Properties and Design of Dissipative Visco-recentring SMA members for Civil Structures

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***Abstract*—**In the paper one focuses on some fundamental issues in the modeling and design of dynamic control devices conceived for structural applications, based on the exploitation of Shape Memory Alloys (SMAs).

General properties and advantages are described which make these alloys particularly suitable for applications aimed at the response reduction under dynamic events, and some indications to be considered at the design stage of the SMA devices are outlined in function of the re-centring and/or dissipation tasks one wants to accomplish. Numerical investigation is presented as well relevant to some possible application.

***Keywords*—**Smart materials, Structural applications, Dynamic control of vibrations, Shape Memory Alloys, Control devices.

I. Introduction

CONTROL strategies may be successfully adopted for dynamic control of vibrations in civil structures [1]-[21].

Actually the need of supplying self-adjusting capacity with respect to unknown dynamic events to structures, thus making them smart, it is one of the main objectives of any control system and the major inspiring idea when conceiving a structural dynamic control strategy.

New technologies allow to couple benefits of passive and active control strategies in semi-active systems, also by adopting smart materials able to change their state during the dynamic motion or to exploit some special peculiar properties, as in the case of Shape Memory Alloys (SMAs) [1]-[15].

Shape Memory Alloys (SMA) are a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their shape prior to the deformation.

Materials that exhibit shape memory only upon heating are referred to as having a *one-way shape memory*. Some materials also undergo a change in shape upon recooling. These materials have a *two-way shape memory*.

Although a relatively wide variety of alloys are known to exhibit the shape memory effect, only those that can recover substantial amounts of strain or that generate significant force upon changing shape are of commercial interest. To date, this has been the nickel-titanium (NiTi) alloys and copper-base alloys such as CuZnAl and CuAlNi.

Because of the complex load–deformation–temperature behaviour, besides the shape memory effect, SMAs exhibit a pseudo-elastic behaviour at high temperatures.

Therefore two major features may be observed at the macroscopic level: the shape memory effect (depending on the capability in recovering possible accumulated deformations by heat treatment) and the super-elasticity (i.e. the recovery of large deformations in loading-unloading cycles, occurring at sufficiently high temperatures).

The shape-memory effect derives from a first-order martensitic phase transformation and gives the SMAs a high dissipative capacity with comparison to ordinary metals, achieving large hysteretic loops without incurring plastic deformation.

The model body is composed of lattice particles arranged in layers and stacks as shown in Fig.1. Tensile loads make the layers shear and flip thus producing elastic and quasi-plastic deformation respectively. Heating produces the austenitic phase and leads to shape recovery.

The hysteresis, here actually due to the growth and re-orientation of the martensite crystals (that can be reduced to their original configuration upon the application of heat), renders particularly interesting the SMAs applications in the field of earthquake engineering for the realization of dissipative devices.

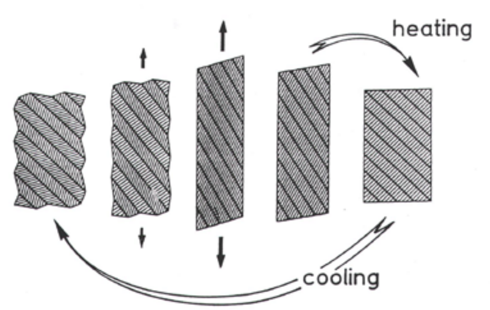

Fig.1: Model body.

The super-elastic behaviour of SMAs, due to elastic loading of the austenitic parent up to the threshold stress where-upon the transformation from austenite to martensite occurs, is able to provide an energy-absorbing effect combined with a theoretically zero residual strain upon unloading.

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The behaviour of SMAs then allows lower invasiveness and power supply with respect to active control devices for structural engineering applications, and increased reliability with respect to classical passive devices, also making them suitable for innovative applications on already existing and even ancient masonry construction, beyond composites' applications [22]-[24].

