An overview of research on SMAs with a focus on seismic risk mitigation

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ABSTRACT: Shape Memory Alloys (SMAs) are smart materials that have plenty of distinctive features. Having huge damping capability, combined with good corrosion resistance and ability to recover their original shape up to 8% strain by heating the material or removing the stress, SMAs have been widely investigated for civil engineering applications in last decades. Owing to its high fatigue resistance and re-centering capacity under repetitive cyclic loading, SMA devices or reinforcements can perform well during and after multiple strong seismic excitations without causing any significant residual drifts in the structure. In this paper, after an overview of unique properties of SMAs, such as shape memory effect and superelasticity, recent research on the use of SMAs in terms of seismic risk mitigation such as braces, retrofitting systems, dampers, restrainers, isolation systems and reinforcement are discussed in a comparative manner. Then the benefit of using SMAs as a part of diagonal braces in a substructure system has been demonstrated by numerical modelling and nonlinear time history analyses of these structural systems.

1 INTRODUCTION

Presence of a seismically vulnerable building inventory and exposure of earthquake hazard compose the seismic risk. Today, reinforced concrete buildings form the building stock of many countries. A vast majority of these reinforced concrete buildings especially in developing countries exposed to earthquake hazard were built when the former seismic codes were in force; and those buildings have grave structural deficiencies such as low material quality, inadequate amount of transverse reinforcement, use of plain reinforcement bars, the lack of proper detailing and poor joint details.

For decades, plenty of materials and methods have been investigated appropriately retrofitting inferior buildings to satisfy the de rigueur seismic demand that is recommended in current codes. Among these materials, shape memory alloys (SMAs) have attracted increasing attention in earthquake engineering owing to their various superior characteristics. SMAs have a good damping capability combined with good corrosion resistance. Ability to recover its original shape up to 8% strain by heating the material or removing the stress makes SMAs a promising material for strengthening vulnerable buildings against earthquake actions. Due to its great fatigue resistance and excellent re-centering capacity under repetitive cyclic loading, SMAs can work well during multiple strong seismic loadings without experiencing noteworthy residual displacements in the structure.

An overview of distinctive properties of SMAs and latest research on the use of SMAs in terms of seismic risk mitigation such as braces, retrofitting systems, dampers, restrainers, isolation systems and reinforcement are discussed in this paper. Afterwards, the advantages of using SMAs in the form of a part of diagonal bracing have been demonstrated by numerical modelling and

nonlinear time history analyses of a sub-structure extracted from an actual structure, which collapsed during Kocaeli (1999) earthquake.

2 SHAPE MEMORY ALLOYS

2.1 Characteristics of Shape Memory Alloys

SMAs have two different phases with different crystal structures. One is named martensite phase that is stable at high stresses and low temperatures with monoclinic crystal structure, and the other one is named austenite phase that is stable at low stresses and high temperatures with cubic crystal structure (Janke et al., 2005). SMAs have four characteristic transformation temperatures that are martensite finish temperature M_f, martensite start temperature M_s, austenite finish temperature A_f and austenite start temperature A_s. As seen in Figure 1a, SMAs show two unique responses as a result of reversible phase transformation. Shape memory effect (SME) is that the material returns to the original shape when heated at the temperature that is lower than the martensite finish temperature. In this phase, the material undergoes large residual strain and almost no shape recovery occurs after unloading unless external heating is applied. Superelasticity (SE) is flag shaped response, which is represented in $T>A_f$ range of Figure 1a and Figure 1c, that the material completely recovers large inelastic deformations after removal of the loading at the temperature that is higher than the austenite finish temperature. Superelastic behavior of SMAs dissipate less energy than SME behavior. However, superelastic SMAs do not experience any noticeable residual strain under cyclic loading, and yet they dissipate satisfying amount of energy.

