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STRUCTURAL APPLICATIONS OF SHAPE MEMORY ALLOYS FOR SEISMIC RESILIENCE ENHANCEMENT

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Abstract. *Shape Memory Alloys (SMAs) are metallic materials with advanced properties enabling them to recover their initial geometry by the application of heat or by unloading which indicates the shape memory and the superelastic effect respectively, through the phase change (austenitic-martensitic). The discovery of their special nature was made in the 1960s. It was noticed that they possessed a shape recovery capability, apart from their good mechanical properties, a characteristic that since then has made SMAs popular in a wide range of industrial fields. As far as engineering applications are concerned, research studies of implementations of the SMAs have increased in recent years. In the present paper a comprehensive and thorough look is attempted to familiarize with their use for structural engineering purposes while particular emphasis is shown to their deployment towards improving buildings' seismic resilience. In this framework, recent advances in scientific research are summarized and presented aiming to provide an up-to-date scientific knowledge, highlighting thus also the SMA potential in construction sector.*

1 INTRODUCTION

Shape memory alloys (SMAs) are metallic materials with special properties enabling them "to recover their original shape after mechanical distortion via the application of heat which indicates the shape memory effect, or by unloading, which indicates the superelastic effect" [1], exhibiting zero or insignificant residual strain. These advanced properties are the consequences of the material phase change (austenitic-martensitic). The reversible switching between the phases in SMAs and the associated changes in the mechanical properties allow for a wide variety of applications such as aerospace, automotive, dental, biomedical and as dissipation devices in earthquake engineering. Shape memory alloys have several advantages some of which are: "ductility, large stiffness at large levels of strain, re-centering capability, excellent fatigue and corrosion resistance, low elastic anisotropy, resistance to repeatable cyclic loading" [2] and that the extent of the martensitic transformation and their hysteretic behavior "can be controlled by the selection of the material composition and various heat treatments" [3]. The wide applicability and the aforementioned advantages of SMAs have made them popular despite their high cost.

There exist several alloys exhibiting the properties discussed above, but not all of them have commercial use. Copper-based alloys such as Cu-Zn-Al and Cu-Al-Ni are low-cost, made via conventional metallurgical methods and commercially available. However, they exhibit instability, impracticability, brittleness and poor thermo-mechanic performance. Cu-Zn-Al alloys have the disadvantage that the martensitic phase is stabilized by long term ageing at room temperatures. This causes an increase in transformation temperature over time and a decomposition of their structure when exposed to high temperatures. Cu-Al-Ni alloys have the drawback that they can be only hot-worked and the final heat treatment has to be tightly controlled to produce the desired product [4].

Nickel-Titanium (NiTi) alloys, on the other hand, have the greatest recoverable strains of commercially available SMAs. They are related to "high stability in cyclic applications", possess elevated electrical resistivity, corrosion resistance and a moderate solubility range, which enables "changes in composition and alloying with other elements to modify their mechanical characteristics" [5]. The temperature at which the phase change associated with the shape memory effect takes place can be adjusted by altering the percentage of nickel and titanium. Manufacturing of NiTi alloys is a difficult task and machining techniques are used with difficulty, facts raising their cost. Despite this drawback, the excellent properties of NiTi alloys make them the most frequently used SMAs for commercial use.

Iron-based alloys (Fe-SMAs), on the other hand, "are most attractive due to their lower cost, higher elastic modulus, and relatively low activation temperature compared to NiTi or copper-based alloys" [6]. The shape-memory effect in Fe-SMAs "is attributed to the stress-induced martensite transformation" from the austenite to the martensite phase "at low and medium temperatures and the reverse transformation at high temperatures (≈100–250 ◦C)" [7].

SMAs have been intensively investigated for their possible use in structural engineering as current research efforts are oriented to the combined use of materials with advanced properties and technologies, possibly endowed with reversibility features, in order to achieve an optimized performance from all points of view [8]. In the present paper a comprehensive and thorough examination is attempted to highlight the use of SMAs in structural engineering applications, as advanced metallic materials, while particular emphasis is shown to their deployment towards improving buildings' seismic resilience. In this framework, recent advances in scientific research are summarized and presented providing a current scientific knowledge, focusing on the SMA potential in construction sector.