To this regard, one should consider that difficulties in exact prediction of response variables even in the static phase [25]-[41] and of vulnerability assessment [42]-[44], even under the usually adopted assumptions of complete inability to resist tensile stresses, make the design of control devices based on SMAs particularly attracting, because of their robustness with respect to uncertainties, and usefulness in the absence of environmental seismic forecasts [45], [46].

II. General characteristics of shape memory alloys

As mentioned, shape memory alloys have the ability to recall their original shape after serious deformations.

These materials possess this ability because they exist in two distinctly different phases: martensite and austenite. The austenitic phase and the martensitic phase each have distinctly different physical properties and strengths. Austenite is the parent phase of shape memory alloy materials and has higher yielding limits than the material in its martensitic phase.

Through heating, a shape memory alloy can be transformed from martensite to austenite. Similarly, cooling will produce the reverse transformation, from austenite to martensite.

The details of martensitic transformation are very complicated but not necessary to understanding how shape memory alloys can be implemented in many engineering designs.

Essentially, a shape memory alloy can be taken in its martensitic phase and subjected to plastic deformation. This deformed martensite can then be heated to its austenitic phase, recovering all of its deformations.

Once cooled again to martensite, the material will remain undeformed.

Fig.2 visually shows this transformation, while Fig.3 shows a series of photographs demonstrating the one way shape memory effect for a nickel-titanium wire.

The synthetic scheme of SMAs transition phases for mono-axial stress in Fig.3 gives a short insight in the SMA behaviour. Typically, austenite is stable at high temperatures, while martensite at low temperatures; the conditions for activating transition phases depend on stress σ and temperature T.

Experimental investigation shows that, in case of monoaxial stress, transition regions in stress-temperature diagrams are approximately bounded by lines. Regions characterized by stable fractions are indicated by S for single variant martensite, by M for multiple variant martensite and by A for austenite. Phase transition processes are responsible of SMAs super-elasticity and shape memory effect.

The shape memory effect is linked to variations either in stress or in temperature . At T< T_f^{AM} martensite is stable both in single and multiple variant.

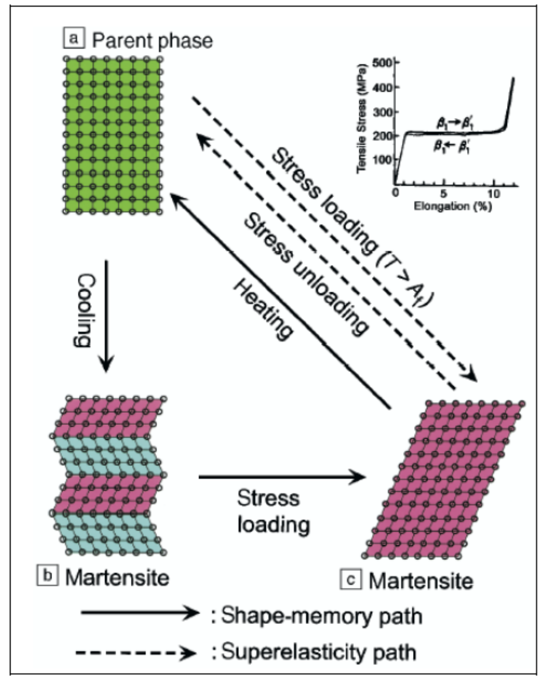


Fig.2: Schematic illustration of the mechanism of the shape-memory effect and superelasticity.

Starting the loading process (Fig.5) in case of multiple variant, the first phase 0-1, due to the transformation of martensite from multiple to single variant is non-linear.

The unloading 1-2 is characterised by a residual deformation 0-2, which can be recovered by heating. Actually heating (up to a temperature higher than T_f^{SA}) allows the transition 2-3 from martensite to austenite.