2.2 Types of Shape Memory Alloys

The most investigated types of SMAs are Nickel-Titanium based SMAs. These materials are widely used in biomedical, aerospace, mechanical, civil applications (Zhu and Zhang, 2007); they have excellent corrosion resistance and can recover the achieved strains up to 8%. The system is attributed to equiatomic compound of nickel and titanium. To improve its properties and widen the temperature window of the material, generally a third metal is added to the system or nickel contribution of the system is increased by 1% (Fugazza, 2003). For example, addition of niobium as third element (NiTiNb) grants wider thermal hyseresis and large recovery stress (Dommer and Andrawes, 2012)

Although NiTi is the most used alloy, currently less expensive alternatives such as Copper based and Iron based alloys are also being investigated intensely due to the high cost of NiTi. The main advantage of Cu-based alloys is that these materials have superelastic behavior at a wide temperature range of -65 to 180 ºC. Thus Cu-based SMAs are suitable for outdoor applications. However, relatively limited amount of strain recovery ability and low corrosion resistance are the major weaknesses of these alloys (Ozbulut et al., 2011). Iron based SMAs show relatively low shape recovery, larger hysteresis, high ductility and secant stiffness compared to NiTi alloys. These alloys are extremely attractive for prestressing applications since the prestressing of SMA is carried out by heating and there are no friction loss and no space needed for force application (Cladera et al., 2014).

2.3 Thermomechanical Behavior of SMAs

As aforementioned, phase transformation can be induced either by stress or by temperature. Figure 1a depicts the temperature-induced phase transformation of a NiTi alloy. Ambient temperature is not only important for phase-transformation of the alloy, but also critical for mechanical properties of the alloy in terms of hysteresis size. Figure 1b represents the stress-strain diagrams of a NiTi alloy at various temperatures. The residual strain, damping capability which

depends on the size of hysteresis curve, and transformation stress values vary with changes in temperature.

Potential of using SMAs for seismic mitigation has led researchers to investigate the behavior of SMAs under cyclic loading. Figure 1c shows the cyclic behavior of a superelastic NiTi alloy, (Malecot et al., 2006). To achieve a stable response, it would be beneficial to make the cyclic training a couple of times according to cyclic loading tests.
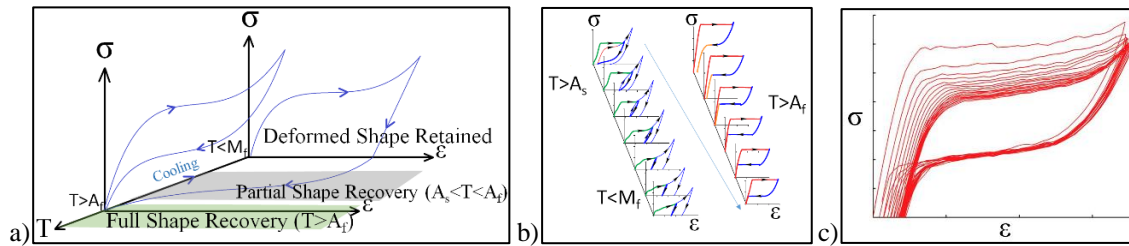

Figure 1. a) Temperature induced phase transformation, b) Phase transformations of a SMA at various temperature, modified from Churchill et al. (2009), c) Cyclic behavior of NiTi alloy at 25 °C, modified from Malecot et al., (2006).

Prestraining the SMAs changes the phase transformation temperatures. Park et al., (2011) performed an experimental research on prestraining. As seen in Table 1, the temperature window of a NiTiNb wire expands significantly with prestraining. The authors above claimed that the wire without prestrain has too low A_s value to store the deformed SMA wires under ambient temperatures of the seismically active regions. To achieve desirable characteristics for ambient temperature and to widen the difference of A_s-M_s temperatures, prestraining the alloys would be useful for outdoor applications.

Table 1. Temperature window of the NiTiNb wires with/without prestrain, (Park et al., 2011).

Prestrain	M_f °C	M_s °C	A_s °C	A_f °C	A_s-M_s °C
Without prestrain	-65.9	-33.7	-9.5	22.0	24.2
With prestrain	-74.3	-17.6	104.9	139.2	122.5

3 APPLICATION OF SHAPE MEMORY ALLOYS IN SEISMIC MITIGATION

Having unique characteristics as a smart material that do not exist in most of the common materials in civil engineering, SMAs offer innovative seismic mitigation techniques. These alloys have a variety of different applications such as re-centering devices, dampers, braces, reinforcements, restrainers, prestressing and active confinement. A brief summary about recent research is presented in this section.