2 PHENOMENOLOGY OF SMAS

SMAs are unique materials that "have the ability to form two crystal structures through the rearrangement of atoms within the crystal lattice, the austenitic and the martensitic". "Their features are the consequences of shape changes due to martensitic phase transformations which are reversible diffusionless shear transformations that occur by some form of cooperative movement of a relatively large number of atoms, each being displaced by a small distance relative to its neighbors, and that results in a change in crystal structure. The diffusionless character makes the martensitic transformation almost instantaneous" [9].

The austenitic crystal structure, that SMAs form, is characterized by a "cubic high-symmetry structure stable at higher temperatures, whereas the martensitic one by a monoclinic low-symmetry structure stable at lower temperatures. The austenitic phase is called the "parent" phase and it presents only one crystal orientation direction, which is called a variant, whereas the martensitic phase presents twenty-four variants and their structure depends on the type of the transformation the material has undergone" [9]. This is due to the fact that "when the austenite shears to form the martensite, there are different directions to do this" [1]. In a stress-free state, an SMA is characterized by four transformation temperatures: M_s, M_f and A_s, A_f. The first two indicate "the temperatures at which the transformation of austenite to martensite starts and finishes respectively during cooling" and the latter "are the temperatures at which the transformation of martensite into austenite starts and finishes during heating" [1]. These temperatures can be perceived in the schematic representation of a superelastic loading path [10], illustrated in Figure 1a.

The shape memory effect is the ability of an SMA material to recover its original shape after being deformed through thermal cycling (Figure 1b). If the temperature is below M_f, the SMA is in its twinned martensitic phase. When a stress above a critical level is applied, the material transforms to detwinned martensite phase and retains this phase upon the removal of the load. [11]. The residual strain recovers by the reverse transformation from martensite to the parent phase upon heating to temperatures above A_f.

The superelastic effect regards "the loading and the unloading of an SMA in the austenitic state that results in a hysteresis loop with zero or insignificant residual strain. This is due to the fact that the austenitic phase is loaded elastically up to a "yield" stress where a stress-induced transformation from austenite to martensite takes place" [9]. The martensite that is formed due to the application of stress is called "detwinned" martensite or "stress-induced martensite" and its formation process consists of the spatial re-orientation of the original martensite variants. The product phase is then called single-variant martensite and is characterized by a detwinned structure [12]. During transformation the proportion of the specimen that has been transformed to martensite progressively rises and the stress-strain curve follows a stress plateau until the martensite is fully detwinned. After the complete transformation to martensite further straining causes its elastic loading at a modulus lower than that of elastic austenite but much higher than that of the phase transition portion of the loading curve. Upon unloading, since martensite is stable due to the presence of the applied stress, the reverse transformation takes place but at a lower stress plateau. After full unloading, the material ideally returns to its undeformed geometry [13], as illustrated in Figure 1c. Overall, the loop presents "high stiffness for small strain levels, reduced stiffness for intermediate levels of strain due to the formation of martensite and high stiffness at large levels of strain due to the elastic loading of martensite" [9]. Also, it usually presents "higher critical transformation stress and smaller reverse transformation stress due to the strong orientation dependence of the martensitic transformation" [9]. There are limits to stress ranges between which superelastic deformation can occur. Excessive stress will lead to irreversible plastic deformation and the superelastic effect will not be exhibited.

