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SMA-based devices: insight across recent proposals toward civil engineering applications

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Abstract. Metallic shape memory alloys present fascinating physical properties such as their super-elastic behavior in austenite phase, which can be exploited for providing a structure with both a self-centering capability and an increased ductility. More or less accurate numerical models have been introduced to model their behavior along the last 25 years. This is the reason for which the literature is rich of suggestions/proposals on how to implement this material in devices for passive and semi-active control. Nevertheless, the thermo-mechanical coupling characterizing the first-order martensite phase transformation process results in several macroscopic features affecting the alloy performance. In particular, the effects of day-night and winter-summer temperature excursions require special attention. This aspect might imply that the deployment of some devices should be restricted to indoor solutions. A further aspect is the dependence of the behavior from the geometry one adopts. Two fundamental lacks of symmetry should also be carefully considered when implementing a SMA-based application: the behavior in tension is different from that in compression, and the heating is easy and fast whereas the cooling is not. This manuscript focuses on the passive devices recently proposed in the literature for civil engineering applications. Based on the challenges above identified, their actual feasibility is investigated in detail and their long term performance is discussed with reference to their fatigue life. A few available semi-active solutions are also considered.

Keywords: devices; fatigue; hysteresis cycles; passive and semi-active control; shape memory alloy

1. Introduction

The increasing number of studies published over the past few years demonstrates the interest aroused by the functional properties of metallic shape memory alloys (SMA) in the domain of Civil Engineering. At present, most of these works remain in the field of research alone, and the lack of their actual adoption is not only due to the high cost of SMA's in relation to that of conventional construction material, but also to the negligence of proving the actual feasibility of the technical proposal. Indeed, a set of basic information concerning the thermo-mechanical behavior of the material in both its initial conditions and in the conditions of approaching its *fatigue* end-life is crucial in understanding the *applicability constraints* of the proposed device. The initial conditions are the ones obtained at the end of a thermo-mechanical treatment that stabilizes the "*training*" effect, i.e., the variation of the stress-strain curves in the initial cycles.

As mentioned above, the interest in the shape memory materials is due to the functional properties that they offer. For metallic SMA's (e.g., NiTi, copper-based ones, etc.), these properties are the consequence of a solid-to-solid phase transformation between a parent phase called *austenite*, **A**, and a produced phase named *martensite*, **M**. This phase transformation in SMA's is *thermo-elastic* (Lexcellent 2013) and it involves a change of the crystalline lattice between the phase **A**, also known as the "high temperature" phase, and the phase **M**, also known as the "low temperature" phase. This change is named a *martensitic transformation* between austenite and martensite.

If a stress-free transformation is induced by temperature (**A** → $\mathbf{M_T}$), the austenite is transformed into a mixture of *martensite variants* which are characterized by different layouts in the resulting crystalline lattice. The **A** → $\mathbf{M_T}$ transformation begins when a critical temperature named *martensite start*, M_s^0, is reached during the cooling. Although the change might be abrupt and the distortion of the lattice very significant, there is no diffusion and no alteration in the relative positions of the atoms during the transformation. This transformation is said to be *displacive* and *of the first order*. The need of the crystals to form mixture of variants while the whole must remain consistent gives rise to a complex microstructure of the martensite which is referred to as *twinned martensite*.

During the transformation $\mathbf{M_T}$ → $\mathbf{M_\sigma}$, an external stress σ produces major deformations associated with the reorientation of the martensite variants thus showing the so called *super-plastic* behavior (Fig. 1). In contrast to the temperature induced martensite or *self-accomodating martensite*, $\mathbf{M_T}$, which is obtained by simply cooling the alloy without any particular direction being favored during the transformation, in the stress induced martensite or *oriented martensite*, $\mathbf{M_\sigma}$, the stress direction favors the appearance of certain variants over the others. As a result, at the microstructure one obtains a monovariant martensite or

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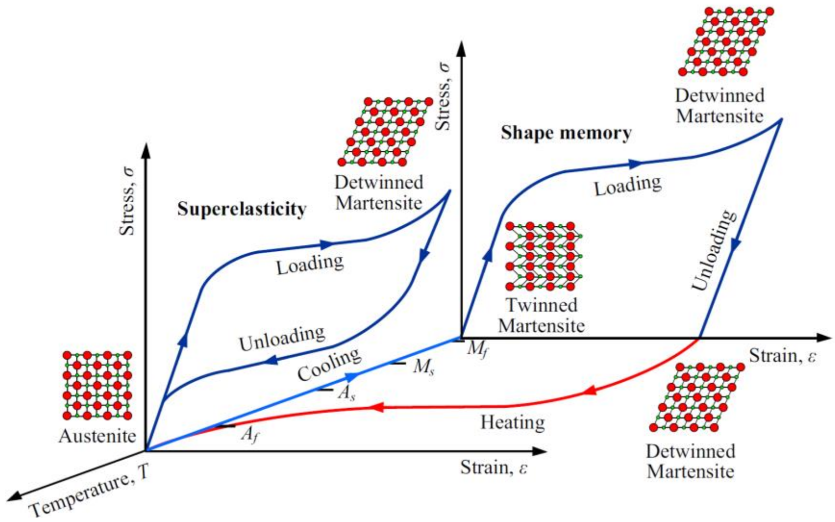


Fig. 1 Schematic of the stress–strain responses of SMAs: super-elastic traction-deformation curve and shape memory effect (re-elaborated from Wang and Zhu 2018a)

detwinned martensite.

The so-called *one-way shape memory effect* shown in Fig. 1 consists of a three stages process:

i) first (**A → M$_T$**), thermal martensite or self-accomodating martensite is obtained by cooling the austenite sample below a critical temperature M_f^0 at which the austenite is no longer present in the lattice;

ii) second (**M$_T$ → M$_\sigma$**), a re-orientation of the martensite platelets is achieved by applying a stress at constant temperature;

iii) third, the unloading is performed and a residual strain is found at the end of the process.

If the alloy is heated, it undergoes a thermal expansion until the reverse transformation **M$_\sigma$ → A** takes place at another critical temperature named *austenite start*, A_s^0. By continuing the heating above the critical temperature, A_f^0, at which the martensite is no longer present in the lattice, the sample regains its initial shape in austenite phase by virtue of the *shape memory effect*. This constitutes an excellent situation for *actuation*. The difference between the two critical temperatures, M_s^0 and A_s^0, shows that the behavior of SMA's is thermally hysteretic.

