can also be solved or at least alleviated using simple-structured isolators. As far as the implementation is considered, application of wires is technically preferred to bars (Wang *et al*. 2016) but large-scale elements are required in real structures. Recently developed SMA cables leverage the superior characteristics of SMA wires into large-scale structural elements (Reedlunn *et al*. 2013, Mercuri 2014, Carboni *et al*. 2015, Kitamura 2016, Ozbulut *et al*. 2016, Biggs 2017, Fang *et al*. 2019) and make the practical application possible. In this regard, in this paper, Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS) is proposed based on simple-structured application of the modern SMA cables to practically provide the required self-centering capability for

FSBs. In the next sections, SSS is characterized for its alternative configurations and the practical feasibility of the system is demonstrated.

2. Concept proposal

Practical combination of SMA-based superelasticity and low-friction sliding for aseismic isolation is the idea behind SSS. For the realization of this concept, the FSBs in SSS are accompanied by effectively arranged SMA cables (or wire ropes) that simply connect to the sliding surfaces using the commonly applied thimbles and ferrules. The recentering SMA elements of SSS can also be arranged in conventional configurations. Vertical, diagonal, horizontal, and closed-loop or O-shaped configurations are the conventional configurations known for steel and SMA wires, bars, wire bundles, and cables. These are useful configurations, but the performances can be improved, and the practical limitations can be removed. L-shaped, U-shaped, and C-shaped configurations are the three new configurations, studied to find a way for the above-mentioned enhancements. Structural engineering details are given below for each of the configurations, providing the required technical drawings in both the traditional and industrialized styles of construction as the alternative forms of application of SSS.

2.1 Vertical arrangement of SMA cables

The vertical arrangement of SMA cables results in the first conventional configuration of SSS, which will be referred to as SSS-v, hereinafter. SSS-v is indeed the upgrade of the vertical configuration of SRSBIS (Cardone *et al*. 2009) through the application of SMA cables instead of SMA wires. The arrangement geometry of the SMA cables in SSS-v is shown in Fig. 1(a). A three-dimensional sketch of the cables with their connecting elements (ferrules, thimbles, and the hinging rings) in the case of SSS-v is also provided in Fig. 2(b). The scheme sketched is specifically devised and engineered to obtain a construction-industry-friendly structure making the implementation practical in both the traditional and industrialized styles of construction.

The isolation level of a typical multi-story building equipped with the sliding devices of the system (a pad of polytetrafluoroethylene referred to as PTFE pad and the mirror-polished stainless-steel plate referred to as SUS plate) is represented in Fig. 2(a). The scheme provided in Fig. 2(b) can easily be implemented in the building, connecting the cables to the base slab and the foundation around each column, and this results in the aseismic isolation of the building using SSS-v in the traditional style of construction. Implementation in the traditional style is a mostly on-site process without the need for the utilization of Isolation Units (IUs). In this regard, it can also be referred to as the IU-less style of construction. This is indeed an important practical advantage for SSS, while the utilization of IUs is inherently inevitable for most of the currently-used ISs because of interconnections in their structures.

As far as the industrialized style of construction is considered, a two-point perspective of the isolation level of a typical building is represented in Fig. 2(i) to illustrate how this style of construction looks like. To provide a general view inclusive for all the configurations, the off-site fabricated IUs are shown without the SMA cables mounted. The scheme provided in Fig. 2(b) can be used to obtain the IUs for SSS-v.

A quick comparison with the other configurations in Figs. 1 and 2 shows that SSS-v has the simplest structure. This is the reason that this configuration was introduced first. The behavior, however, will include a high degree of geometric nonlinearity due to the continuous change in the inclination angle of the cables. The self-centering capability seems also to be affected from this nonlinearity. All the relevant details are discussed later in the following sections, comparing the mechanical behavior and the seismic performances to those of the other alternative configurations.

2.2 Diagonal arrangement of SMA cables

The diagonal arrangement of SMA cables within the proposed SSS creates SSS-d as another conventional configuration. SSS-d has a configuration which is mostly used in construction industry along with the utilization of steel braces. Its parent systems, pertaining to the application of SMA elements in the same configurations, are the system proposed by Casciati *et al*. (2007) which is based on the implementation of SMA bars and the bracing configuration of the wire based SRSBIS (Cardone *et al*. 2009). SSS-d can be implemented with various initial inclination angles of SMA cables. The arrangement geometry of the SMA cables in the case of SSS-d is shown in Fig. 1(b), with the inclination angle defined on the figure. The scheme that can be used in both the traditional and industrialized styles of construction is then sketched in Fig. 2(c). As discussed, it is also possible for SSS-d to be used in both the traditional IU-less and currently incorporated and utilized industrialized IU-based styles of construction.

The similarity of the configuration of SSS-d to that of familiar steel braces can be considered as a practical advantage for this configuration of the proposed system. SSS-d, however, requires a high volume of SMAs due to the tension-only nature of cables. As far as the geometric nonlinearity is considered, that will be available at different levels depending on the initial inclination angle of the SMA cables and the behavior of the IS will consequently be affected (details can be found in section 3).

2.3 Horizontal arrangement of SMA cables

The horizontal arrangement of SMA elements is the mostly referred style of the application of superelastic SMAs in ISs. This has been considered in the investigations by Dolce *et al*. (2000), Cardone *et al*. (2003, 2009), Attanasi *et al*. (2008), Ozbulut and Hurlebaus (2010), Khodaverdian *et al*. (2012). This configuration eliminates the geometric nonlinearity and provides the highest degree of self-centering capability. The problem with this configuration, however, is the long length of the SMA elements required for the high strains due to superelasticity. Dolce *et al*. (2000) and Cardone *et al*. (2003) solved the problem by using a mechanical apparatus controlling the large strains in SMA wires. Attanasi *et al*. (2008) proposed the application of coil spring SMA bars to solve the problem. Cardone *et al*. (2009) discussed the practical limitations and proposed vertical and bracing arrangements as two alternative configurations which can effectively reduce the displacement demand. Ozbulut and Hurlebaus (2010) conducted a study of this kind of application referred to as S-FBI, and Khodaverdian *et al*. (2012) studied this configuration without any additional mechanisms, in bridges and similar structures, which allow the application of long SMA elements. The approach followed here is to arrange the cables in multiple horizontal levels to make the application possible in all types of structures.