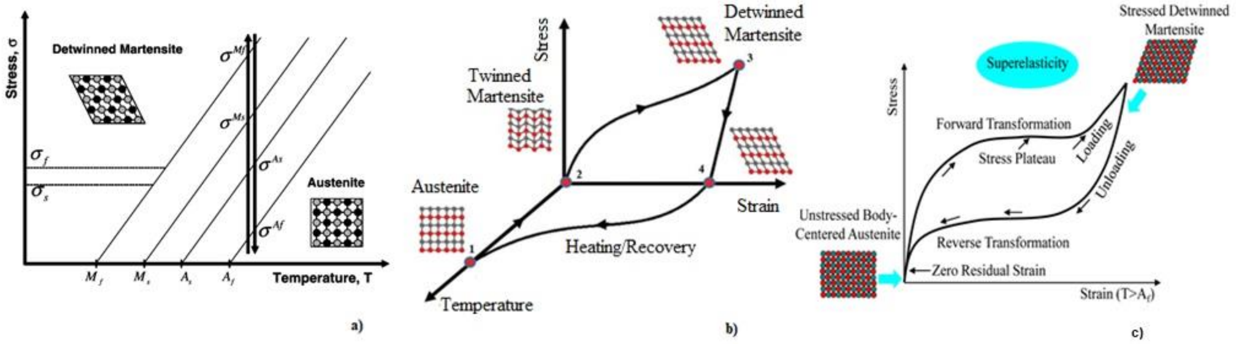

Figure 1. a) A superelastic loading path [10], b) Schematic stress-strain curve of the shape memory effect of SMAs [14], c) Schematic stress-strain curve of superelastic effect of SMAs [15]

3 TECHNOLOGICAL EVOLUTION

The discovery of the special nature of SMAs was made in the 1960s at the U.S. Naval Ordnance Laboratory in the early phases of research on the 55-Nitinol alloys (NiTi) by Buehler and his coworkers, while investigating materials useful for heat shielding [16]. It was noticed that apart from their good mechanical properties, they possessed a shape recovery capability. The damping change in relation to temperature, the composition of the alloy, the temperature and the mode of plastic deformation, were some aspects that attracted at that time the interest of researchers. In 1965, Wang et al. [17] described in more detail the shape memory effect, and by conducting x-ray diffraction studies on NiTi crystals, proved that the alloy undergoes a martensitic transition, which was recognized to be responsible for its unique physical properties. Later, in 1968 [18], during their study to estimate NiTi alloys suitability for hydrospace applications, they investigated the change of transformation temperature due to the variation of the NiTi composition ratio and the substitution of nickel by cobalt. Results showed that the maximum transformation temperature occurs near stoichiometric NiTi, while the substitution of cobalt decreases the transformation temperatures.

In the following years, the interest of researchers on SMAs grew as they focused on the influence of temperature, loading rate, number of cycles, material composition and mechanical treatment on their response. In 1981, Miyazaki et al. [19] investigated the influence of temperature and the effect of cyclic deformation on the stress-strain curves. They showed that the forward and the reverse transformation stress are influenced by the temperature and the number of cycles. Shaw and Kyriakides in 1995, [20] conducted uniaxial tensile tests on Ni-Ti wires at two different temperatures at isothermal (water) and non-isothermal (air) conditions proving that the self-heating and cooling of the specimen that result from transformations alters the stress required for the forward and the reverse transformation. A few years later, in 2001, Dolce and Cardone [21] conducted experiments on martensite and austenite specimens to evaluate the cyclic behavior as a function of loading frequency and strain amplitude and the fatigue behavior under both ordinary and extreme strain amplitudes. Results on martensite specimens showed that loading frequency seems to affect the results only when passing from static to dynamic conditions, while fatigue resistance was extraordinary compared to usual metals and the specimens exhibited stable and repeatable mechanical behavior. Austenite specimens on the other hand, exhibited low influence of strain rate and a considerable fatigue resistance. The same year, tests on austenite wires [22] under tensile stress focusing on temperature, loading frequency and number of cycles, proved that the increase of temperature has as a result in the upward translation of hysteresis loops. The loading frequency affects the behavior mostly when passing from low frequency to the frequency of seismic interest and the increasing number of cycles deteriorates the energy dissipation capability and increases the strain rate hardening. In 2020, Nespoli et al. [23] studied experimentally the behavior of an NiTi SMA element by conducting "uniaxial tensile tests at different temperatures". Moreover they studied the fatigue behavior by conducting "numerous fatigue tests", performed at different load levels, to determine "the corresponding maximum number of cycles that can be reached without failure". More recently, in 2021, Heredia Rosa et al. [24] investigated the "behavior of iron-based shape memory alloys (Fe-SMAs) subjected to cyclic inelastic straining". The experimental results suggest that "the Fe-SMA under investigation exhibits an asymmetric stress-strain relation, with limited superelastic behavior with strain-rate and temperature dependency". Although the studied Fe-SMA has a similar energy dissipation per loading excursion with respect to conventional steel, the Fe-SMA's hardening response is appreciably higher, leading to comparatively larger elastic strain energies being stored. The same year, Collazo et al. [25] studied the effect of "mechanical and heat treatments" on the microstructure of commercial iron-based SMAs together with an assessment of the transformation temperatures and the kinetics of the transitions. Results showed that the mechanical properties are strongly affected by the thermomechanical history of the material.