If the martensitic phase transformation **A → M$_\sigma$** occurs under stress and at a constant temperature $T \geq A_f^0$, by considering also the reverse tranformation **M$_\sigma$ → A** during the unloading one obtains the so-called *super-elastic* traction-deformation curve also shown in Fig. 1. The behavior tends to be hysteretic because the direct and reverse transformation paths are not the same. As a result, the dissipated energy in cyclical super-eleasticity gives rise to the SMA's applications in dampers. Whereas conventional metallic alloys exhibit a restricted elastic domain so that traction tests are typically carried out up to about 0.2% strain, SMA's are able to accommodate extremely high reversible strains (up to 7% for NiTi) with very low residual strain. Furthermore, the transformation branches are characterized by a slope that is far less steep than the elastic one. Consequently, during the transformations, significant changes of strain occur at a nearly constant stress, as in classical first order phase transitions.

Pioneering works (Auricchio *et al.* 2001) targeted the adoption of SMA-based devices for the structural rehabilitation and seismic protection of monuments made of either stone assembles (Casciati and Osman 2005) or masonry (Casciati and Hamdaoui 2008). Indeed, when structures of historical value are considered, the material cost becomes secondary as compared to the cultural loss and the labor necessary to repair the structure. Most of the earliest applications consist of classical strengthening techniques (e.g., longitudinal reinforcement, connections and lateral confinement) where the rigid steel ties are either partially or entirely replaced by tensioned SMA wires. The idea is to take advantage of the super-elastic behavior of SMA's to both dissipate energy and avoid transferring large forces to the main structure. Indeed, one of the drawbacks of the steel connections consists of their high stiffness and the consequent "punching" effect of their anchorage. By limiting the forces transmitted between the connected structural elements and by permitting at the same time small relative displacements between them, the use of tensioned SMA-based devices increases the seismic capacity of the whole structure and prevents it from failing due to excessive stress concentrations during an earthquake. In summary, three main goals are pursued in SMA's seismic application: strengthening, energy dissipation, and absence of extreme stress concentrations in the main structure.

The technique of using SMA-based devices as longitudinal reinforcement placed in series with conventional steel tendons was actually implemented in the restoration of the San Giorgio church's bell-tower in Trignano, which was highly damaged by the 15th October 1996 Modena and Reggio Emilia earthquake (Indirli *et al.* 2001). Another application of SMA-based devices concerns the two transept tympana of the Basilica of San Francesco in Assisi which were highly damaged by the 1997 Marche and Umbria earthquake. In this case, they serve as connections between the roof and the church façade with the aim of dissipating energy without a pounding effect. Both the works represent the first pilot realizations in the civil engineering domain of the SMA technology and demonstrate the effectiveness of this technique to protect cultural heritage structures (Indirli and Castellano 2008). The proposed technology is based on adopting several NiTi wires working in parallel. Alternatively, tensioned CuAlBe wires are adopted in the not invasive and reversible retrofit of an ancient Roman aqueduct located at Larnaca, in Cyprus. The task of this application is a confinement of the loose stone blocks under out-of-plane seismic forces (Chrisostomou *et al*. 2008).

However, the adoption of tensioned SMA wires requires that some challenging aspects must be addressed at their design stage. For example, when considering a *seismic* application (Zhang *et al.* 2008, Qiu and Zhu 2014), their cyclic performance needs to be assessed at different *high frequency paces* (i.e., greater than 1 Hz.). In Auricchio et al. (2001), an improvement of the high frequency performance of SMA's is obtained by "surrounding the wires with a *thermal conductive liquid* which improves the thermal exchange and therefore increases the number of phase transformations during the cyclic test".

Furthermore, the behavior of the SMA's under different frequency paces and working temperatures needs to be thoroughly investigated in view of field applications where the SMA's are to be left with the structure for a long time and the temperature fluctuates over time. One recalls that the ranges of the transformation temperatures are a key-parameter in determining the applicability domain of a certain family of shape memory alloys (Chang and Araki 2016). Fatigue tests are also required to investigate the durability of the alloy (Casciati *et al.* 2011).

The design of smart devices based on metallic SMA and their potential applications to Civil Engineering structures were extensively reviewed in books (Auricchio *et al.* 2001, Lexcellent 2013, Lecce and Concilio 2014) and papers (Saadat *et al*. 2002, Song *et al.* 2006, Casciati and Faravelli 2009, Ozbulut *et al*. 2011, Torra *et al.* 2015, Chang and Araki 2016). However, the literature is growing so fast (as reported, for example, in Casciati *et al.* 2018a), that even by focusing the attention on the last two years it is hard to say that a review exhaustively covers the topic. Nowadays, a multitude of technical proposals pursue the adoption of SMA elements in base isolators, dampers, steel bracing systems, and reinforcement of concrete structural elements.

The present contribution is an attempt to provide an inner insight across recent proposals of adopting SMA-based devices in Civil Engineering applications. The first section of this manuscript aims to outline the basic information required when introducing one of the aforementioned applications. The remaining two sections are devoted to discuss recently proposed SMA-based solutions in the areas of passive and semi-active control, respectively. Selected less recent applications are also discussed and revisited in light of the novel technological developments.

2. Fundamentals in developing a SMA-based application

The approach in Qiu and Zhu (2017a) offers a convenient starting point to illustrate all the information that a reader expects to gather when a SMA-based application (in this case, of the passive type) is discussed. The authors first state the *supplier*, which can either be directly the producer of the alloy, or simply a market operator. The knowledge of the production technique is also an important information in understanding the physical properties of the alloy in its delivery state. For example, when adopting NiTi, one recalls that titanium is highly oxyphilic (Lexcellent 2013) and that oxygen tends to position itself in the interstitial site in crystalline lattices. This situation affects the martensitic transformations and causes an increase in the fragility of the material. Therefore, production techniques that decrease the percentage of oxygen absorbed and lead to a ductility increase are desirable. On the other hand, the homogeneity of the material benefits from the oxygen absorption.

Next, the authors specify the chemical composition of the alloy. As an example, the physical and mechanical properties of two metallic SMAs (namely, NiTi and CuAlBe) are compared in Table 1. Often the alloy chemical elements are given in *weight percentage*. By specifying the weight percentages, the equilibrium temperature of the alloy (i.e., the temperature at which its initial cubic configuration at the micro-scale, or "beta phase", is thermo-mechanically stable) can be drawn from its phase diagram (Fig. 2).

Furthermore, the martensitic transformation temperature is a function of the composition of the alloy. Hence, by altering the chemical composition of the alloy, it is possible to adjust the transformation temperatures so that they meet the requirements of the envisaged application. Four phase transformation temperatures are typically specified by the SMA's supplier upon delivery. One recalls that these temperatures are defined as follows:

- *martensite start temperature,* M_s^0,which corresponds to the appearance of the first martensite platelet in the austenite during cooling;
- *martensite finish temperature,* M_f^0,which corresponds to the appearance of the last martensite platelet during cooling, i.e., when the austenite has disappeared completely;
- *austenite start temperature,* A_s^0,which corresponds to the disappearance of the first martensite platelet during heating;
- *austenite finish temperature,* A_f^0,which corresponds to the disappearance of the last martensite platelet during heating (which is the same platelet that appeared first during the cooling), i.e., when the martensite has disappeared completely.