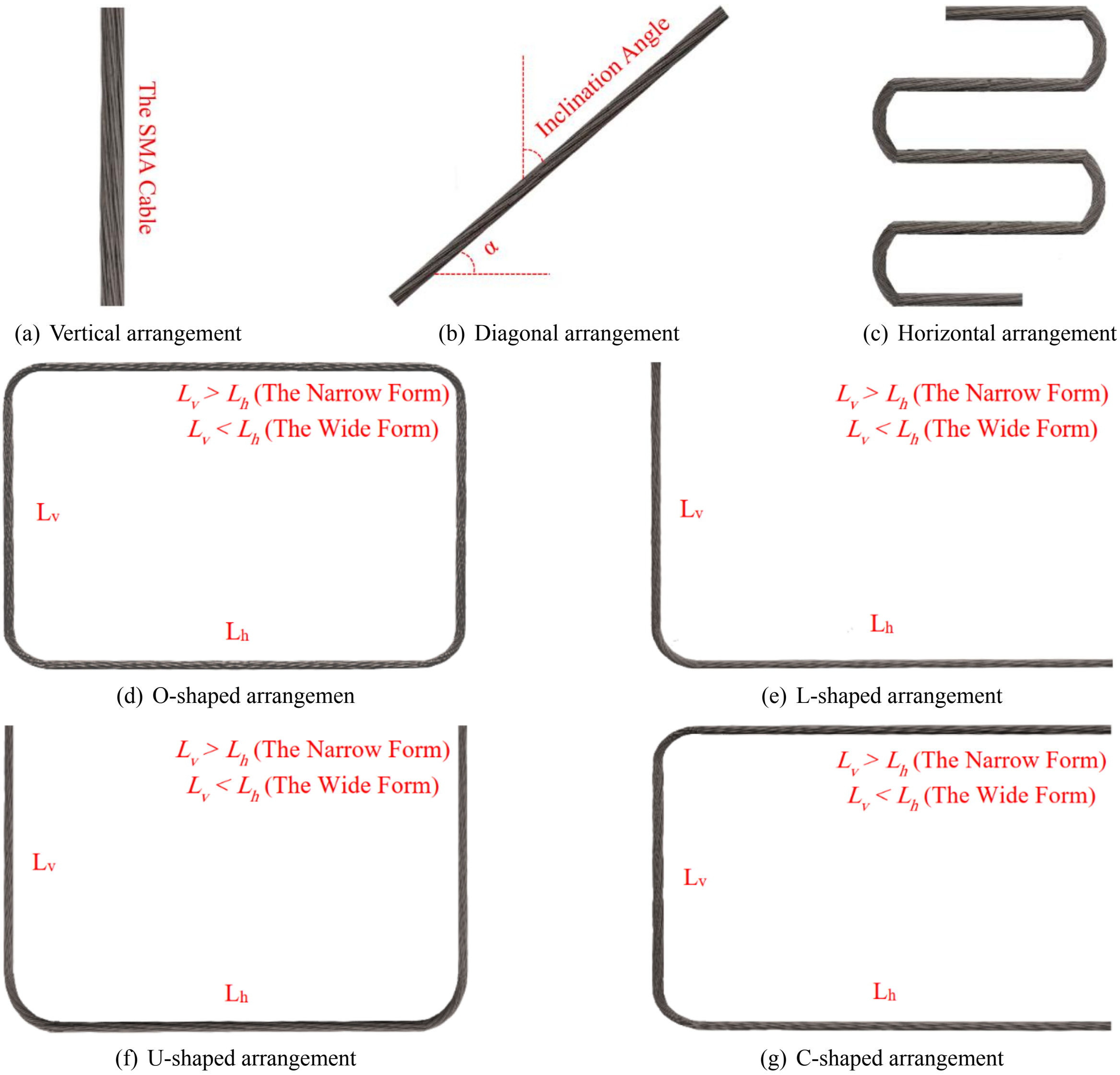
The arrangement geometry of the SMA cables in the case of SSS-h is shown in Fig. 1(c) and the scheme that can be used in both the traditional and industrialized styles of construction is sketched in Fig. 2(d).

2.4 O-shaped arrangement of SMA cables

The O-shaped arrangement of SMA cables results in the last conventional configuration of SSS that will be referred to as SSS-o. This kind of application has previously been investigated by Ozbulut and Silwal (2014) for S-FBI, which was already studied by Ozbulut and Hurlebaus (2010) as an IS with horizontal SMA elements same as those studied by Dolce *et al*. (2000), Cardone *et al*. (2003, 2009). SSS-o provides the possibility of implementation in narrow or wide forms, with respectively longer vertical or longer horizontal dimensions. The arrangement geometry of the SMA cables in the case of SSS-o is shown in Fig. 1(d), defining also the narrow and wide forms.

Similar to the other configurations, it is possible to use also this configuration both in the IU-less traditional style of construction and in the IU-based industrialized style of construction. The scheme that can be used in both the styles of construction is sketched out in Fig. 2(e).

Since SSS-o combines the vertical and horizontal arrangements together, its behavior will consequently vary