4 SEISMIC ENGINEERING APPLICATIONS

4.1 SMA-based energy-dissipation devices

The development of SMA-based energy-dissipation devices has attracted the interest of the research community to achieve vibration control and enhance the structures' seismic resilience. Dolce et al. [26] within the MANSIDE project investigated the design, the implementation and the experimental testing of SMA-based devices (Figure 2a) for passive control of buildings, bridges and other structures. SMA-devices were designed equipped with re-centering austenite wire loops only (SRCD), re-centering austenite wire loops and martensite bars (RCD) and re-centring and dissipating austenite wire loops (RCD). The main targets of the device were to ensure the re-centering capability and at the same time provide energy dissipation. To examine the mechanical behavior of the three categories of the devices cyclic sinusoidal tests were conducted at room temperature as well as tests under different temperature conditions. Results showed excellent mechanical properties that justified the use of SMAs as dissipation devices.

Zhang and Zhu [27] proposed a novel "SMA-based damper" consisting of "two blocks sliding past each other with superelastic SMA NiTi wires attached to them" (Figure 2b). The hysteretic behavior of the damper can be modified to "best fit passive structural control applications by adjusting the damper's design parameters such as the inclination angle of the wires, pretension level, and friction effect". Nonlinear dynamic time-history analysis was carried out to examine the efficiency of the proposed damper incorporated in a steel moment resisting frame structure showing smaller interstory drift when using a pre-strained damper.

Qian et al. [28] experimentally investigated the effectiveness of a new "superelastic shape memory alloy friction damper (SSMAFD)" in seismic vibration control by conducting shaking table tests (Figure 2c). The damper consisted of "pre-tensioned superelastic SMA wires and friction devices". The main function of SMA wires was to provide re-centering capacity and energy dissipation, while the integrated friction devices provide the most energy dissipation. A scaled-down building structure was tested under several representative seismic signals as well as white noise motions. Comparative studies of dynamic behaviors, of the structural model with and without the proposed damper under seismic loading were performed. Results demonstrated that "the SSMAFD was effective in suppressing the dynamic response of the building structure subjected to strong earthquakes by dissipating a large portion of the energy. In addition, with the re-centering capacity of the proposed damper, the structure was able to undergo strong earthquakes without remarkable residual drift under different seismic loads".

Asfaw and Ozbulut [29] examined a new shape memory alloy (SMA) damping device named "confined superelastic dissipator (CSD)", depicted in Figure 2d. SMAs were used as an innovative material that can contribute to realize a resilient structural design. The proposed dissipator consists of "a fused superelastic NiTi SMA bar as the functional kernel component encased in grout-filled steel tube" while "the bar carries the axial load and dissipates energy through axial deformation while the steel tube and infill grout restrain the bar and precludes buckling in compression". The researchers investigated the hysteretic behavior of CSDs through cyclic quasistatic tests. Results showed that "all specimens exhibited stable and flag-shaped hysteretic behavior with excellent self-centering characteristics". Some parameters evaluated were the energy dissipation, equivalent viscous damping, and self-centering capability as well as the effect of geometric parameters such as fuse diameter and bar length on the aforementioned parameters as well as failure mechanisms of CSDs. Based on the experimental results and visual observations of failed specimens, specific recommendations were made to improve the performance of the CSDs.