Measurements of the above defined phase transformation temperatures can be obtained by differential scanning calorimetry (Casciati and van der Eijk 2008). The amounts of heat released during the direct martensitic transformation ($Q_{\mathrm{A}\rightarrow\mathrm{M}}$) and absorbed during the reverse transformation ($Q_{\mathrm{M}\rightarrow\mathrm{A}}$) are also measured and plotted as functions of the temperature in Fig. 3.

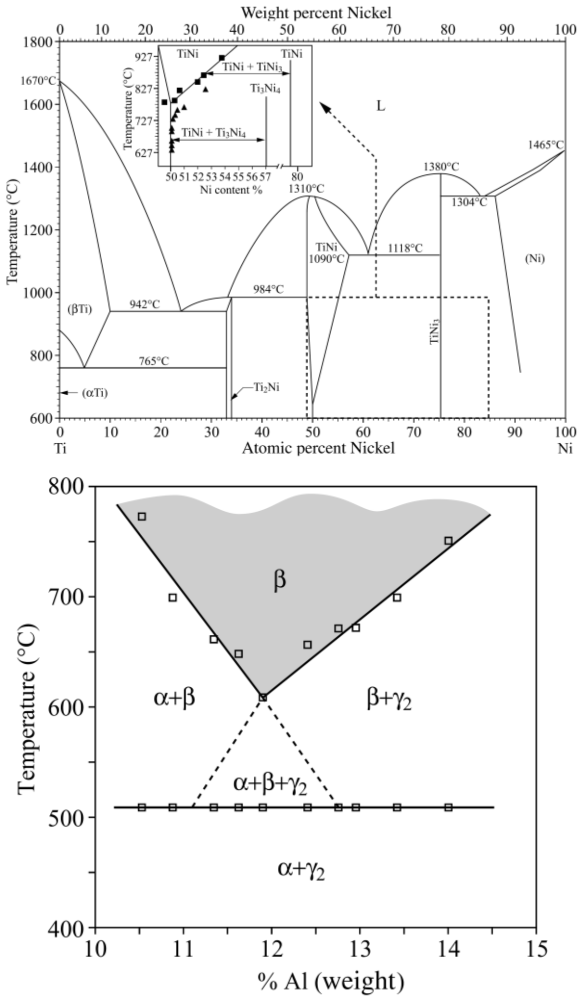


Fig. 2 Phase diagrams: (a) NiTi alloy and (b) vertical cross-section of the CuAlBe diagram with 0.47%wt Be (re-elaborated from Lexcellent 2013)

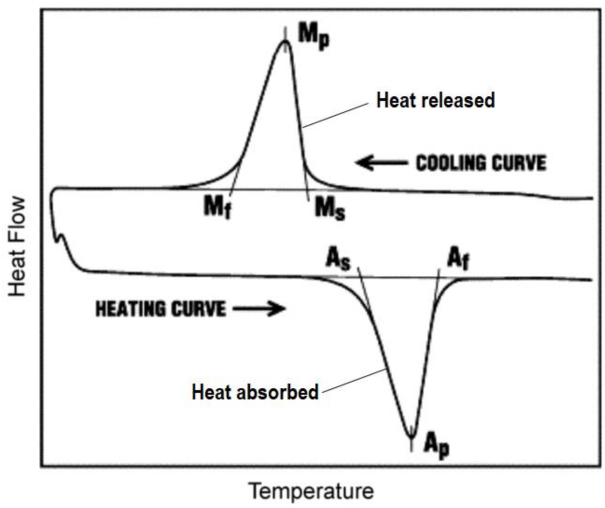


Fig. 3 Schematic representation of measuring the phase transformation temperatures via differential scanning calorimetry (re-elaborated from Casciati and van der Eijk 2008)

Table 1 Comparison of the physical and mechanical properties of two metallic SMA's: NiTi and CuAlBe

Property	Units	NiTi	CuAlBe
Melting point	℃	1260-1310	970-990
Density	kg/m^3	6400-6500	7300
Electrical resistance (austenite; martensite)	Ωm 10^4	0.5; 1.1	0.7; 0.09
Transformation enthalpy	J/kg	28000	7200
Young's modulus	GPa	95	90
Tensile resistance	MPa	800-1000	900-1000
Fracture elongation (in martensite)	%	30-50	15
Grain size	μm	20-100	100-500
Transformation domain	℃	-100 to 100	-200 to 150
Hysteresis (As-Mf)	℃	20-40	20-25
Spread (Af-As)	℃	30	15-20
Maximum strain of the shape memory effect	%	8	3-5
Super-elatic maximum strain (polycristal; monocrystal)	%	4; 10	3; 10
Corrosion resistance		Excellent	Average
Biocompatibility		Good	Poor

Alternatively, electrical resistance measurements can be used to measure the four phase transition temperatures. Indeed, the resistivity of the austenite is different from the one of the martensite so that it can be used as an indicator of the advancement of the phase transformation.

When discussing a novel application of SMA's in smart devices, at least the austenite finish temperature should be assigned to identify the SMA behavior at room temperature. For a super-elastic performance, one is expecting an austenite finish temperature of several degrees below the zero. Nevertheless, day/night and winter/summer temperature cycles are better identified when also the austenite start, martensite start and martensite finish temperatures are specified.

The *geometry* of the alloy elements distinguishes between wires, bars and plate retails. Wires are typically preferred over Ni–Ti bars due their easy machinability. For Ni–Ti wires, the diameters range from 0.01 mm to 2.5 mm. Actually, wires are better categorized as *thin or thick wires*, according to their diameter which can be lower or greater than 0.5 mm, respectively.

A further step toward the alloy characterization moves into its mechanical properties. For instance, Ni–Ti wires can recover from *working strains* up to 6–8% upon unloading. The mechanical properties also account for the *energy dissipation capability* and the alloy *fatigue* properties.

The wires should be preloaded for 100 cycles, as described in Casciati *et al*. (2018b), to stabilize the hysteresis before their use. Such a pre-loading process can stabilize the slight accumulation of residual deformation and the slight variation of the hysteretic loops during the initial loading cycles, often known as the 'training' effect. It is worth noticing that the phenomenon of cumulating residual deformation is not referred univocally in the literature: in papers by Torra it is named "creep", while other authors, having in mind the quite different viscous creep, would prefer to regard it as "transformation induced fatigue". Moreover, different training processes are described in the literature: each particular author recommends his/her specific procedure.

Four aspects of the thermo-mechanical characterization process are outlined as follows. First, tests are recommended in order to check that the cyclic behavior of the alloy wires are nearly insensitive to the *loading frequency* within the dynamic frequency range of 0.5–4.0 Hz (Zhu and Zhang 2013). In any case, it is suggested to run the pre-loading cycles as slow as possible, since the cycling frequency produces different training effects and associate cumulated residual deformation.