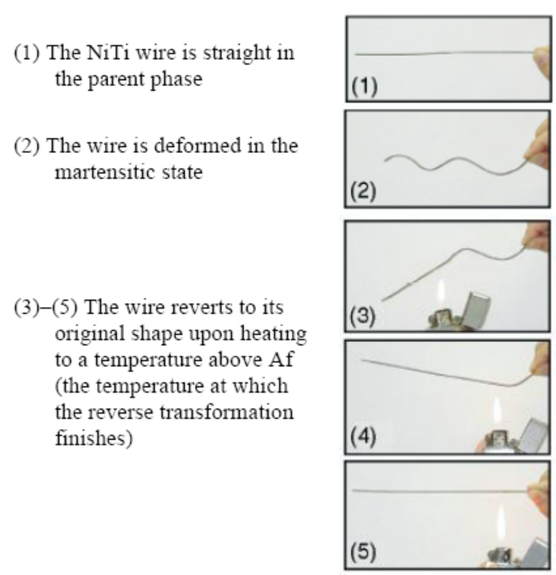


Fig.3: A series of photographs showing the one way shape memory effect for a nickel-titanium wire.

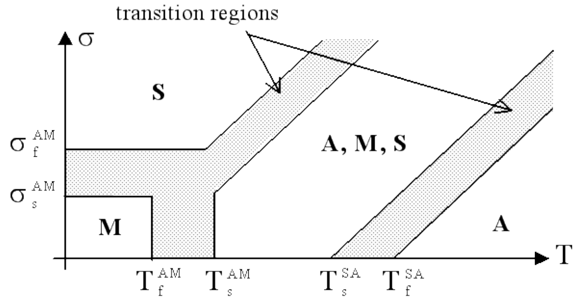


Fig.4: Phase transition zones in SMAs.

The final step of the path is cooling, which determines the reduction 3-0 of austenite to multiple variant martensite, leading to the initial alloy configuration and giving rise to the shape memory effect.

The volume variation in the austenite-martensite transition can be neglected as it is very small (-0.16%) and the process can be supposed to occur at constant volume.

III. Conceptual Design of SMA Devices for Control of Structural Vibrations

The first step in the conceptual design of SMA devices is the selection of the most suitable alloy for the SMA kernel components of a device, which deform in the inelastic range to give the device the most suitable mechanical behaviour for passive control of vibrations.

SMA components differ for the type and phase (austenitic or martensitic) of alloy. Table 1 shows the prerequisites that an alloy should satisfy to be used in control devices. Fig. 6 shows the quantities used in Table 1 to define the mechanical behaviour of SMA.

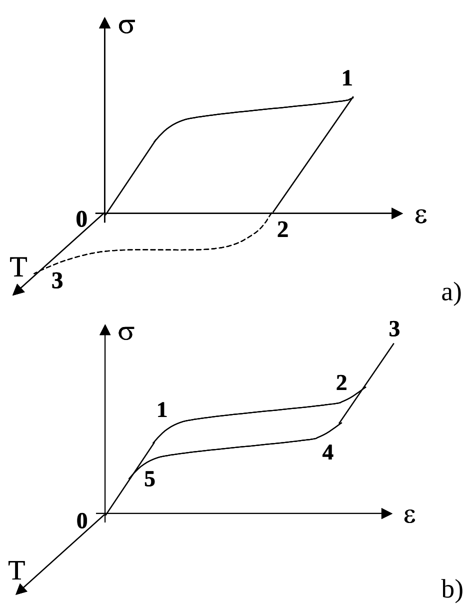


Fig.5: a) Shape memory effect; b) super-elasticity.

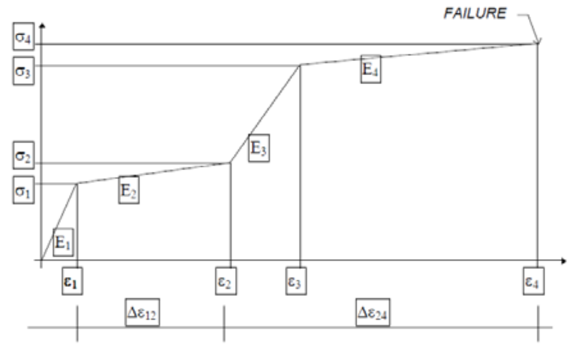


Fig.6. Characteristic quantities defining the mechanical behaviour of SMA.