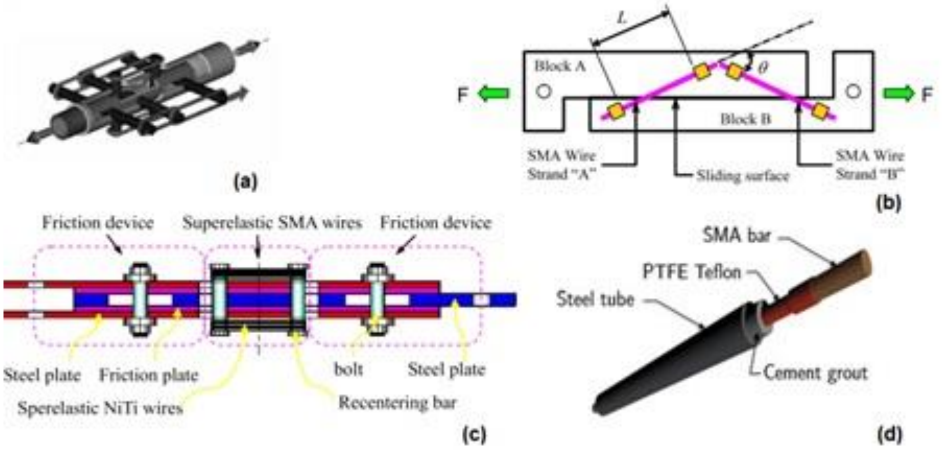

Figure 2. (a) The proposed damper of Dolce et al. [26], (b) The proposed damper of Zhang and Zhu [27], (c) Qian et al. new superelastic shape memory alloy friction damper [28], (d) The confined superelastic dissipator [29].

4.2 SMA-based connectors

Studies have considered the use of SMAs as structural connecting elements. Ocel et al. [30] studied the effectiveness of partially restrained connections using SMA connecting elements, showing promising results for the use of SMA in seismic resistant design and retrofit. SMA-based connections were tested to determine their cyclic behavior. Following the initial loading protocol, the shape memory effect was initiated by heating the SMAs above their transformation temperature and retested. Testing results for the two connections demonstrated stable hysteresis with no pinching behavior, no strength degradation, and good energy dissipation.

Fang et al. [31] investigated the "potential of using NiTi shape memory alloy (SMA) bolts for self-centring connections against seismic action, with the main focus on the influence of composite slab systems on the connection performance". A total of four full-scale connections were tested, one of them is depicted in Figure 3, followed by "a numerical study which comprehensively discusses the influences of varying bolt and slab details". A preliminary design recommendation was also proposed based on the test data and the numerical study result. The results indicated that "the steel specimens, classified as semi-rigid and partial-strength connections, exhibited satisfactory self-centring ability and ductility". The composite specimens, their steel parts were identical to the steel specimens though a composite concrete slab, due to the yielding of the reinforcement and metal deck, accompanied by cracking of the concrete slab, the self-centering ability is compromised to a certain extent. Another observation was that "all the connections showed moderate energy dissipation capacity, with a stable equivalent viscous damping (EVD) of approximately 10% at large deformations".

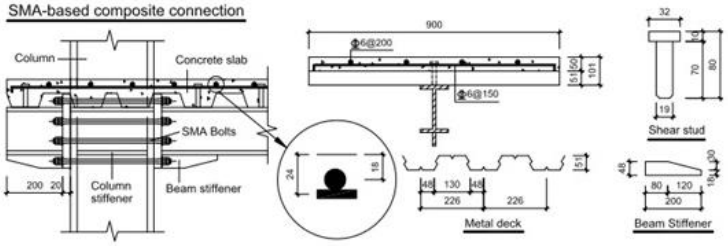

Figure 3. SMA-based composite connection [31].