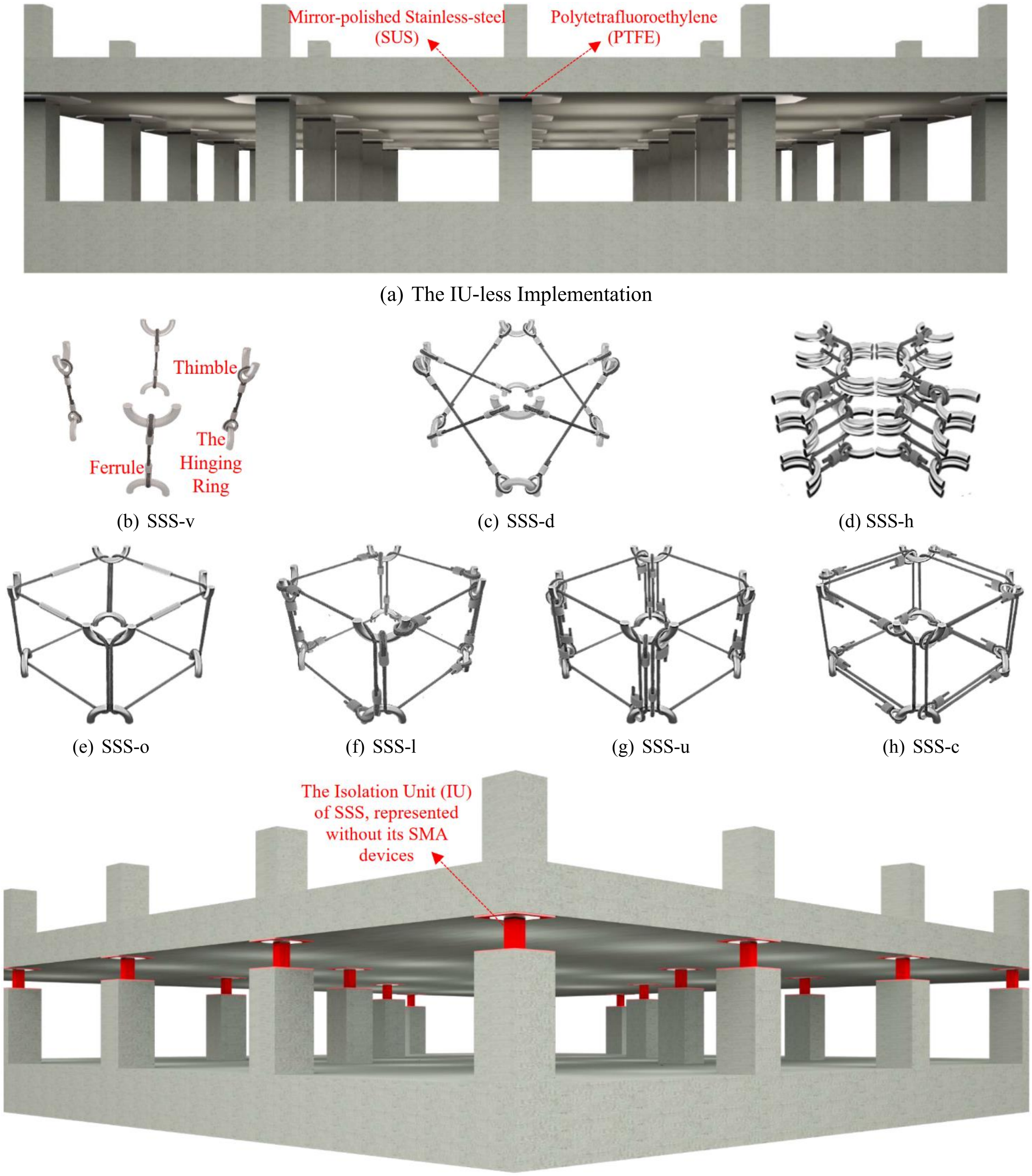


(a) Vertical arrangement (b) Diagonal arrangement (c) Horizontal arrangement

(d) O-shaped arrangemen (e) L-shaped arrangement

(f) U-shaped arrangement (g) C-shaped arrangement

Fig. 1 Alternative arrangements of SMA cables in SSS



(a) The IU-less Implementation

(b) SSS-v (c) SSS-d (d) SSS-h

(e) SSS-o (f) SSS-l (g) SSS-u (h) SSS-c

(i)The IU-based Implementation

Fig. 2 Implementation styles of SSS

between the behaviors of the vertical and horizontal configurations. The extent of the geometric nonlinearity depends also on the ratio between the lengths of vertical and horizontal parts of the SMA cable. All the details regarding the extent of the nonlinearity, the mechanical behavior, and the seismic performances are discussed later in the following sections.

2.5 L-shaped arrangement of SMA cables

The L-shaped arrangement of SMA cables creates a new configuration for the proposed SSS, which will be referred to as SSS-l. In SSS-l, the SMA cables are arranged as L and inverted-L, while only one can also be used. Each cable (L or inverted-L) works similarly in all directions and orientations of earthquake forces. The lengths of horizontal and vertical arms of an L or inverted-L cable can be different, and this will result in wide and narrow forms like those described in the previous configuration. This will also define the mechanical behavior based on the extent of geometric nonlinearity included, depending on the ratio between the lengths of horizontal and vertical arms. If the vertical arm is longer, the nonlinearity will be more than the case when the horizontal arm is longer. As in the cases of other configurations of the proposed IS, SSS-l can be used in both the IU-less traditional style of construction and the more advanced IU-based industrialized style of construction.

The arrangement geometry of the SMA cables in SSS-l is shown in Fig. 1(e) and the scheme that can be used in both the traditional and industrialized styles of construction is sketched in Fig. 2(f).

The mechanical behavior and the seismic performances of SSS-l is expected to be same as those of SSS-o with the same ratio between the horizontal and vertical dimensions. SSS-l, however, is more robust than SSS-o because of the presence of two separate recentering elements in SSS-l instead of one continuous element available in SSS-o.

2.6 U-shaped arrangement of SMA cables

The U-shaped arrangement of SMA cables results in SSS-u as another new configuration of SSS, suitable for structures allowing for larger plan dimensions of the IS. SSS-u is larger in plan, compared to the previously introduced SSS-l and SSS-o with the same heights. This is because the elongation applied by the two vertical arms should be accommodated by the assistance of just one horizontal part of the SMA cable. The plan dimensions of SSS-u are indeed two times of SSS-l and SSS-o. As in the cases of SSS-o and SSS-l, wide and narrow forms are also available for SSS-u depending on the ratio between the horizontal and vertical dimensions of the IS. Geometric nonlinearity in the IS will be higher if the vertical dimension is larger. As it was discussed in the previously introduced configurations, both the IU-less traditional and the IU-base industrialized styles of construction are also possible for SSS-u.

The arrangement geometry of the SMA cables in the case of SSS-u is shown in Fig. 1(f) and the scheme that can be used in both the traditional and industrialized styles of construction is sketched in Fig. 2(g).

2.7 C-shaped arrangement of SMA cables

The innovative C-shaped arrangement of SMA cables creates the last novel configuration of the proposed modern IS, which will be referred to as SSS-c. SSS-c is indeed an optimized configuration, capable of providing effective aseismic isolation with a controllable level of geometric nonlinearity at the minimum space occupied. This is because there are two horizontal arms connected to the only vertical part of the SMA cable. Shorter arms are then required in this configuration for the accommodation of the superelastic strains, topping about 10%, typical for SMAs. More specifically, SSS-c results in more practical IUs for construction practice. For the aseismic base isolation of a typical 3-story building, for example, assuming a length of for example 0.3m for the vertical segment of each SMA cable (L_v) the length of each horizontal segment of each SMA cable (L_h) in the case of SSS-c will be equal to about 0.8 m, while it is about 1.6 m in SSS-o and SSS-l, being equal to about 3.2 m in SSS-u. The variation of L_h against L_v in the last four configurations of the proposed system (SSS-o, SSS-l, SSS-u, and SSS-c) designed for a practical IS displacement equal to 0.3m is discussed later in the next section. SSS-c, such as the previously discussed other configurations of SSS, can be applied in both the traditional IU-less and modern IU-based styles of construction.

The arrangement geometry of the SMA cables in the case of SSS-c is shown in Fig. 1(g) and the scheme that can be used in both the traditional and industrialized styles of construction is sketched in Fig. 2(h).

3. Feasibility study

The characterization of the proposed system in the previous section is followed by a feasibility study in this section by the investigation of mechanical behaviors, seismic performances, and practical considerations.