To improve the seismic performance of concentrically braced frames, Jalaeefar and Asgarian (2013) developed a hybrid damping device with re-centering and energy dissipation characteristics. As seen in Figure 2a, the damping device is formed of two rigid plates at each end that are connected with 8 mm diameter bars. The bars are made up of either superelastic SMA or structural steel. To obtain the optimum SMA/steel ratio, a parametric study is conducted (Figure 2b). An increase in SMA/steel ratio enhances re-centering capacity, on the other hand it also decreases the energy dissipation. Stress-strain curves for all values of SMA/steel ratios are represented in Figure 2c. Afterwards, a self-centering hybrid damper (Figure 3a) that is consisted of two components: (i) two pairs of transverse SMA wires as re-centering component, (ii) a steel pipe as energy dissipation component upon yielding developed by Asgarian et al., (2016). Cyclic

performance of the damper is evaluated through numerical modelling. Later, a parametric study is performed to compare the relation between energy dissipation capacity and re-centering ability, which showed that energy dissipation capacity decreases while re-centering ability increases (Asgarian et al., 2016).
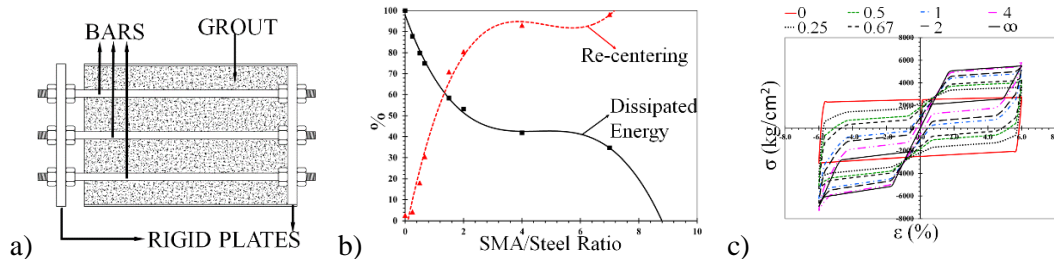

Figure 2. a) Details of the hybrid device, b) Optimum SMA/steel ratio, c) Stress–strain curves for all eight dampers, modified from Jalaeefar and Asgarian (2013).

Hooshmand et al., (2015) proposed a cost efficient hybrid brace that is composed of steel and SMA. A parametric study with time-history analysis was carried out to find an optimum SMA/steel ratio for the brace, which is shown in Figure 3b. Analysis unveiled that using 20% SMA in the brace provides 54% improvement in seismic performance in terms of strain energy while using 100% SMA provides 94%. Seismic isolation devices and energy-dissipative braces were developed and produced within a EU project named as Memory Alloys for New Seismic Isolation Devices (Figure 3c). Laboratory tests demonstrated that the oscillation frequency did not affect the secant stiffness and equivalent damping of the devices at the earthquake frequency window. Moreover, release tests were conducted on a small building (Dolce et al., 2001) to monitor the performance of the SMA based isolation device. After, 140 mm top displacement was applied to the structure, then structure was released. Due to re-centering ability of the SMA device, the structure recovered the given displacement. Figure 3d demonstrates the free vibration history of the structure (Dolce et al., 2001).
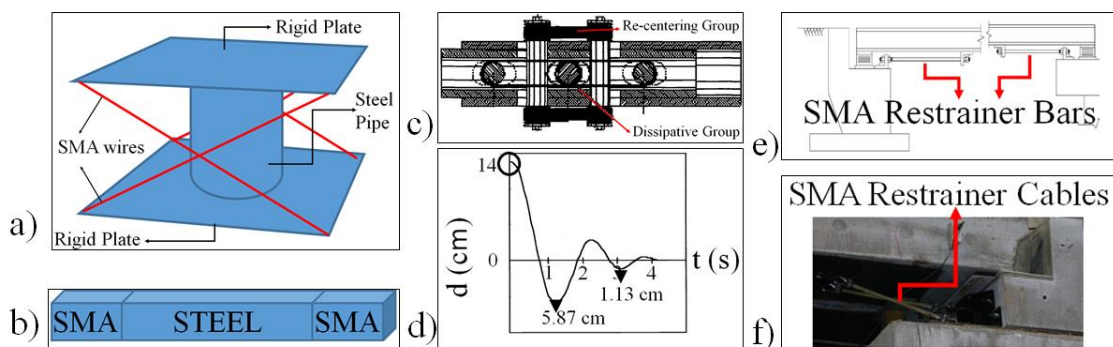