4.3 Framing systems

Several researchers have studied the application of SMAs as diagonal braces in frame structures. Lafortune et al. [32] studied the "behavior of superelastic SMAs and their applicability to earthquake engineering applications" via the "use of a small-scale shake table" (Figure 4a). Initially, the material behavior of superelastic SMA wire was studied "under loading rates and strain levels equivalent to that expected to be undergone by structural members during an earthquake" to assess the effectiveness of SMA braces to reduce the seismic response of a small scale frame. For this, a finite element model (FEM) of the structure was developed and validated. The effect of pre-straining the SMA wires was also studied experimentally using the small-scale frame and then studied analytically to gain a better understanding of the brace and system behavior. Results showed that "the SMA bracing system provides a consistent reduction in the response due to the re-centering capability associated with the material" compared to the response of a steel braced structure.

McCormick and his co-workers [33] investigated the "performance of both a conventional, concentrically-braced frame system configuration and a concentrically-braced frame system with superelastic SMAs through a series of nonlinear time history analyses to determine the potential of using SMAs in earthquake engineering applications for the dynamic control of building structures", (Figure 4b). This study involved "an extensive analysis of both three- and six story concentrically braced frame systems implementing either conventional steel braces or superelastic shape memory alloy braces". The effect of the unique flag shape and re-centering behavior of the SMA braces on the performance of the concentrically braced frames was evaluated through nonlinear dynamic time history analyses and compared to the performance of the conventional steel bracing system with respect to interstory drift levels and residual roof drift. Results showed reduced column drift ratios for the SMA brace. Moreover, the ability of the SMA braces to provide re-centering leads to smaller overall elongation in the bracing members.

Qiu and Zhu [34] proposed a "performance-based seismic design (PBSD) method for steel braced frames with novel self-centering braces that utilize SMAs" (Figure 4c). The presented PBSD method takes into consideration "some special features of SMA-based braced frames" such as "the variability in the hysteretic parameters of SMAs, such as the phase-transformation stiffness ratio and the energy dissipation factor". To illustrate the efficacy of the proposed design method, four six-story concentrically braced frames with SMA-based braces were designed with different combinations of hysteretic parameters. The seismic performance of the designed frames is examined at various seismic intensity levels. Results of nonlinear time-history analyses indicate that "the four frames can successfully achieve the prescribed performance objectives at three seismic hazard levels". The comparisons among the designed frames reveal that the SMAs with greater hysteretic parameters result in a more economical design in terms of the consumption of steel and SMA materials.

Shi et al. [35] investigated "the seismic and collapse performance of an SMA braced steel frame structure considering the effects of various brace design parameters and ultimate state of SMAs" (Figure 4d). To illustrate the significance of SMA brace failure consideration in seismic performance assessment of steel frames with SMA elements, static pushover and incremental dynamic analysis were employed. The influence of SMA brace initial stiffness and ultimate deformation capacity on the seismic and collapse performance of SMA braced frames were also studied through a series of analysis. The results showed that the SMA brace initial stiffness does not affect the interstory drift and floor absolute acceleration response at design and maximum considered earthquake level seismic hazard or collapse capacity of the frame, but it had considerable influence on post-event functionality of the frame. Another observation was that the SMA brace ultimate deformation capacity should be at least 80% of maximum interstory drift demand at maximum considered earthquake level for satisfactory seismic performance, whereas larger values provide higher collapse capacity for the SMA-braced frame.