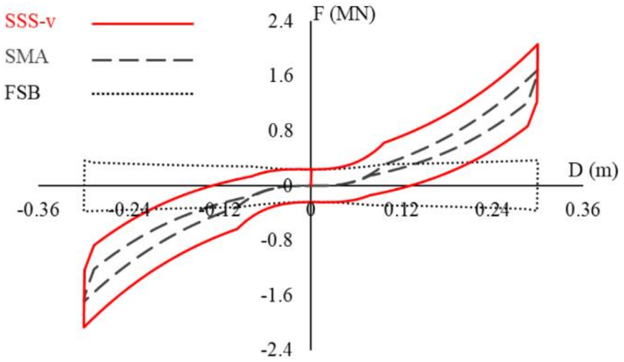
Force-Displacement (F-D) relations are first obtained by explicit mathematical calculations based on a performance-based design developed. Isolation and self-centering capabilities are then examined, practical considerations are investigated, and seismic performances are compared to those of other ISs.

3.1 Force-displacement relations

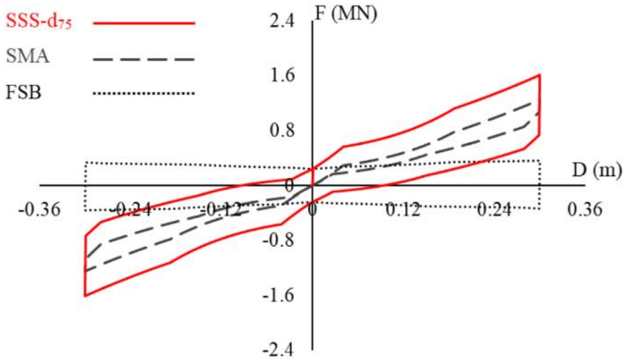
Fig. 3 shows the F-D diagrams of the alternative configurations of SSS designed for the same assumptions. SSS-d is studied in three different cases, based on three initial inclination angles of SMA cables. SSS-d_{75} in Fig. 3(b), for example, has an inclination angle of 25° (see Fig. 1(b) for the details, where α is considered for the design purposes). The extreme narrow (SSS-c_n) and wide (SSS-c_w) forms are reported for SSS-c, representing also the same for SSS-u, SSS-l, and SSS-o. As it was expected, the geometric nonlinearity has the highest effect in SSS-v, decreasing when the inclination angles are increased in the different cases of SSS-d (Figs. 3(b)-(d)). There is no geometric nonlinearity in SSS-h. The effect of geometric nonlinearity in SSS-c (and SSS-u/SSS-l/SSS-o) is always between those of SSS-v and SSS-h. SSS-c_n, with the highest ratio of L_v to L_h, has the highest nonlinearity within the other forms of this configuration when the lowest nonlinearity occurs in SSS-c_w (compare Figs. 3(f) and (g) with Figs. 3(a) and (e)). These differences may result in different performances, discussed in the next subsections, regarding two main criteria.

3.2 Isolation capabilities

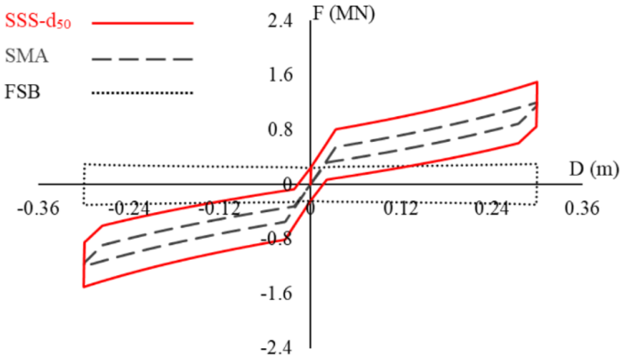
Isolation Capability (IC) is the first performance criterion investigated. Fig. 4 reports on the ICs of SSS with its alternative configurations designed for the same assumptions at various deign displacements (D_d).



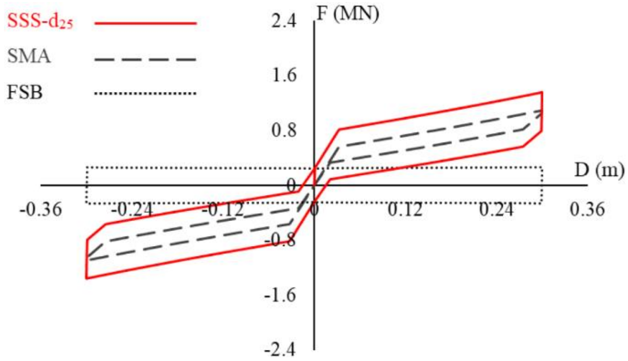
(a) Cyclic F-D behavior of SSS-v



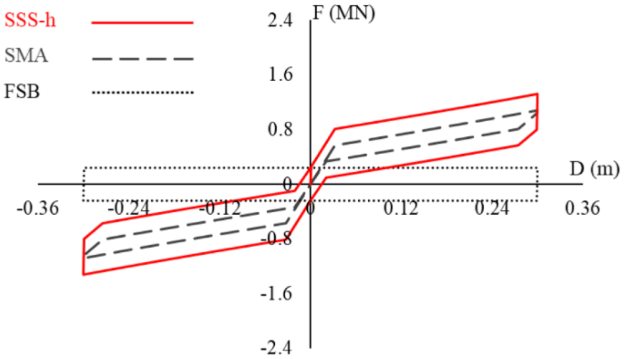
(b) Cyclic F-D behavior of SSS-d with α = 75°



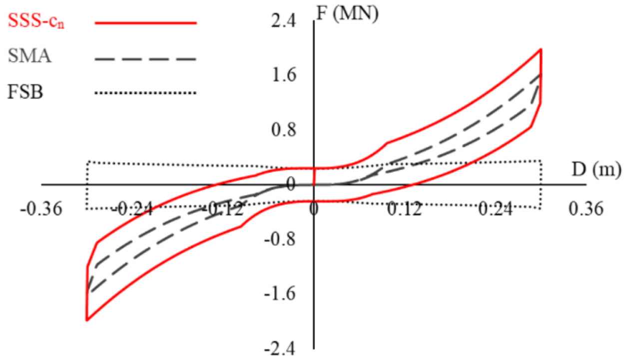
(c) Cyclic F-D behavior of SSS-d with α = 50°



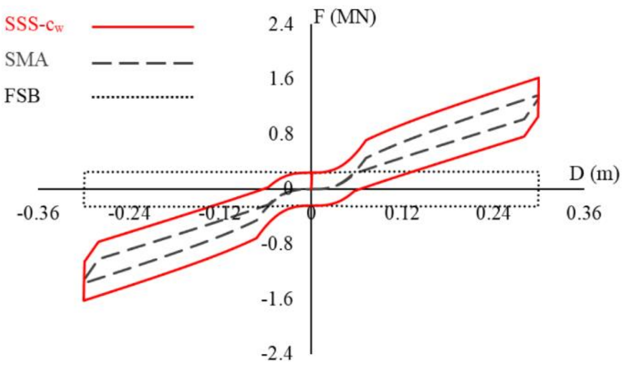
(d) Cyclic F-D behavior of SSS-d with α = 25°



(e) Cyclic F-D behavior of SSS-h



(f) Cyclic F-D behavior of SSS-c in narrow configuration



(g) Cyclic F-D behavior of SSS-c in wide configuration

Fig. 3 Cyclic force-displacement relations of the alternative configurations of SSS

The *ICs* are predicted based on the decreases in seismic demands. This is estimated by increases in the effective periods (T_{eff}) and equivalent damping ratios (ζ_{eq}), controlling the spectral ordinates. Each *IC*, in this regard, is calculated by Eq. (1) according to the specifications of the European code for seismic design (EC8) referred in this study.