MARTENSITE	AUSTENITE
High energy dissipation	Superelasticity
High fatigue resistance	
Low sensitivity to temperature in the range **5 to 35°C** for buildings and **-5 to 45°C** for bridges	
Low sensitivity to strain rate or to frequency in sinusoidal vibrations, in the range **0.4 to 1 Hz** for seismic isolation and **1 to 10 Hz** for energy dissipation.	
Stability of cyclic behaviour: $0.9 \le \sigma_{1,1}/\sigma_{1,i} \le 1.1$, $0.9 \le \sigma_{2,1}/\sigma_{2,i} \le 1.1$ where i is the number of the cycle	
No degradation for environmental actions or as low as possible (applications on buidings are much less sensitive than applications on bridges)	
$\varepsilon_2 \ge 8\%$, $\gamma_2 \ge 12\%$ or as large as possible	
$\varepsilon_4/\varepsilon_2 \ge 2$, $\gamma_4/\gamma_2 \ge 2$ or as large as possible	
$E_2 \le 0.10\ E_1$ or as low as possible	
$E_3 \le 0.5\ E_1$ or as low as possible	
$E_1 \ge 30000$ **MPa** (as large as possible)	$E_1 \ge 70000$ **MPa** (as large as possible)
$\sigma_1 \ge 300$ **MPa** or as large as possible	$\sigma_1 \ge 500$ **MPa** or as large as possible
$\sigma_3/\sigma_1 \le 1.5$ or as low as possible	

Table 1. Optimal prerequisites of SMA to be used in Control devices.

Five different alloys can be considered for constructing passive control devices, namely:

- **NiTi** (Nikel-Titanium),
- **CuAlNi** (Copper, Allumnium, Nickel),
- **CuZnAl** (Copper, Zinc, Allumnium),
- **FeMn[Si]** (Iron, Manganese, [Silicium]),
- **MnCu** (Manganese, Copper).

Nickel-Titanium (NiTi) based alloys proved to be the best candidates for control devices.

Focusing on these alloys, each of their phases generally implies peculiar mechanical properties: austenite is superelastic, i.e. shape memory effect occurs when stresses are removed, while martensite has better dissipation capabilities, but shape memory effect occurs only when heat is supplied. Taking into account the limited workability of the material, kernel components for devices can only be drawn from wires or bars. They differ f

rom each other in the diameter (up to 2 mm for commercial wires, from 6 to 8 mm for commercial solid bars, up to 50 mm for special production bars).

Austenitic elements can provide devices with some energy dissipation and/or good re-centring capabilities, because of their stress-induced transformation properties. Martensitic elements can dissipate energy, through the stress-induced grain re-orientation, which also implies a very high fatigue resistance. Wires are used only in the austenitic phase. On the other hand bars can be employed either in martensite or in austenite phase, according to the desired device behaviour.

In addition to the favourable mechanical behaviours mentioned above, other advantages can be achieved by using NiTi SMA‘s, since they are practically corrosion free, thus ensuring higher durability as compared to other metals. On the other hand, the mechanical properties of SMA‘s, especially in the austenitic phase, depend on temperature and strain rate. A careful design of the material is therefore needed, in order to calibrate its mechanical behaviour with respect to the strain rate requested by the specific application and limit its variability when varying temperature in the practical range.

III. Selection of SMA Elements For Seismic Devices

Both martensitic and austenitic SMA elements can be used in passive control seismic devices. Different stress conditions can be chosen for such elements.

As far as martensitic elements are concerned, cyclic tests in tension - compression, torsion and bending revealed a mechanical behaviour which was mainly characterised by:

- Good energy dissipating capability;
- Large residual strains after removing the external force (eventually recoverable mechanically or by heating);
- Extraordinary fatigue resistance;
- No temperature dependence in the usual range of civil structures.
- Practical absence of corrosion effects.