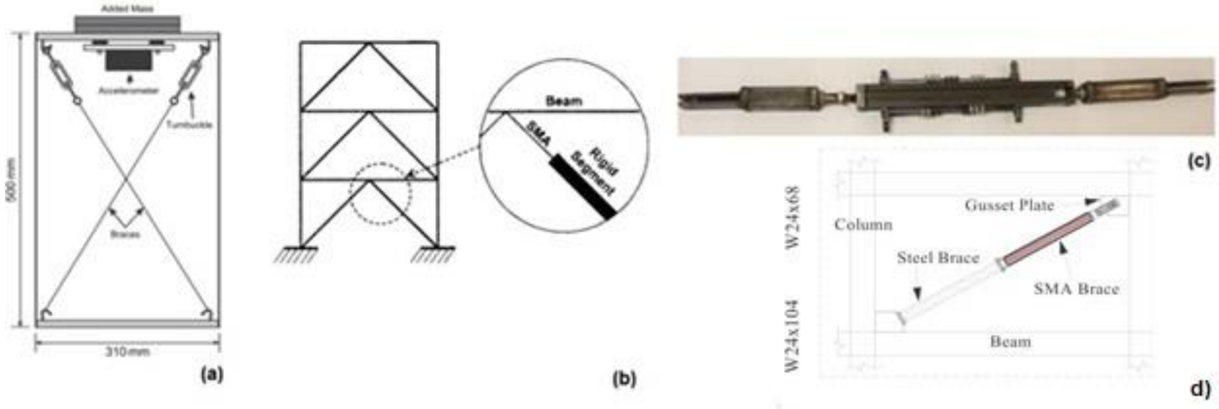

Figure 4. (a) Schematics of the experimental test setup with SMA braces [32], b) Detail of the SMA brace installed in a 3-story frame [33], c) A small-scale prototype of the damper incorporated in steel-braced frames [34], (d) The SMA braced frame building and the configuration of SMA [35]

4.4 Bridges

Research efforts have been made towards the application of SMAs in vibration mitigation in bridges. In 2000, Wilde et al. [36] studied the behavior of "an SMA bar damper added to laminated rubber bearing isolation system". The optimization of the size of the SMA device was performed on the Kobe earthquake record (January, 1995) scaled to different magnitudes. The performance of the proposed smart isolation system was presented together with the performance of a conventional isolation system using lead laminated rubber bearings with an additional stopper device. Results showed that "for a medium size earthquake, the SMA bars increased the damping capacity of the isolation due to stress induced martensitic transformation of the alloy". For the largest considered earthquake, the SMA bars provided hysteretic damping and acted as a displacement controlling device due to hardening of the alloys after completeness of the phase transformation. The damage energy of the bridge with SMA isolation system was small, although the input energy to the structure was large compared to a bridge with lead rubber bearings. Moreover, the SMA isolation system has inherent centering ability due to the superelastic response of the alloy.

DesRoches and Delemont [37] developed and tested under cyclical loads in tension a "25.4 mm SMA restrainer bar" for use in bridges. "The results of the experimental tests are used to develop an analytical model of the SMA restrainer, which is used to evaluate the effectiveness of the restrainer in multi-span simply supported bridges". "To evaluate the effectiveness of the SMA restrainers, an analytical model of the bridge is subjected to a set of ground motion records". A comparison was made between the SMA and commonly used steel restrainers. Results showed that "the SMA restrainers reduce the relative hinge displacements at the abutment much more effectively than conventional steel cable restrainers". The ability of SMAs to the large elastic strain range of the SMA restrainers allows them to undergo large deformations while remaining elastic.

Saiidi and his co-workers were interested in SMA applications in bridges. They conducted experiments [38] on an SMA device to be used as restrainer cable of in-span hinges of concrete bridges, analytical studies [39] on five different bridge types, one of them with superelestic NiTi SMA reinforcing bars and experimental and analytical studies [40] on a novel concept for bridge columns with SMA bars placed inside a plastic hinge element of rubber. Results of all studies proved that the use of SMAs is effective in eliminating damage, constituting them as appealing materials to bridge engineers and researchers.

4.5 Retrofit activities

A number of researchers have investigated the potential use of SMAs in developing advanced seismic protective systems for structure retrofitting. Izadi et al. [41] presented a "new retrofit solution for strengthening metallic I-girders". The retrofit system involves "two iron-based shape memory alloy (Fe-SMA, 'memory-steel') strips" that are mechanically anchored to the girders. The shape memory effect (SME) of the Fe-SMA material has been used to activate/prestress the strips by heating to a predefined temperature. The main advantage of the proposed SMA-retrofit system is that “it can prestress itself without a need for heavy hydraulic jacks, which then results in a significant reduction of the required time, labor works and cost of prestressing process”. A series of static and fatigue four-point bending tests were performed to evaluate the efficiency of the proposed retrofit system, on an SMA-retrofitted beam. The test results indicated that “the Fe-SMAs could be re-activated for multiple times even up to higher temperatures (than the initial activation temperature), which would then result in higher prestressing levels”. These features make the proposed SMA-based system a versatile and adaptable retrofit solution. High-cycle fatigue (HCF) tests showed no slippage in the anchorage system and a stable prestressing in the Fe-SMA members during the tests, which demonstrates the reliability of the proposed system under HCF loading regime.