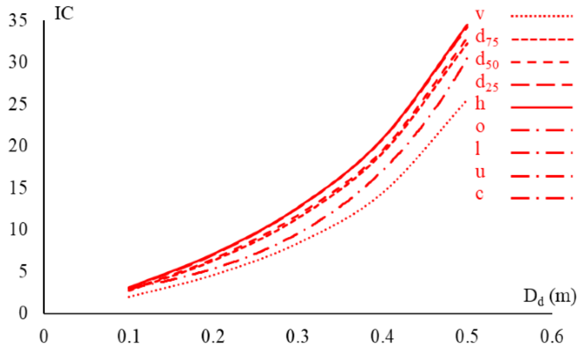


Fig. 4 The *ICs* of alternative configurations of SSS

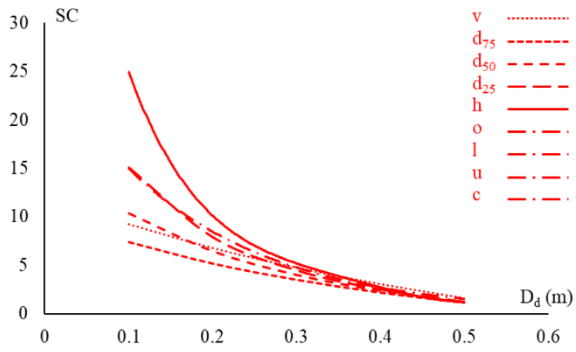


Fig. 5 The *SCs* of alternative configurations of SSS

$$IC = \frac{T^i_{\text{eff}}\sqrt{5 + 100\zeta^i_{\text{eq}}}}{T^f_{\text{fun}}\sqrt{5 + 100\zeta^f_{\text{eq}}}} \tag{1}$$

where T^i_{eff} is the effective period of isolation in the isolated structure, ζ^i_{eq} is the equivalent damping ratio of isolation in the isolated structure, T^f_{fun} is the fundamental period of the fixed-base structure, and ζ^f_{eq} is the equivalent damping ratio of the fixed-base structure. The structure, herein, is a typical multi-story building with the fundamental period of 0.5 s and the equivalent damping ratio equal to 5%, located on soil type C in a high seismicity region according to EC8. Three design angles (α, defined as the complementary angle of the initial inclination angle in Fig. 1) are considered for SSS-d, and in the cases of SSS-o, SSS-l, SSS-u, and SSS-c the average responses over all practical ratios of L_v to L_h (as defined in Fig. 1) are reported. The *IC* of the configuration with vertically arranged SMA cables is always lower than the *ICs* of the other configurations. This is because of the geometric nonlinearity requiring stronger elements in the design of IS and these strong elements result in relatively low *IC*.

3.3 Self-centering capabilities

Self-centering Capability (*SC*) is a fundamental feature of ISs, identified by majority of the current design codes as a practical criterion in aseismic base isolation of structures. The *SCs*, in this study, for all the alternative configurations of SSS are assessed by Eq. (2) calculating maximum values of the restoring forces (F_s) normalized relative to maximum values of the resisting forces (F_r).

$$SC = \frac{F_s}{F_r} \tag{2}$$

where F_s and F_r are both calculated numerically for all the configurations and cases considered.

Fig. 5 shows that the *SC* is highly nonlinear over D_d and the configuration. The maximum and minimum values of *SC* are respectively expected by SSS-h and SSS-d75, referring to the discussions provided already in the previous section. SSS-v has a low *SC* but the *SC* in this configuration changes less than the other configurations, being also slightly more than that of other configurations with D_d

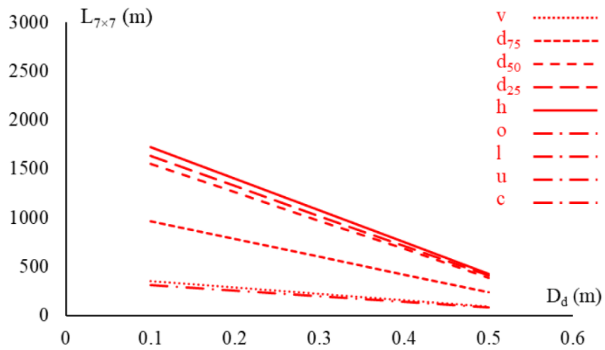


Fig. 6 The total lengths of SMA cables required with the alternative configurations of SSS, assuming the application of the practical 7×7 cables made up of 1 mm diameter NiTi wires

larger than about 0.35 m. It is, however, clear that the *SCs* of SSS-c, SSS-u, SSS-l, SSS-o, and SSS-d25 can be acceptably high for all the practical values of D_d. This preliminary study, then, reveals that the alternative configurations of SSS can be sorted as SSS-h, SSS-d25/SSS-o/SSS-l/SSS-u/SSS-c, SSS-v, SSS-d50, and SSS-d75 in terms of SC.

3.4 Practical considerations

As it was discussed in section 1, the main concerns in the practical application of SMA-based ISs are the cost and the complexity of implementation. It was explained that the problem with the high price of SMA material is expected to be solved soon because of continuous decrease in price due to the improving technologies and/or possibility of using modern alloys. Reducing the cost, however, is always an engineering preference. In this regard, the total lengths of SMA cables required in each alternative configuration of SSS are calculated to assess the cost. Fig. 6 shows the lengths of SMA cables required, assuming the application of the practical 7×7 cables made up of 1 mm diameter NiTi wires.