Figure 3. a) F.E. model of the hybrid damper, modified from Asgarian et al., (2016), b) Steel-SMA hybrid brace, modified from Hooshmand et al., (2015), c) Schematic view of the proposed SMA device, modified from Dolce et al., (2001) d) Isolated building subjected to test, modified from Dolce et al., (2001), e) SMA restrainers used in a scaled multi-span bridge test, modified from DesRoches and Delemont, (2002), f) SMA restrainer placed in the four-span bridge, modified from Padgett et al., (2009).

Efficiency of SMA restrainers was examined by DesRoches and Delemont, (2002). Configuration of the SMA restrainer bars used in the bridge abutments is shown in Figure 3e. Time-history analysis showed that the bars were subjected to strains up to 8% and residual displacements were negligible. Padgett et al., (2009) tested four span RC slab bridge with superelastic SMA restrainer cables on a 1/4th scale experiment (Figure 3f). Main objective of the design was a 50% reduction

in hinge openings. The results demonstrated that SMA cables reduced hinge openings and column drifts by 52% and 47% respectively.

Being damaged during an earthquake in 1996 (M_w=5.4, PGA_{NS}=0.20g, PGA_{NS}=0.13g), Trignano S. Giorgio Church Bell-Tower (Figure 4a) was retrofitted by superelastic SMA devices, which consist of 60 NiTi superelastic wires of 1 mm diameter and 300 mm length, and prestressed steel tie bars at the corners of the structure (Figure 4b) (Indirli et al., 2001). SMA devices were placed at the third level of the tower. Anchorages at the top of the building and the foundation were used to establish the retrofitting scheme. Dynamic tests indicated that the modal periods of the bell-tower were significantly decreased after the strengthening (Before retrofitting: T_{NS}= 0.44s and T_{NS}= 0.38s, after retrofitting: T_{NS}= 0.31s and T_{NS}= 0.29s). The structure also performed well during a similar seismic event in 2000, which occurred after retrofitting. Investigations after the main shock revealed that the structure performed well under seismic loading.

Seismic performance of Al-Sultaniya and Qusun Minarets were evaluated by El-Attar et al., (2008) and retrofitting schemes proposed. Then, 1/16th scale model of a minaret was constructed and an experimental study, as well as numerical simulations was conducted with/without SMA wire dampers. The retrofitting scheme consisted of combination of SMA wire dampers and vertical pre-stressing cables. The object of the dampers was reducing seismic response while pre-stressing cables were designed to reduce the tensile stresses in the stone blocks. The results show that retrofitting technique satisfactorily reduced the tensile stresses and improved dynamic response.