Czaderski et al. [42] studied a “new iron-based shape memory alloy (‘memory-steel’) in the form of U-shaped (stirrups) ribbed bars were used in combination with sprayed mortar for shear strengthening of reinforced concrete (RC) structures”. The researchers in this study activated the memory-steel bars with electric resistive heating. This activation resulted in a prestress of about 300 N/mm^2 in the memory-steel reinforcement and consequently in vertical compressive stresses in the web of the RC beams. To show the practicability and efficiency of the memory-steel shear strengthening, large-scale experiments on T-beams were performed. Results have shown that “the new strengthening system works well in practice”, allowing for significant increase of the shear capacity. Another observation was that “at the serviceability limit state, the prestressed memory-steel stirrups reduced the overall beam deflections, the stresses in the internal steel stirrups, the number of cracks, and the crack widths”.

Rezapour et al. [43] investigated numerically the “effect of SMA post-tensioning on masonry walls’ behavior”. SMA strips made of Fe-SMA were installed on the wall. They considered two general methods for installing the strips on the masonry walls, vertically and as a cross, using mortar to connect the masonry and the strips. Based on the analysis, the results demonstrated that “the use of Fe-based strips increases the stiffness of the specimens relative to the reference wall” while “cross-strip models have more stiffness than vertical-strip models. In the vertical-strip walls, the stiffness increases by 98.1%, and in the cross-strip model's position, the stiffness increases by 127.9%.”

5 CONCLUSIONS

In this paper, the fundamental knowledge of SMAs and their unique properties have been briefly discussed and the recent applications in structural engineering have been reviewed, highlighting their wide applicability to achieve vibration control and enhance the structures’ resilience.

SMAs are materials with undoubtedly unique properties. They combine the ability to return to their undeformed geometry (re-centering capability) with the energy dissipation capacity which makes them ideal candidates for aseismic applications. These properties are the consequences of their ability to form two crystal structures and perform a switch of the one to the other under particular circumstances exhibiting the shape memory or the superelastic effect. Their mechanical characteristics are affected by various factors such as the composition of the alloy and the heat treatment, meaning that different characteristics can be obtained by altering them. Moreover, their behavior is affected by the temperature and the loading rate, allowing their use for a wide variety of applications.

SMAs are being investigated in various sectors among which the engineering sector possesses a considerable place. The aforementioned publications regarding structural engineering illustrate their wide applicability in this area and prove their effectiveness and feasibility. Experimental and analytical studies show that they are an effective means of improving the response of buildings and bridges subjected to seismic loading. Systems with SMA-based elements may enhance the stability and reliability of civil structures and preserve their structural integrity and functionality. The use of innovative materials technologies in structural design enables to realize resilient structural systems and address the demand for high structural performance, avoiding costly repairs after natural hazards.

All the above illustrate the potential of SMAs. On the other hand, their sensitivity to compositional changes and heat treatments as well as to temperature and imposed loading rate requires particular attention to the selection process of the appropriate alloy in accordance with the desired use. An important drawback is their high cost which fortunately has decreased significantly compared to the past [44]. As demands for high performance of structural systems are continuously increasing, SMAs constitute a potential candidate for replacing conventional materials and techniques as they can upgrade the stability and reliability of structures by increasing the energy dissipation capacity and providing the re-centering capability. Further research efforts need to be conducted on SMAs to ameliorate the currently studied devices and practices. Codes and design guidelines need to be developed to establish the SMA application in civil structures.

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