Second, plots of the stress–strain relationship for *n* consecutive cycles at the selected loading frequency can be easily obtained so that the *equivalent viscous damping ratio* corresponding to the resulting hysteresis loop can be assessed according to the procedure in Chopra (1995). Nevertheless, this estimate has to be framed in the correct theoretical scheme (Genta, 2008).

Third, one observes from Fig. 4 that stable and repeatable hysteretic loops present the typical *flag shape* for thin NiTi wires only. Thick NiTi wires (of diameter larger than 0.5 mm) show a behavior which is commonly reported as the "*S-shape*" loop (Casciati *et al.* 2018b). In other words, the stress slowly increases with the strain in a nonlinear manner throughout the phase transformation. This observation is related to a more distributed heat dissipation capability in a large diameter wire. A possible thermomechanical interpretation of the S-shaped cycles consists of an anomaly in the heat capacity (which is related to the stress-strain ratio) due to the local effects induced by the dynamic load self-heating (Casciati *et al.* 2018b). Tracking the absorbed/released heat requires a representation of the specimen temperature against time. In Fig. 4, the temperature signals are plotted for two different positions of the K-thermocouples in the NiTi wires: top (solid line) and bottom (dashed line).

For applications in dampers, the adoption of wires with an S-shaped super-elastic curve have some beneficial consequence. Indeed, they remain liable for temperatures as low as 253K (-20℃) or lower. Instead, for thin wires at 273K (0℃), a shift of the loop associated with a Clausius-Clapeyron coefficient of 6.63 MPa/K induces a reduction of

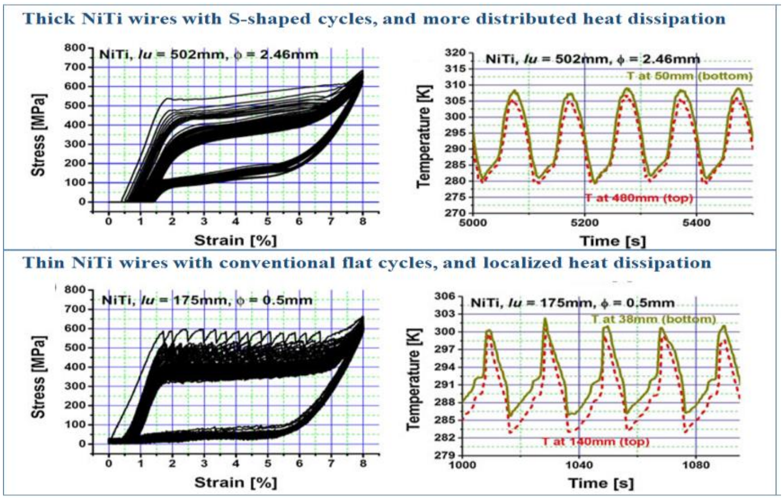
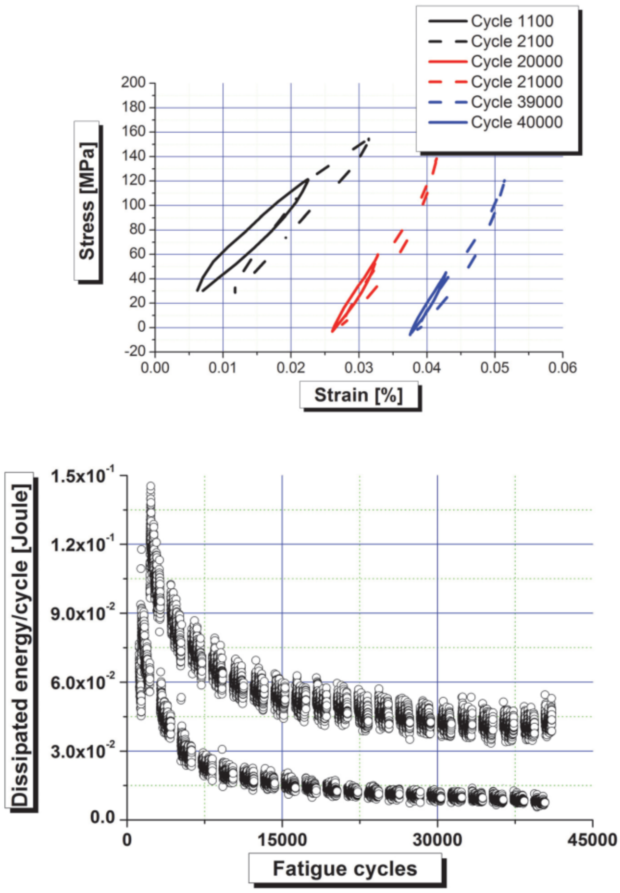


Fig. 4 NiTi wires: experimental super-elastic traction-deformation curves of a thick (top) and a thin (bottom) wire, with their temperature time histories during the stabilization tests of 100 sinusoidal cycles. (re-elaborated from Casciati *et al.* 2017b)



a)

b)

Fig. 5 Fatigue of a CuAlBe specimen of diameter 3.5 mm: (a) progressive change of the super-elastic traction-deformation curve and (b) correspondent decrease of the energy dissipated per cycle (re-elaborated from Casciati *et al.* 2011) stress level for the first-order martensitic transformation of nearly 165 MPa. Consequently, the thin wire cannot retransform and remains in martensite, that is, it is unsuitable to cold winter applications. On the other hand, the fatigue performance of thick wires needs to be carefully evaluated.

Fourth, the loops are stable and repeatable until the deterioration due to *fatigue* phenomena becomes evident (Casciati *et al*. 2011, Casciati *et al.* 2017). SMAs are very susceptible to both thermal and mechanical fatigue due to the phase-change phenomena. In general, one distinguishes between *structural fatigue*, which relates to the lifetime of the material before fracture, and *functional fatigue*, which corresponds to the loss of the thermomechanical properties during cycling. The latter one exhibits itself by means of gradual modifications of the super-elastic traction-deformation curve (Casciati *et al.* 2011). For example, the plots in Fig. 5 are obtained from a test of fatigue accumulation in a CuAlBe wire under sequences of cycles of different amplitude. Each sequence is made of 1000 cycles up to 2.3% of strain and down to zero load followed by 1000 cycles up to 3.2%. Three couples of hysteresis cycles occurred at different times during the test are shown in Fig. 5(a). As the fatigue test proceeds, a drop in the stress value at which the phase transformation starts is observed together with a progressive decrease of the energy dissipated per cycle (i.e., the stress by strain area of the hysteresis loop as calculated in Fig. 5(b)). It is worth mentioning that, in polycrystalline alloys, the resistance to mechanical fatigue is highly dependent on the grains size which is very significant for copper-based SMA's. Therefore, the presence of coarse grains leads to a lower fatigue performance than the one observed in fine-grained specimens.