All the configurations and cases are designed with a practical range of D_d varying between 0.1 m and 0.5 m. As can be seen, the minimum lengths are required in the cases of SSS-o, SSS-l, SSS-u, and SSS-c. The total lengths of SMA cables in SSS-v are slightly more than those in SSS-o, SSS-l, SSS-u, and SSS-c. SSS-h requires the maximum

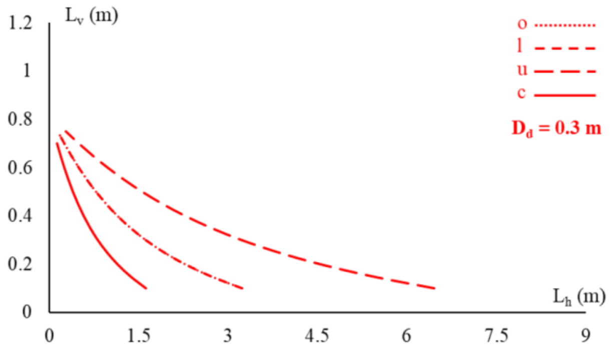


Fig. 7 The variations of L_h against L_v in the practical cases of SSS-o, SSS-l, SSS-u, and SSS-c designed for the same assumptions with D_d equal to 0.3 m

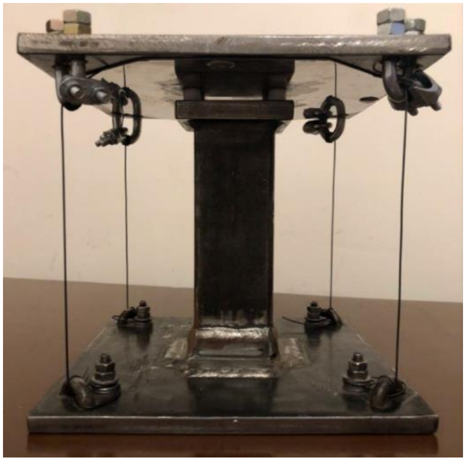


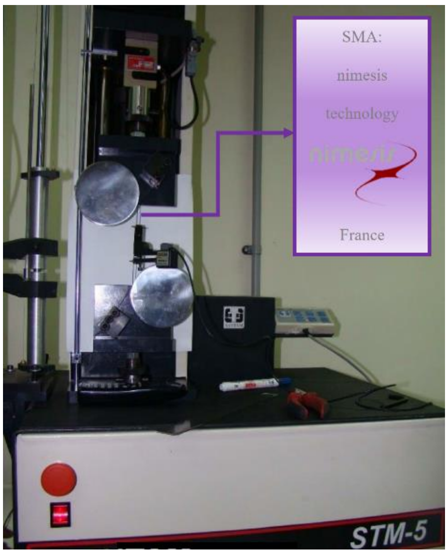
Fig. 8 The 1:5-scale model IU set up for SSS-v

lengths of SMA cables, and the lengths of cables in the cases of SSS-d_{75}, SSS-d_{50}, SSS-d_{25} fall between the maximum and minimum values. So, it can be declared that SSS-o, SSS-l, SSS-u, and SSS-c are much more economical in terms of the lengths of SMA cables required. The geometrical dimensions of the IS (both in the IU-less and IU-based styles of construction) are, however, other important parameters affecting the practical application. As it can be concluded from the discussions provided in section 2, the plan dimensions of SSS-u are four times of those of SSS-c and two times of those of SSS-l or SSS-o, all with the same height. The variations of L_h against L_v in the possible practical cases of SSS-o, SSS-l, SSS-u, and SSS-c designed for the same assumptions are shown in Fig. 7 for D_d equal to 0.3 m. Fig. 7 shows that the application of SSS-u in the traditional style of construction will be possible only in the structures allowing for a long L_h if L_v is shorter and the application in the advanced construction style with IUs is possible only with longer L_v. SSS-l and SSS-o require shorter L_h compared to SSS-u with the same L_v but the IUs again will be available only with larger L_v. SSS-c, however, makes the application more practical due to the shortest L_h required in comparison to SSS-o, SSS-l, and SSS-u with the same L_v.

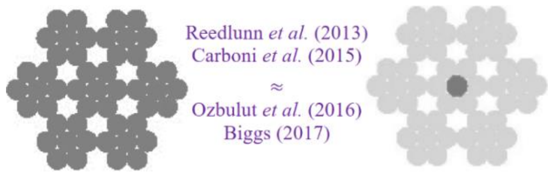
Fig. 7 together with Fig. 6 show that SSS-c is the best configuration of SSS in terms of the minimum length of SMA cables required, the minimum dimensions of IS, and the practicality of IUs. SSS-v can also be considered as an economical IS, because based on Fig. 6 the lengths of SMA cables required are close to those of SSS-c, being highly less than those of SSS-d and SSS-h, even though the *ICs* and *SCs* can be less than or equal to those of these configurations. In this regard, a small-scale IU with the scale factor S_L equal to 5 has been set up for SSS-v to investigate the practicality, when this configuration is also included in a case study to compare the performances of SSS with the other practical ISs.

Fig. 8 shows the 1:5-scale model IU set up for SSS-v with the SMA wires representing 7×7 SMA cables in the prototype (a single-story hospital building located on soil type C in a high seismicity region).

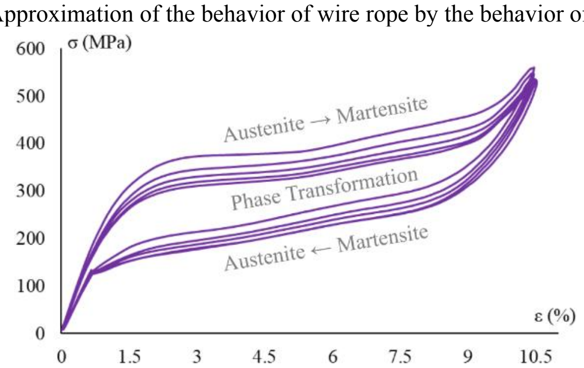
The alloy composition of the wires used in the model IU



(a) The test apparatus



(b) Approximation of the behavior of wire rope by the behavior of wire



(c) The stress-strain behavior

Fig. 9 Characterization of the behavior of SMAs is “Ni(55.9 to 56.2)wt-Ti”, the transition temperature of the material is -35 to -15°C, and the cross-section of each wire is circular (round type) with 1 mm diameter. They had been ordered from “nimesis” (a leading French company) in mid-2013 referring to the advertised product name of “NTSE01” and no more specific material-related information were unfortunately available from the manufacturer. These wires have been considered as the kernel elements of the cables and their superelastic behavior have been characterized through an experimental investigation in accordance with the outcomes of the researches carried out by Reedlunn *et al*. (2013), Carboni *et al*. (2015), Ozbulut *et al*. (2016), Biggs (2017), and Fang *et al*. (2019) summarized in Fig. 9(b). Fig. 9(c) summarizes the results, representing the stress-strain behavior obtained by applying cyclic deformations at the frequency of 0.5 Hz at room temperature (≈ 20°C) which satisfy the criteria addressed by Dolce and Cardone (2001) for the applications of SMAs in aseismic isolation systems. The moving average method is used with force and strain stacks set to 10 to obtain a smooth diagram with 100 samples recorded per second. The test apparatus is shown in Fig. 9(a).