Martensitic elements can be used only in the form of round or hexagonal bars of different diameters, while wires are excluded for their instability in compression and their permanent strain in tension. As far as energy dissipation is concerned, the most efficient stress mode is tension-compression followed by torsion and then bending. But, on the one hand, torsion needs large clamping lengths and a suitable (often cumbersome) mechanism to transform displacements into rotations, on the other hand, tension-compression needs lateral constraints to avoid buckling in compression. Therefore, the double bending and the roller bending modes are, all in all, the most suitable to realise.

As far as austenitic elements are concerned, the cyclic loading-unloading tensile tests showed a mechanical behaviour characterised by:

- Rather low energy dissipation capability;
- Almost zero residual strain at the end of the action up to maximum values of 10% under arbitrary mechanical loading (pseudoelasticity, or superelasticity);
- Considerable fatigue resistance;
- Dependence on temperature and frequency.
- Practical absence of corrosion effects.

Wires subjected to loading-unloading cycles in tension give the best performances in terms of superelastic features, producing no residual strain after large deformation, and are the best candidates to realise re-centring devices. The energy dissipation capabilities of austenitic alloys strongly depend on frequency. It has turned out to be rather low, if not insufficient, in the usual field of application of seismic devices (0.4 - 4 Hz), being the equivalent viscous damping less than 10%. Finally the variability of the mechanical properties of austenite as a function of its temperature must be considered and related to the actual temperature variation in the field of application of devices in civil structures.

IV. Requirements and Conceptual Design of Devices

The re-centring and the energy dissipation capabilities are the main required features of passive control devices. It must be emphasised, however, that these requirements are somewhat conflicting. As the maximum energy dissipation is obtained in a rigid-plastic behaviour, the re-centring necessarily requires the force-displacement cycle to pass through the axis origin. Therefore, the load displacement cycle area which is proportional to the amount of energy dissipation is reduced as result of the latter condition. The re-centring and dissipating functions are best achieved by means of two separate groups of SMA elements. The re-centring capability is obtained by using austenitic wires. The family of devices that can be obtained by applying the above explained concepts can be subdivided into the following three main categories as shown in Fig.7:

☐ Supplemental Re-Centring Devices (SRCD): a supplemental recovering force is available to re-centre the structural system, even in presence of any possible internal reacting force of the structural system external to the device (e.g. friction in devices, plastic forces in structural elements, etc.);

☐ Non Re-Centring Devices (NRCD): a high energy dissipation capability is available, but large residual displacements occur at the end of the action.

☐ Re-Centring Devices (RCD): these devices recover the initial position at the end of the action with negligible residual displacement, but are not capable to recover the initial shape in presence of external forces.

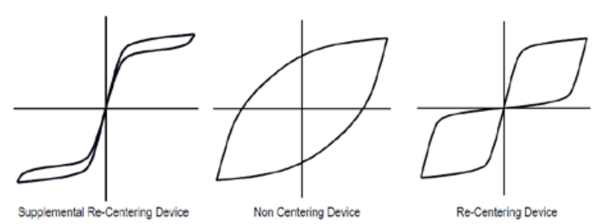


Fig.7. Categories of the types of devices based on SMA.

V. Premise about modeling issue s

Micro-structural models [47]-[49] are usually pretty complex as they try to account for all the many interrelated and highly non-linear thermal and mechanical features of SMAs; the high model sophistication make them pretty unsuitable for practical investigations concerning possible engineering applications; for this purpose, many macroscopic models, able to capture the essential features of the SMA mechanical behaviour, are usually referred to in literature; they are simplified one-dimensional SMA constitutive models, substantially developed as extensions of the Bouc-Wen hysteretic model on the basis of experimental studies and deduced by a general material characterization.

Some fundamental considerations allow to neglect, at a first stage, thermo-mechanical coupling.