If the sample is subjected to a constant stress and thermally cycled between M_f^0 and A_f^0 (*shape memory fatigue* or *thermo-mechanical fatigue*), a shift of the phase transformation temperatures as high as 10℃ (Lexcellent 2013) is observed. In particular, a decrease of M_s and M_f and an increase of A_s and A_f lead to a reduction of both the hysteresis and the amplitude of the shape memory effect.

In conclusion, fatigue studies, which are far from being as advanced as for conventional materials, are a key requirement for the actual implementation of SMA's in civil engineering applications.

When developing a SMA-based application, some further remarks apply. The specific behavior of a SMA is associated to its martensitic transformation, which is a first order phase transition with a classical dependence on *temperature changes* as governed by the Clausius–Clapeyron thermodynamic equation (Torra *et al.* 2015). For this reason, studies using SMA elements in damping devices for civil engineering applications should include an in-depth analysis of the SMA thermo-mechanical properties that would ensure the guaranteed behavior. In particular, in outdoor applications, the effects of daily temperature changes and summer–winter cycles on the performance of the SMA based dampers should be adequately considered (Torra *et al*. 2015, Torra *et al*. 2014).

As for any metal, thermal treatments are quite important. Dealing with copper-based shape memory alloys, one should rely on the so-called "*aging*" process, which consists of a sequence of heating and cooling cycles as reported, among others, in Casciati and van der Eijk (2008). In particular, the martensitic transformation responsible for the shape memory properties occurs starting from a centered cubic intermetallic phased named the "beta-phase" (Fig. 2). If, from the alloy phase diagram, this phase is not thermodynamically stable at ambient temperature, it is necessary to first raise the alloy temperature to the one of the beta domain and then to quench it in order to stabilize it into that state. The quenching is then followed by a reheating in order to eliminate the quenching vacancies and stabilize the state of order of the alloy. Of course, for large or long SMA elements, it should be performed directly by the supplier, whereas, when the size of the SMA element is compatible with the standard quenching equipment, it should be carried out just before mounting the element. The aging is quite important in managing the so called "*creep*", i.e., the phenomenon of cumulating residual displacement as the result of loading unloading cycles (Casciati *et al*. 2018b).

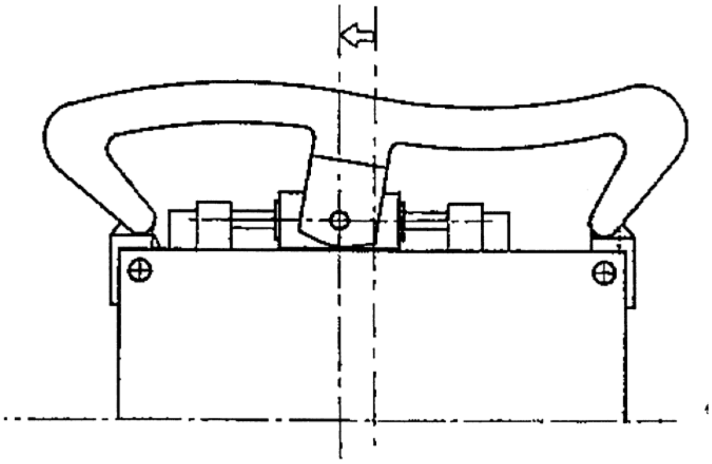
Finally, when moving from the material to the device, a common target for all the designers is to ensure the re-utilization of the device after a sequence of strong vibrations. This requirement is commonly summarized in the attribute "*self-centring*" as reported, among others, in Qiu and Zhu (2017a). This attribute is also referred to the whole structural system in the cases where it dissipates energy with minimum structural damage and returns to its initial position after an extreme event.

3. SMA based devices for Civil Engineering applications: passive control

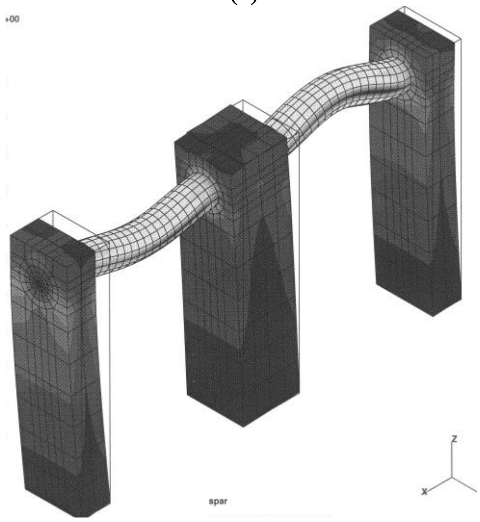
As stated in the introduction, the aim of this manuscript is to cover recent applications that have been developed within the last two-three years. Nevertheless, new proposals are sometimes inspired by solutions proposed several years ago and abandoned mainly due to technological problems (or simply ignored). For this reason, a brief coverage of selected past implementations is given before discussing the latest devices. In the following, the discussed devices are grouped according to their geometry and scope so that one distinguishes those based on SMA bars from the devices based on SMA wires, which are further categorized as either cable-stay dampers or generic dampers.

3.1 Devices exploiting alloy bars

In the late nineties, an American supplier of Ni-Ti alloys offered to an Italian company, producing base isolators and energy dissipation devices, samples of bars of diameter 10 mm at the martensite state. The idea was to replace steel elements in an existing device by these bars to achieve extra-damping. A numerical study was developed and the results were summarized in Casciati *et al.* (1998). The deforming structural element in Fig. 6(a) is named the E-



(a)



(b)

Fig. 6 Response of an E-shaped damper exploiting the SMA bars in martensite: (a) working scheme of the device linking the bridge deck with the foundation pile and (b) numerical study showing the bending response of the SMA bar (re-elaborated from Casciati *et al.* 1998)

shaped damper and consists of three steel vertical legs and a NiTi horizontal beam. The steel central leg is linked to the vibrating foundation while the other two steel legs are joined to the bridge deck to be protected. The super-plastic flexure of the NiTi beam during an earthquake gives rise to the required dissipation properties (super-plastic curve in Fig. 1). Hence, in the proposed device, the energy is dissipated via the hysteretic super-plastic cycles of the SMA structural bars. Their capability of recovering the plastic deformation is then exploited by applying a suitable thermal cycle.

In this application, the working temperature of the NiTi alloy with 49% wt Ti is lower than M_f^0 which is measured to be equal to 54.9°C. Therefore, the functional properties offered by SMA's permit to conceive bars that, at working temperature, are in a fully martensitic state, present large hysteresis under loading-unloading cycles, and show a suitable ductility to reach high dissipation levels.