The model IU in Fig. 8 is represented to show the practicality of the proposed system. Specific experiments on the system with cables have not been carried out yet and we are programming for them. The mechanical behavior of the proposed system, however, is typically verified based on the shake table tests of the parent system reported in our previous publication (Cardone *et al*. 2011) when the outcomes of the recent researches on SMA cables (Reedlunn *et al*. 2013, Carboni *et al*. 2015, Ozbulut *et al*. 2016, Biggs 2017, Fang *et al*. 2019) are taken into account. The new computer model developed for SSS is similarly validated regarding the fact that its framework is same as that of the computer model of the parent system investigated by Jalali *et al*. (2010) and Cardone *et al*. (2011) and the only difference is in the hysteresis type upgraded to include the new configurations that are proposed by SSS. The total cost spent to set the model IU up is almost 50 euros, including the money paid for SMAs, PTFE pads with dimpled recesses, SUS sheet, top and bottom steel plates, the steel pier, and connections. As far as the case study is considered, the next sub-section compares the seismic performances of SSS-v to those of Friction Pendulum System (FPS) and High-damping laminated-Rubber Bearing (HRB), regarding the rehabilitation of the case study building located on soil type C in a high seismicity region in southern Italy.

Table 1 Dynamic characteristics of the case study building

Mode number	Period (s)	Mass participation ratios		
		Ux	*Uy*	*Rz*
1	0.60	0.000	0.822	0.000
2	0.56	0.841	0.000	0.003
3	0.55	0.003	0.000	0.835
4	0.18	0.099	0.000	0.006
5	0.17	0.000	0.115	0.000
6	0.16	0.006	0.000	0.103

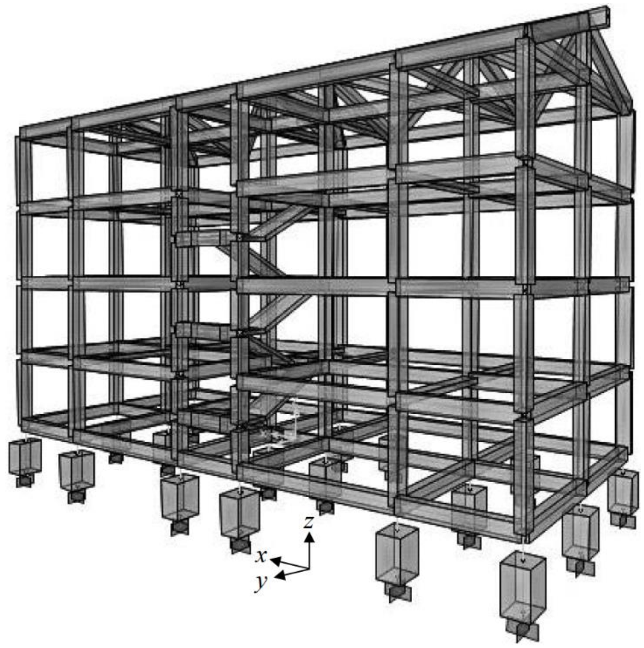


Fig. 10 The structural model of the case study building

3.5 Comparison to other practical isolation systems

Seismic performances of SSS are numerically compared here to those of FPS and HRB, through a case study. The case study building is a four-story moment resisting reinforced concrete residential building, previously studied by Dolce *et al*. (2004). The vertical arrangement of the cables is considered in the IS to obtain the meaningful comparison including all the other configurations that result in better performances referred to Fig. 4. Dynamic characteristics of the case study building are abbreviated in Table 1.

The rehabilitated building is modeled as shown in Fig. 10 using an innovative phenomenological model for the IS. The constitutive law adopted for the sliding material is Constantinou’s friction, which has been developed by Constantinou *et al*. (1990) and calibrated by Dolce *et al*. (2005) for aseismic isolation systems. The model adopted for the SMAs is the superelastic model, which has been proposed by Jalali *et al*. (2010) and validated experimentally by Cardone *et al*. (2011). This structural model has been subjected to seven natural, natural/artificial, and artificial accelerograms suggested by Italian seismic engineering network of laboratories at national universities (ReLUIS: Rete dei Laboratori Universitari di Ingegneria Sismica) for the studies of isolators. The accelerograms are scaled to match (on average) the relevant spectrum of EC8.

Table 2 summarizes the main information regarding the accelerograms used in this study.

The first three records in the table above are natural and the last three records are artificial, when R4 is rather artificial (i.e., natural/artificial) because its duration is doubled to impose higher demands at larger periods.

The set of accelerograms are compatible on average with the type I spectra of EC8 for the soil type C. Fig. 11

Table 2 The seismic actions used in this study

Record	Origin/Earthquake	PGA (g)	Duration (s)
R1	Port Island	0.43	109.98
R2	Kocaeli – 2	0.66	20
R3	Northridge – Baldwin	1.1	60
R4	Kalamata	0.36	60
R5	SIMQKE – Aritif.1	0.6	19.99
R6	SIMQKE – Aritif.2	0.6	19.99
R7	SIMQKE – Aritif.3	0.57	19.99

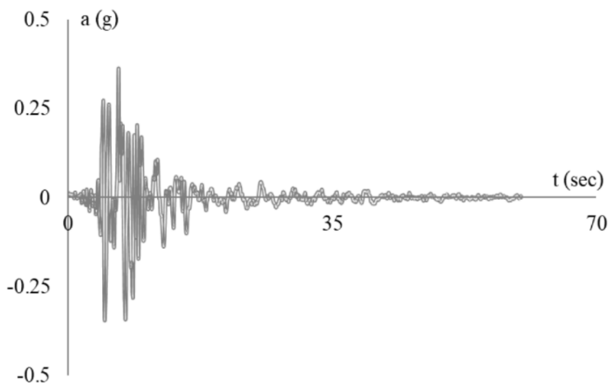


Fig. 11 The acceleration time-history of the record R4

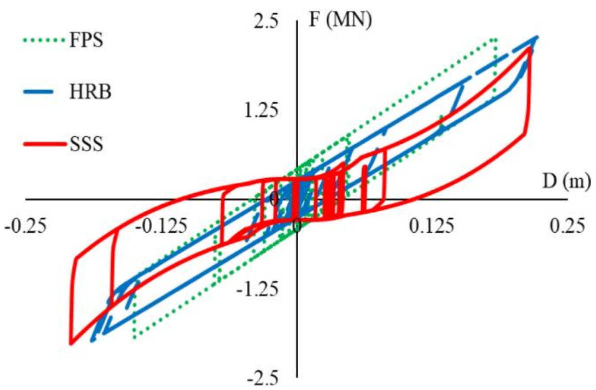


Fig. 12 The force-displacement behaviors of SSS, HRB, and FPS under the case study building subjected to R4

shows the acceleration time-history of the record R4, for example. The force-displacement behavior of SSS under the case study building subjected to this record is compared in Fig. 12 to those of FPS and HRB.