- In practice, SMA materials exhibit hysteresis cycles with a dissipated energy amount that, substantially, does not dependent on temperature.
- This effect is demonstrated by experimental evidence that shows that the threshold for forward ($A \rightarrow M$) transformations (and for triggering the apparent plastic phase) rises at a rate of the order 5÷7 MPa per °C, only dragging upward the whole hysteresis loop, which remains unvaried in its amplitude.
- The material temperature changes during the deformation, due to the latent transformation heat and to the dissipation of energy during the cycle. Considering that the temperature decreases during the reverse transformation, the overall result is a kind of apparent kinematic strain hardening, which may be significant when the strain velocity is large.
- Therefore, when neglecting the temperature variation during deformation, one adopts a degree of approximation that is comparable to assuming the perfectly plastic behaviour in elastic-plastic analyses, where strain hardening is often ignored.

In the following one refers to the isothermal one-dimensional stress-strain rate relation

$$\dot{\sigma} = E\left[\dot{\varepsilon} - |\dot{\varepsilon}|\left|\frac{\sigma-\Lambda}{\sigma_c}\right|^{n-1}\left(\frac{\sigma-\Lambda}{\sigma_c}\right)\right] \tag{1}$$

with

$$\Lambda = E\gamma\left\{\hat{\varepsilon} - \frac{\sigma}{E} + 2\frac{\psi}{\pi}|\varepsilon|^p\left[\tan^{-1}(\bar{x})\right]\right\}, \qquad \bar{x} = x^3|x|^q,\; x = \xi\varepsilon,\; q<1 \tag{2}$$

and

$$\bar{x} = x^3|x|^q,\;\; x = \xi\varepsilon,\;\; q<1,\;\; \hat{\varepsilon} = \varepsilon, \tag{3}$$

$$\gamma = \frac{\sigma_0 - \sigma_c}{E\cdot\psi - \sigma_0},\;\; \psi = c_\psi\cdot\frac{\sigma_0}{E} \tag{4}$$

where σ and ε represent the stress and strain respectively, with their first derivatives denoted by the superimposed dot, Λ is the evolutionary one-dimensional *back-stress*, σ_c is the critical stress, and all other symbols represent material constants.

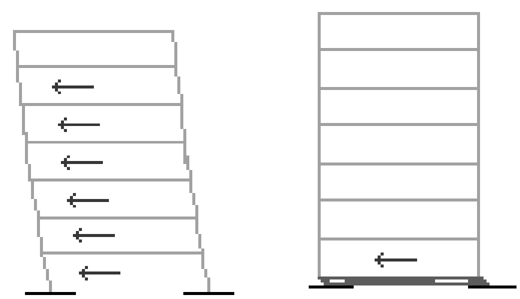
This model [50],[51] is based on the material characterization proposed by Graesser and Cozzarelli [52], which has been modified in order to better the computational implementation of the problem, i.e. the numerical integration of the rate equation Eq.(1), and, thereafter, to improve the simulation of the SMA's behaviour.

VI. SMA Base Isolation Device

SMAs may be used for designing innovative Base Isolation (BI) devices for multi-storey buildings. The primary effect is the one shown in Fig.8 (the sketches from the calculus code are reported captured during the motion running for the non-isolated and the SMA-isolated cases), typical of BI systems, to make the structure to act as a rigid block, thus drastically reducing the inter-storey drifts and the plastic excursions, marked by the arrows.

The second one, still typical of BI devices, consists of reducing absolute displacements of the structure.

Actually the main objective of the SMA BI-system is to provide the main structure with a dissipation device able to attenuate the effects induced by the incoming dynamic excitation also in terms of recovering of residual plastic deformations; obviously, the exploitation of the pseudo-elastic character of the SMA members requires a suitable tuning of the alloy parameters on the basis of the structure mechanical and geometrical characteristics.



(a) (b)

Fig.8: Sketches of the shear frame during the motion: a) structure without SMA isolation, b) structure with SMA isolation.