At that time, the technological constraints were dominating. It was quite impossible to cut a specimen from the bar, and, even so, it was not clear whether this cutting would have modified the material properties. It was quite expensive to ensure the wished preliminary thermal treatment, and mainly it was quite complicate to connect the bar with the supports. Indeed, in Fig. 6(a), the bars are just inserted in holes drilled in the steel supports, and the holes are then tight by special screws. The mechanical scheme in Fig. 6(b) is therefore arranged as a contact problem with friction to carry out the numerical study. Some of these limiting aspects were removed by the technological progress (Wang *et al.* 2016). Among others, the most recent laser cutting technology allows the designer to retain structural elements of the desired shape (for instance, U shaped bars), to be used as components of base isolators (Zhu 2018, Wang and Zhu 2018b).

(a)

(b)

Fig. 7 SMA-based devices for limiting bridge columns residual displacements: (a) NiTi bars in austenite phase and (b) completed longitudinal reinforcement with SMA bars in the top plastic hinge region coupled in series with steel rebars and enclosed in circular hoops. (re-elaborated from Saiidi *et al.* 2017)

Applications of super-elatic SMA bars for energy dissipating mechanisms are mainly reported in bridge columns (Saiidi *et al.* 2017). Indeed, there is a need to minimize bridge damage and replacement after a seismic event. For this purpose, alternative performance-based design approaches using advanced materials and unconventional seismic techniques are studied to improve the current practice of concentrating permanent damage in selected "sacrificial" regions after an earthquake. In May 2017, the R99 Bridge in Seattle, USA, was constructed with columns in Engineered Cementitious Composites (ECC) longitudinally reinforced by SMA bars that are coupled in series to conventional steel rebars (Fig. 7). The SMA elements and the ECC are located in the region where the top plastic hinge typically forms in a conventional reinforced concrete column according to the current design practice. The tasks are to both limit the residual displacements in virtue of the super-elastic property of SMA's and to reduce damage by ECC. In particular, the super-elastic effect and the ability for the SMA to undergo large strains and recover most of the deformation upon removal of the applied load are of interest for this application because they can help minimize permanent deformations in structures where residual drifts caused by large earthquakes are a concern.

For the described application, thirty NiTi bars of length 1.22 m and diameter 32 mm are used for a longitudinal reinforcement ratio of 1%. An austenite finish temperature equal to or lower than -10℃ is suggested. As a result, the columns show excellent re-centring capabilities with minimal damage. At the same time, the comparatively low stiffness of the SMA bars with respect to the steel rebar leads to higher values of the maximum drifts than the ones calculated in a reinforced concrete bridge. Consequently, this situation requires that a high ductility and damage tolerant material such as ECC must be used along with SMA, because conventional confined concrete cannot accommodate the high strain capacity of SMA's.

Furthermore, super-elastic Cu-Al-Mn bars of diameter 4 mm and length 110 mm were tested in Japan (Araki *et al*. 2014) for use as top members of the bracing system in the single degree of freedom frame of Fig. 8. Indeed, conventional steel frame braces suffer from pinching (with significant deterioration of strength and stiffness) when they are subjected to the cyclic loading induced by strong earthquakes. Pinching is undesirable because it may lead to excessive residual deformations and/or instability of the steel frame after the earthquake. To overcome this difficulty, a partial replacement of the steel bars with the super-elastic Cu-Al-Mn bars in the tension braces is proposed as

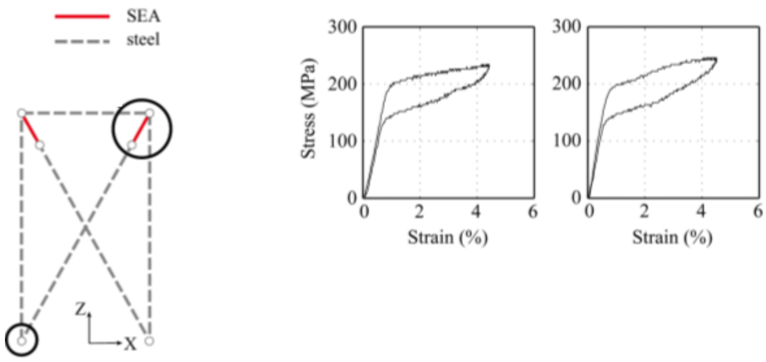


Fig. 8 Schematic representation of the SMA bars as top members of a bracing system and super-elastic curves resulting from preliminary cyclic loading tests. (re-elaborated from Araki *et al.* 2014)

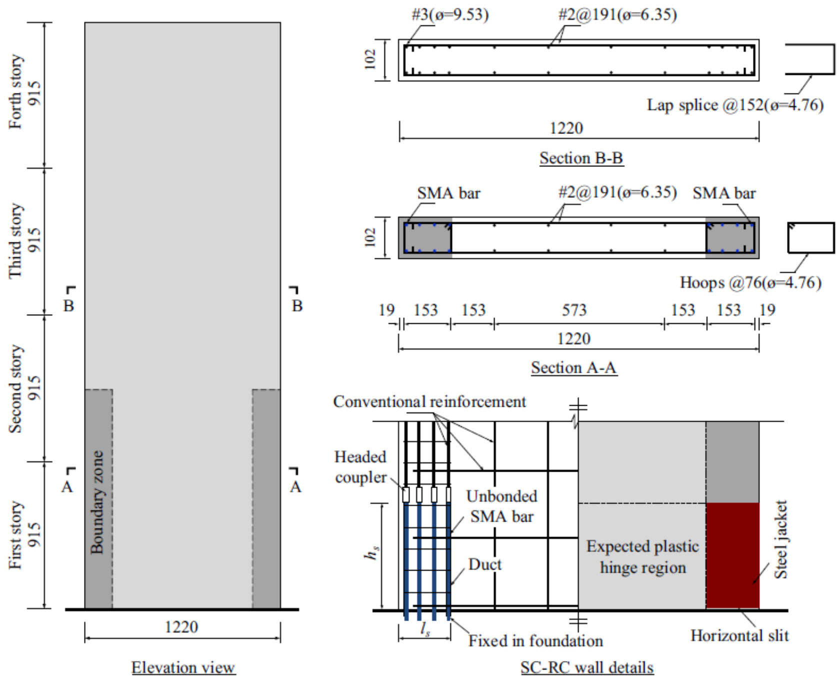


Fig. 9 Self-centering reinforced concrete wall, enabled by superelastic NiTi shape memory alloy bars (re-elaborated from Wang and Zhu 2018a)

illustrated in Fig. 8.

The superelastic alloy (SEA) bars are pre-trained up to a strain of over 4%. The stress–strain curve of each SEA bar under quasi-static cyclic loading (sinusoidal load of 0.001 Hz frequency) is also shown in Fig. 8. These alloys have composition Cu 16.7%wt., Al 11.6% wt., and transformation temperatures given as follows: Ms=-74℃, Mf=-91℃, As=-54℃, and Af=-39℃. They offer large recovery strain (up to 8%), low material cost, and high machinability. As a result, they provide the steel frame in Fig. 8 with a self-centring capability, a good ductility, and a satisfactory reduction of the strong input ground acceleration. The rate dependence of the frame response is studied and it is shown to be negligible up to a loading frequency of 6 Hz.