Figs. 13 and 14 compare the seismic performances in terms of story accelerations and drift ratios, respectively. As can be seen, the story accelerations and especially the inter-story drifts in the isolated building subjected to this ground motion are effectively controlled by SSS compared with FPS and HRB. The practical comparison, however, can be sketched out based on the average responses over all the accelerograms. Figs. 15 and 16 compare these average responses between SSS, HRB, and FPS. The maximum values over the stories are compared together.

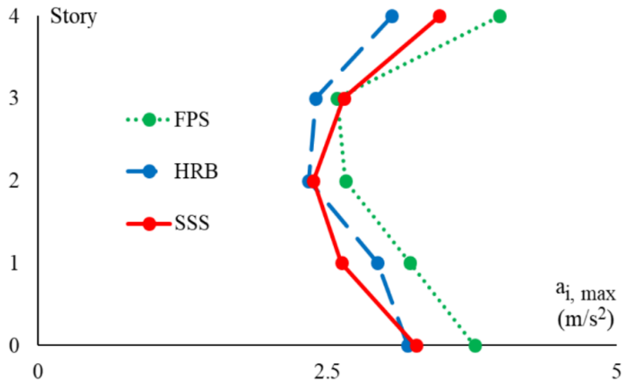


Fig. 13 Maximum story accelerations in the case study building isolated with SSS, HRB, and FPS subjected to R4

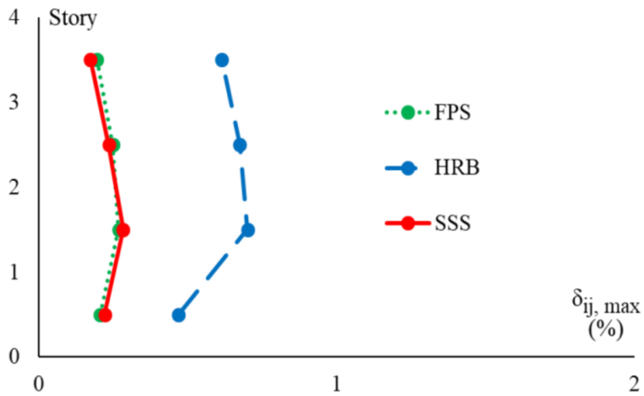


Fig. 14 Maximum inter-story drift ratios in the case study building isolated with SSS, HRB, and FPS subjected to R4

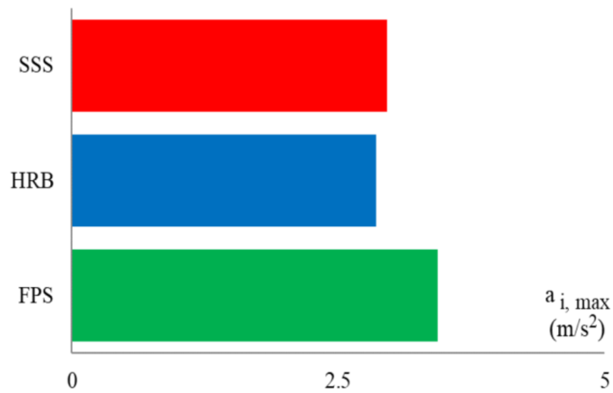


Fig. 15 The maximum story accelerations of the case study building isolated with SSS, HRB, and FPS over all the seven accelerograms

The results show that, even though the rubber isolators generally perform better in terms of controlling the story accelerations, the story accelerations controlled by SSS are closed to those by HRB, being less than FPS. It is also seen that, SSS performs better in controlling the inter-story drifts, compared to both FPS and HRB. These performances make SSS suitable for the aseismic control of both

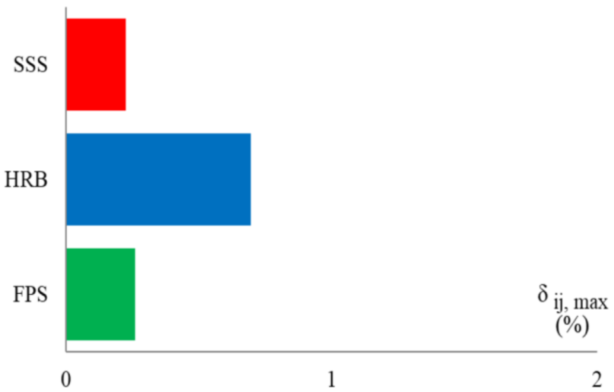


Fig. 16 The maximum inter-story drift ratios in the case study building isolated with SSS, HRB, and FPS over all the seven accelerograms

structural and nonstructural elements, displacement-sensitive or acceleration-sensitive.

4. Conclusions

The paper was aimed at introducing SSS (Shape memory alloy (SMA)-based Superelasticity-assisted Slider) as a practical system for SMA-based aseismic isolation. A thorough review of the literature was first conducted, focusing on the main subject category of the proposed system. In this regard, since SSS falls into the category of SMA-based sliding Isolation Systems (ISs), proposals and scientific engineering studies dealing with combination of SMA-based devices with rubber bearings (Wilde *et al*. 1997, Choi *et al*. 2005, Shinozuka *et al*. 2015, and Hedayati Dezfuli and Shahria Alam 2018) or application of steel cables in ISs (Demetriades *et al*. 1992, Dang *et al*. 2013, and Spizzuoco *et al*. 2017) were excluded from the review provided. The alternative configurations of the system were then sketched out based on detailed technical drawings. The force-displacement behaviors were also examined numerically for the all configurations. The seismic performances were studied and compared to those of FPS (Friction Pendulum System) and HRB (High-damping laminated-Rubber Bearing) as the most famous currently used ISs. As a result of the feasibility study carried out, it was shown that SSS can easily be implemented with or without Isolation Units (IUs), providing effective performances, both in terms of controlling displacements and accelerations. The practice-oriented design and the phenomenology-based computer modeling of the proposed system will be published soon. Following studies are in progress within a comprehensive research program, being carried out through an international collaboration between experts from Asian, European, and American universities and research institutes:

- experimental characterization of the seismic behaviors of the SMA cables (with a layout sensitivity analysis),
- accurate finite element modeling (based on the experimentally characterized behaviors of the cables),
- detailed seismic performance assessment (including a wide variety of far and near -fault records),
- meticulous comparison with all the currently used ISs (regarding both seismic performances and practical considerations), and
- engineering and prototyping (after the performance-based assessment of the system through shaking table tests on small and full -scale models of the IU-based and the traditional styles of application).

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