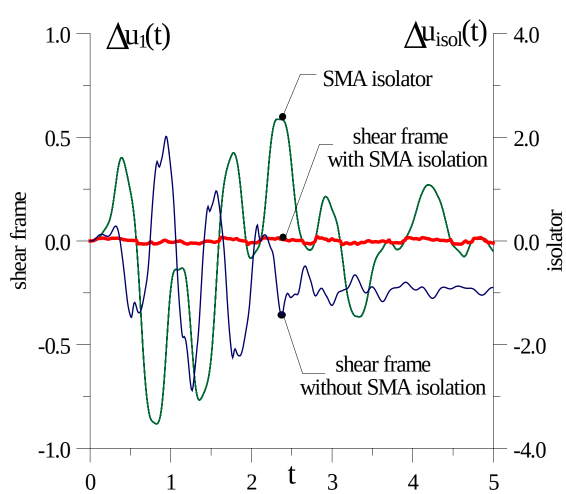


Fig.9: Drift in the shear frame with and without SMA isolation for the 1st floor.

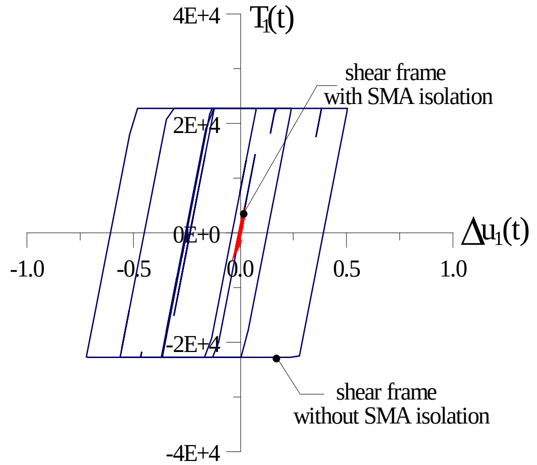


Fig.10: The 1st floor hysteresis loops.

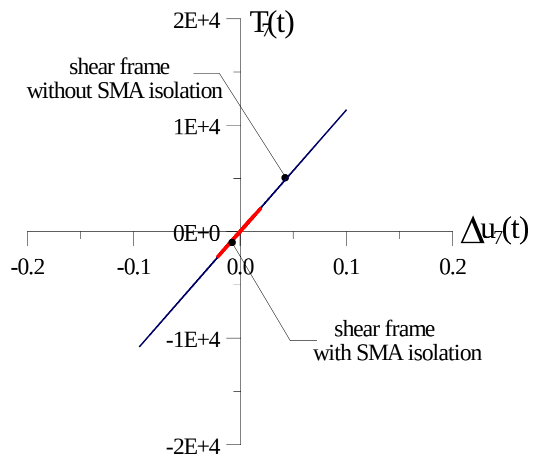


Fig.11: The 7th floor hysteresis loops.

Therefore, the analysis of the dynamics of the main structure is necessary in order to set up the isolation device in such a manner to make the SMA elements exhibit hysteresis loops, i.e. the classical super-elastic behaviour.

Numerical investigation developed on the 7-degrees of freedom in Fig.8 shows that a drastic reduction of inter-storey drift may be obtained, as illustrated in Fig.9, where the uncontrolled and controlled drifts $\Delta u_1(t)$ are compared with reference to the 1st floor vs the time variable t. In the meanwhile one is able to get a high re-centring at the end of the motion as clear from the shear-drifts diagrams reported in Figs 10 and 11, with reference to the 1st and 7th floor respectively .

VII. Conclusion

In the paper one presents an overview of basic properties of shape memory alloys under the perspective of possible structural engineering applications for the mitigation of dynamic vibrations.

Main SMA features and their possible exploitation are discussed, along with modelling and design issues of dissipative and visco-recentring SMA devices.

It is made clear that one of the primary advantages with respect to classical strategies consists of giving the structure a re-centring capacity, with recording of small residual displacements after the dynamic event, which still represents the primary advantage with respect to more classical control strategies.

The device should be suitably designed on the basis of the characteristics of the structure, making the alloy to develop the classical super-elastic effect with theoretically no or small residual strain upon unloading.

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