Recently, a self-centering reinforced concrete wall, enabled by superelastic NiTi shape memory alloy bars, was introduced in Wang and Zhu (2018a). The aim is to avoid costly repair or even demolition due to excessive residual deformation following a moderate-to-strong earthquake. For this purpose, the capability of super-elastic SMA to recover most of the deformation upon load removal is exploited similarly to what was done in the latter two applications above described. In particular, unbounded super-elastic NiTi bars of diameter 6 mm and length 600 mm are used as the longitudinal reinforcement in both sides of the bottom boundary zones of the wall system, where the regions of plastic hinges are expected (Fig. 9). Steel jackets are armoured in the wall boundary zones to avoid damage (e.g., spalling and crushing) at wall toes under cyclic loading. The upper ends of SMA bars are connected to the conventional steel bars beyond the expected plastic hinge regions using steel headed couplers. The bottom ends are embedded and fixed in the foundation. The SMA bars are designed to be unbounded by steel or plastic *ducts* from the surrounding concrete to allow free and uniform axial deformation. The SMA bars do not transfer tensile stress into the concrete, thereby reducing cracking in the wall boundary zones. Moreover, the duct can prevent the potential buckling of SMA bars under compression. Horizontal *slits* (gaps) are designed symmetrically at the wall-foundation interface where the SMA bars are placed. The horizontal slit separating the wall and foundation can minimize the tensile cracks in the boundary zones, in which the tension force is mainly undertaken by the SMA bars. This design can help achieve self-centring behaviour and improved ductility. An austenite finish temperature between 0 and 5°C is selected for this application.

3.2 Devices based on SMA wires

The SMA wire-based dampers, in principle, are not easily implemented into civil engineering practical applications due to their small load resistance. For example, the load resistance of a damper used in multi-story frames is typically of the order of 500-1000 kN. Potential approaches to overwhelm this situation are discussed below.

3.2.1 Devices for passive structural control of cables

In the literature, the problem of mitigating cable-stays vibrations is approached either by adding a SMA wire along the cable (Casciati *et al.* 2008) or by connecting an external anchorage point with a cable node by a SMA wire. The latter approach was the one adopted within a European project whose results are reported in (Torra *et al*. 2013).

The main issue is that, in this case, the main excitation is the wind load that would ask for millions of loading-unloading cycles, i.e., a number of cycles quite too excessive for any shape memory alloy (Torra *et al.* 2014). Nevertheless, the research is still active in the field as shown in Zhou *et al.* (2018), where the effects of introducing a pre-tension are analysed.

3.2.2 Generic damper devices based on SMA wires

After the pioneering work in Witting and Cozzarelli (1992) and the extensive test campaigns carried out 15 years ago (see Auricchio *et al.* (2001), Casciati and Hamdaoui (2008) among others), the literature focused a lot on the exploitation of SMA properties in brace elements of framed structures (Casciati and Faravelli 2008, Carreras *et al.* 2011, Qiu and Zhu 2017a).

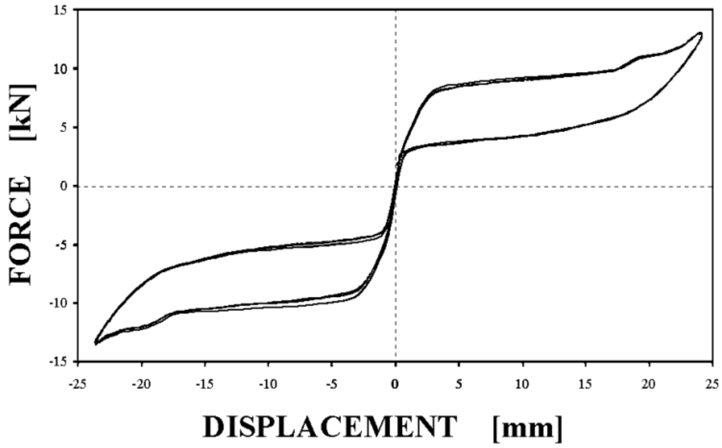
Dampers for this purpose continued to be proposed in Parulekar *et al.* (2012), Qiu and Zhu (2017b), Hou *et al.* (2017), and Zhou et al. (2018). The most recent applications come with the desirable self-centring feature. In the following, further details of these latter applications are discussed.

Recent technical implementations of dampers exploit SMA wires of thin diameters. This requires that several wires in parallel are used to withstand the considered forces. Alternatively, the same wires are deployed as a bundle, which is technologically favourable, but comes with the unfavourable consequence of moving from a reliable parallel system to a weak, “first cut” series system.

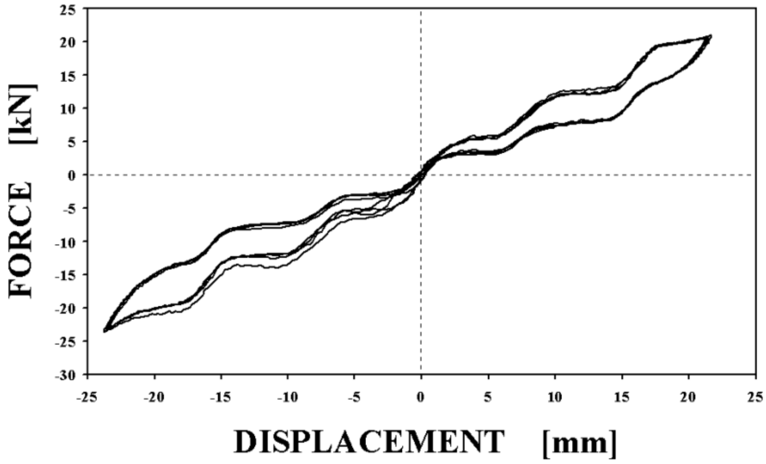
The common characteristics of the technological development of axial damper devices include not only the self-centring feature, but also the symmetry of the global force-displacement diagram (Fig. 7). Indeed, it is well known that the stress-strain relationship of a SMA wire specimen only covers the tension quadrant, due to the definition of wire. On the other hand, the axial loading tests on SMA bars, even if not easily carried out, show an asymmetric response in tension and compression, both in the ductile capability and in the stress intensity at which the flat branch occurs. Thus, the technological aspect relies on having always a set of wires working in tension, and simply disconnecting the others. In this manner, one obtains the single plateau diagram of Fig. 7(a), according to which the SMA-based device becomes active (i.e., it applies a force to the structure) only under a dynamic load inducing horizontal forces greater than the initial one of the plateau. In particular, one distinguishes three operational modes of a single plateau SMA device. At low strain ($\varepsilon<1\%$), the large modulus of elasticity of the austenite phase can limit deformation under *in-service load conditions*. The reduced modulus of the intermediate transformation path ($1\%<\varepsilon<6\%$) can be used to limit the force transmitted to the adjacent structural components when undergoing rather *large displacements*. The increased modulus of elasticity of the martensite state at large strain ($\varepsilon>6\%$) can be used to control displacement during *severe earthquakes* (McCormick *et al.* 2007).