Elbahy et al. (2018) come up with external application of superelastic SMA bars as a retrofitting technique for RC joints. Note that elastic modulus of SMA is less than structural steel. Thus, to provide that behavior of the beam at the plastic zone is governed by SMA bars, the authors proposed cutting the steel reinforcement in the external reinforcement region. Two 3/4 scale RC beam-column joints (Figure 4c) -while one of them was reinforced with structural steel, the other was reinforced with superelastic SMA bars at the plastic hinge region - were tested in laboratory by Youssef et al., (2008). The results show that specimen with steel reinforcement dissipates more energy as a result of the larger plastic deformations of the steel. Nevertheless, the specimen with SMA reinforcement shows negligible residual strain even after experiencing large deformations. A second work was published by Nehdi et al., (2011) subsequently. Specimen with SMA reinforcement in the previous work was repaired by removing the damaged concrete, then it was tested again. As before, the repaired specimen experienced minor residual strains.
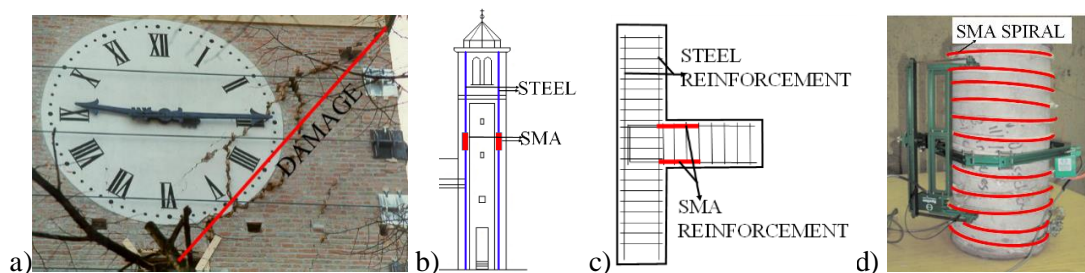

Figure 4. a) Damage on historical bell-tower (Reggio Emilia, Italy), modified from Indirli et al., (2001), b) Retrofitting scheme, modified from Indirli et al., (2001), c) Reinforcement detail of the specimen, modified from Youssef et al., (2008), d) Active confinement application, modified from Andrawes et al., (2010).

SME property of the SMA can be used as a technique to obtain active confinement pressure. Andrawes et al., (2010) performed an experimental study to investigate the efficiency of SMA spirals as active confinement for circular columns (Figure 4d). The proposed technique provides 15% increment in ultimate strength and 310% increment in ultimate strain. SME can also be used

in prestressed concrete applications. Czaderski et al., (2015) investigated a cost-efficient method for prestressing concrete by using prestrained Fe-based SMAs. This method has numerous advantages over conventional prestressing technique, such as not requiring for anchor heads, hydraulic jack and avoiding prestress force loss due to friction.

4   ANALYTICAL STUDY

A single span one-story frame of a 5 story building that was collapsed during 1999 Kocaeli Earthquake was analyzed. Later, to satisfy the seismic demand of the strong ground motion record, a cross braced retrofitting scheme (Figure 5a) with HSS8x8x5/8 steel profile is adapted from Hooshmand et al., (2015). Different than the study of Hooshmand et al., (2015), this study focused on retrofitting seismically deficient frames. Ten percent of the brace length is modelled as superelastic SMA profiles at both ends. SMA and steel parts have same cross-section. Connection of braces to beam-column joints are modelled as hinges. Using Yarımca (YPT00) record (Figure 5b) of the earthquake is a valid approach by the fact that the building was built in Körfez district of Kocaeli, near Yarımca neighborhood. Seismostruct software is used to perform nonlinear time-history analysis. The frame is modelled to represent common deficiencies of RC buildings that were built when former earthquake codes were in force, such as plain reinforcement rebars, low strength materials (220 MPa for steel reinforcement and 16 MPa for concrete) and poor reinforcement details. The columns and the beam are modelled as inelastic force based frame element. Performance levels for nonlinear time-history analysis according to Turkish Building Earthquake Code 2018 (TBDY) are given below.

$$\varepsilon_c^{(G\ddot{O})} = 0.0035 + 0.007\sqrt{\omega_{we}} \leq 0.018 \qquad \varepsilon_s^{(G\ddot{O})} = 0.4\varepsilon_{su} \qquad (1)$$

$$\varepsilon_c^{(KH)} = 0.75\varepsilon_c^{(G\ddot{O})} \qquad \varepsilon_s^{(KH)} = 0.75\varepsilon_s^{(G\ddot{O})} \qquad (2)$$

$$\varepsilon_c^{(SH)} = 0.0025 \qquad \varepsilon_s^{(SH)} = 0.0075 \qquad (3)$$