A further evolution of the described device consists in a multiple-plateau behaviour as the one depicted in Fig. 7(b). The triple plateau behaviour of Fig. 7(b) characterizes the SMA-based devices installed in the tympana of the Basilica di San Francesco in Assisi, where the main goal is to limit the forces transferred between the connected members and permit at the same time small relative displacements which are responsible for the dissipation of energy (Indirli and Castellano 2008). The advantage gained is its capability to work at increasing force levels induced by dynamic loads of different intensities. Furthermore, for masonry, the optimal design force of the single plateau device depends on the masonry tensile strength (i.e., its value increases with σ_t), but this material property is affected by high uncertainties. Instead, by adopting a multi-plateau device, the designer can take into account a wide range of masonry mechanical properties so that the end-result is less sensitive to uncertainties and a good level of optimization can be achieved. The drawback, however, is evident from Figure 7b and it consists of a reduction of the energy dissipated per cycle.

There is another aspect that attracts the attention of the research teams involved in the realization of dampers. As outlined for instance in Casciati and Domaneschi (2007), the dissipation of energy can be pursued by a *rotational*



(a)



(b)

Fig. 10 Examples of experimental load-displacement plots for different SMA-based uni-axial dampers: (a) single plateau and (b) triple plateau (re-elaborated from Indirli and Castellano 2008)

Fig. 11 Example of a ball screw to be adopted in a SMA-based rotational damper. The linear motion is translated into rotational motion

damper which can either be placed at the deck–pier interface in a bridge or as an inter-storey link in a multi-storey building. In this case, a ball screw (Fig. 8) can be used to convert the linear relative motion of the structure into a rotational movement. By a suitable coupling of two rotational dampers, one obtains a simple gear box able to amplify the input relative displacement resulting from the structure response into a larger elongation of the SMA wire. The goal, obviously, is to exploit more conveniently the SMA hysteresis, whose loops are wider as the displacement is larger. A similar result can be obtained in an even simpler manner by realizing a mechanical lever between the input displacement and the induced elongation in the wire bundle.

4. SMA based devices for Civil Engineering applications: semi-active control

In early papers (see Shook *et al.* (2008), among others), the semi-active feature was implemented by simply adding a semi-active device (such as, for instance, a magneto-rheological damper) into an otherwise passive system. In Shook *et al*. (2008), passive SMA wires are included in a hybrid base isolation system to improve the re-centering capability of friction-pendulum bearings. A semi-active component is introduced by means of an array of controllable magnetorheological dampers.

One of the few semi-active applications of SMA-based devices in civil engineering is discussed in Amarante dos Santos *et al*. (2013). Two super elastic, prestressed NiTi wires working in phase opposition are used as restraining cables in unseating prevention devices for bridges. To avoid stress relaxation phenomena, the supports of the wire can temporarily assume an unlocked configuration through a controlled velocity process. As in an active control system, a controller monitors the feedback measurements and generates appropriate command signals for the device and, as in a passive control system, the control forces are developed as a result of the motion of the structure itself, with no need of external energy input. Electromechanical actuators are used to introduce the semi-active feature.

In (Gur *et al.* 2017), the structure protection from near-fault earthquakes is sought by supplementing a friction pendulum isolation system with thermally modulated SMA springs. An effective heating –cooling system would pave the way to a temperature modulation of the SMA which “enhances its energy dissipation capacity, as well as changes its effective stiffness and thereby the time period of the device”. Although the authors clarify that the design of a heating or cooling system is not part of their work, they mention that a temperature increase could be easily achieved by flowing electrical current through the SMA. Nevertheless, the “cooling is an open and potentially difficult problem to solve and implement”. Indeed, the authors suggest that the “cooling could be realized by utilizing quenching techniques used in metallurgy, or cooling techniques used in engines”, but “ingenious ways to switch from heating to cooling and then back to heating at a fast pace would have to be found”. One of the drawbacks of these alloys, indeed, consists of having a prolonged period of heat transfer which results in a slow dynamic of use.

5. Conclusions

The manuscript covers applications of shape memory alloys (SMAs) in Civil Engineering. The first goal is to emphasize the basic information on the material that one needs to consider for a technical proposal to be feasible and replicable. Several critical aspects, whose negligence could lead to material failure sources and likely mismatches between the target performance and the actually achieved one, are identified.

Recently proposed applications are discussed with focus on both passive and semi-active control schemes. Based on these applications, several concluding remarks can be drawn as follows.

The adoption of SMA bars in either passive dampers or base isolators was a challenging topic in the past, but it should now be revisited in light of the most recent technological developments. For example, the laser cutting technologies permit one to obtain the SMA bars shaped with cross-sections of different geometry. So far, however, applications are limited to column reinforcements, bracing systems, and re-centering reinforced walls. It is worth mentioning that several innovative studies on energy dissipative beam-to-column connections equipped with SMA bolts or other novel SMA elements were also published; see for instance (Fang *et al.* 2017, Fang *et al*. 2018, Wang *et al*. 2017).

When SMA wires are adopted to mitigate the vibrations of cable stays, the main concern should be the fatigue lifetime of the proposed device. From recent studies, pre-straining seems to be a viable strategy to enhance the SMA performance.

SMA thin wires are often adopted as elements of the devices connecting the steel braces to a multi-story-frame. Several wires working in parallel are necessary to withstand the forces. The design of the devices is such that there are always some wires working in tension, whereas their compression is avoided by a disconnecting mechanism so that no rotation induced by wires instabilities due to compression may occur.

Dampers that permit the relative motion of the structure and produce significant elongations of the SMA wires are desirable in order to better exploit the hysteretic behavior of the alloy for energy dissipation purposes. The realization of rotational dampers offers, for example, this capability.

In the literature, only few semi-active solutions are found for the development of SMA-based devices targeted to civil engineering applications. Among those, the most classical ones add semi-active devices such as MR dampers to an otherwise passive solution. Another application consists of programming a linear actuator to avoid excessive stress and remove the residual displacements in a base isolated structure. The practical realization of a SMA-based, semi-active solution requires to implement a heating-cooling strategy and the challenge of obtaining it with a fast pace still needs to be addressed. The temperature modulation of the SMA device affects its energy dissipation capability, its effective stiffness, and its lifetime. Progress in the design of the SMA devices have appreciably contributed to cure their cyclic degradation.

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