In these equations, ε_c, ε_s, ε_{su}, GÖ, KH, SH express strain of concrete, strain of steel, ultimate strain of steel, collapse prevention, life safety and minimum damage limit states respectively. ω_{we} term is related with effective confinement, which is neglected due to the assumption that the structure does not have proper confinement.
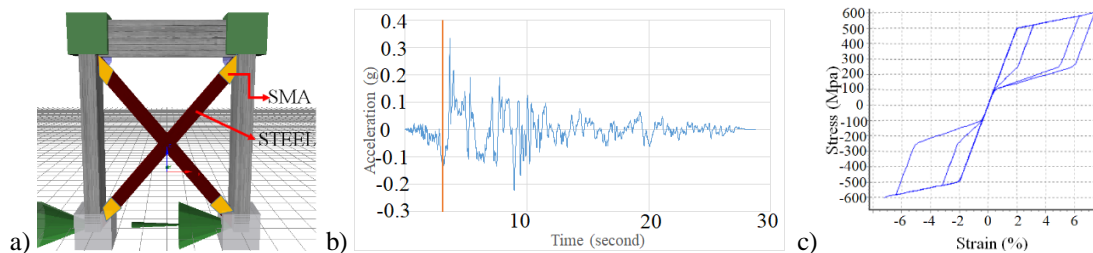

Figure 5. a) Retrofitting scheme, b) The seismic excitation used in analytical study, t=3.1 s is marked to highlight the time that both columns of the existing frame reach the collapse prevention limit state (taken from PEER NGA database), c) Stress-strain model of the superelastic SMA.

Figure 6a shows the displacement-time histories of the frames. At 3.1 second of the analysis, both of the columns frame without braces reach the collapse prevention limit state. Afterwards, the existing frame cannot withstand further seismic actions and it fails. Different than the existing frame, at t=3.7 s., beam of the retrofitted frame reaches the minimum damage limit state for steel reinforcement while the columns of the retrofitted frame do not reach any limit state. Bending moments of the columns of the retrofitted frame are reduced up to 79.4% at the time when frame

without retrofit is failed (Figure 6b). Note that, displacement demand of the retrofitted frame is also reduced significantly.
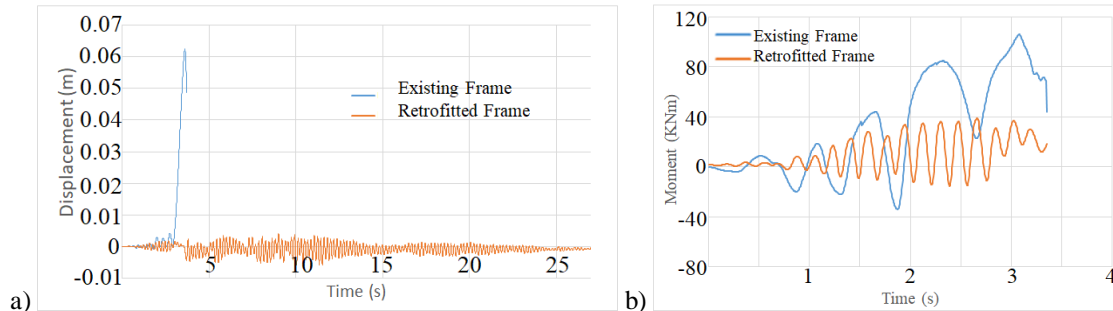

a)   b)

Figure 6. a) Displacement-time histories of the existing and retrofitted frames, b) Comparison of the moment-time histories of the existing and retrofitted frames,

5   CONCLUSIONS

Basic properties of the shape memory alloys are briefly discussed. The aforementioned unique characteristics make SMAs prospective materials for engineering. As a result, there have been a great amount of researches to adapt SMAs for civil engineering applications focusing on seismic behavior. To exhibit the potential of the material, recent studies about different types of structural use of the SMAs are compiled. Additionally, a nonlinear time-history analysis on a single span single-story frame of a building that collapsed during 1999 Kocaeli Earthquake is conducted. An earthquake record that was recorded at the same location was used directly. A SMA-steel hybrid brace system is proposed to make the frame withstand the corresponding seismic excitation. The analysis showed that the brace system is able to reduce the seismic moments and residual displacements in the columns to a level that the frame could survive after the earthquake with only a slight damage.

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