EXPERIMENTAL TESTS ON SEISMIC DEVICES BASED ON SHAPE MEMORY ALLOYS

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SUMMARY

The experimental investigation carried out at the laboratory of DiSGG of the University of Basilicata on the seismic devices implemented within the MANSIDE (Memory Alloys for New Seismic Isolation DEvices) project and the most significant experimental results are described and analysed in terms of typical quantities, such as: stiffness, energy loss and equivalent damping. Two families of seismic devices based on Shape Memory Alloys (SMAs) were tested: special braces for framed structures and isolation devices for buildings and bridges. The most important features of these devices, which were confirmed by the experimental tests, are:

- An extreme versatility, i.e. the possibility to obtain a wide range of cyclic behaviours, from fully re-centring to highly dissipating, just by varying the types and/or the number and/or the characteristics of the SMA elements;
- An extraordinary fatigue resistance, i.e. the capability to undergo a great number of cycles of large amplitude (and therefore many destructive earthquakes) without any need of substitution or maintenance;
- A great durability and reliability in the long run.

INTRODUCTION

Shape memory refers to the ability of certain metallic alloys (Ni-Ti, Cu-Al-Zn, etc.) to undergo large strains (up to 10%) without any permanent deformation, but recovering their initial configuration at the end of the deformation process, spontaneously or by heating [Duerig et al. 1990]. The peculiar properties of Shape Memory Alloys (SMAs) are strictly connected with a reversible solid-to-solid phase transformation, which can be thermal-induced or stress-induced.

At relatively high temperatures a SMA exists in the austenitic state. It undergoes a transformation to the martensitic state when cooled. In the stress-free state a SMA is characterised by four transformation temperatures: M_s and M_f during cooling, A_s and A_f during heating. M_s and M_f are the temperatures at which the transformation from austenite to martensite, respectively, starts and finishes. A_s and A_f are the temperatures at which the inverse transformation starts and finishes.

When an unidirectional stress is applied to a SMA in austenitic state, there is a critical value, dependent on temperature, whereupon a transformation from austenite to martensite takes place. As deformation proceeds, the stress remains almost constant until the material is fully transformed. Further straining cause the elastic loading of martensite. Upon unloading, since the martensite is unstable at such temperatures without stress, a reverse transformation occurs, but at lower stress level as during loading, so that an hysteretic effect is produced.

If the material temperature is greater than A_f, the large strain attained on loading (even 8-10%) is completely and spontaneously recovered at the end of unloading. This remarkable process gives rise to energy-absorbing capacity with zero residual strain and is thus termed *superelasyicity* (or *pseudoelasticity*).

If the material temperature is less than A_f, a residual strain remains after unloading (which is very large if temperature is less than A_s, i.e. if the material is in martensitic state), but it may be recovered by heating above A_f. This phenomenon is generally referred to as *memory effect*.

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Other important features of SMAs are a high resistance to large strain cycle fatigue and, in the case of NiTi alloys, a great durability thanks to an exceptional corrosion resistance and no degradation due to ageing.
All these properties make SMAs very attractive in the field of passive seismic protection of structures. Some experimental and theoretical studies have been performed in recent years [Aiken et al. 1993, Graesser and Cozzarelli 1991, Whittaker et al. 1995, Witting and Cozzarelli 1992]. However a more comprehensive research was needed in order to fully explore the possibilities of applying SMAs in the passive control of structural vibrations. Within this framework, the main aim of the MANSIDE project was the conceptual design, the implementation and the experimental testing of SMA-based devices for passive control of buildings, bridges and other structures.
In this paper the experimental mechanical behaviour of the devices is described and their most remarkable features are discussed. Their functioning principles, instead, are illustrated in [Dolce et al. 2000], while the performances of structural models endowed with them are analysed in [Brancaleoni et al. 2000].

EXPERIMENTAL BEHAVIOUR OF SMA ELEMENTS

The presentation of SMA-based devices necessarily has to start from the knowledge of the performances of the single components.
The mechanical behaviour of several Ni-Ti SMA elements, different as regards shape (wires and bars), physical characteristics (alloy composition, its thermomechanical treatment, material state) and stress state (tension, torsion, bending and shear), was carefully examined through experimental tests, as well as through very accurate numerical simulations by means of a non linear finite element program, in order to find the best way to exploit the SMA properties in passive seismic control devices [Cardone et al. 1999a].
All the experimental tests were carried out by applying cyclic sinusoidal deformation to the specimens. For each group of tests, different strain levels, strain rates and temperatures were considered.
As far as austenitic elements are concerned, cyclic tensile tests on wires showed a mechanical behaviour characterised by (see Fig. 1a):

- Rather low energy dissipation capability, with equivalent damping of the order of 4-5% in the frequency range of interest for seismic application (i.e. for frequency of loading greater than 0.2 Hz);
- Zero residual strain at the end of the action (*Superelasticity*);
- Considerable fatigue resistance, of the order of hundreds of cycles at 6-8% strain levels;
- Some dependence on temperature in the range of application.

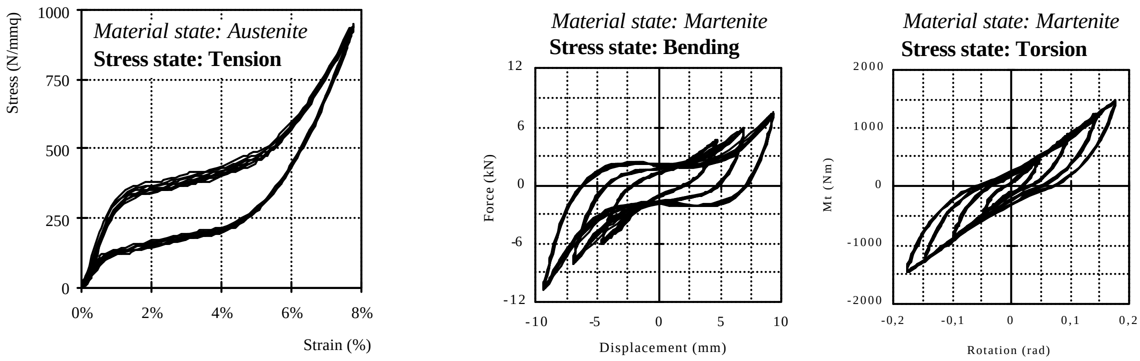


Figure 1. Mechanical behaviour of SMA elements under different stress conditions

As far as martensitic elements are concerned, cyclic torsional and flexural tests on bars showed a mechanical behaviour characterised by (see Figs. 1b,c):

- Good energy dissipation capability, with equivalent damping of the order of 15-20%;
- Large residual strains after removing the external force, eventually recoverable mechanically or by heating;
- Extraordinary fatigue resistance, of the order of several hundreds of cycles even at very large strain amplitudes;
- Independence from temperature and strain rate.

Martensite bars subjected to torsion or bending presented similar behaviours, so that the most important aspect in choosing the SMA components for devices became the simplicity of the mechanism to induce the desired stress state. From this point of view, (double or roller) bending was preferred to torsion because of the very easy arrangement and compactness with respect to the large allowed displacements, while torsion needs a cumbersome mechanism to transform displacements in rotations and larger clamping lengths.

EXPERIMENTAL BEHAVIOUR OF SMA-BASED SEISMIC DEVICES

Self-centring capability at the end of the action and good energy dissipation capability were chosen as the main performance objectives of the devices. In the light of what has been said about SMA elements, it is apparent that the first functional property can be supplied by austenitic superelastic wires subjected to tension, but it is also clear that they must be supplemented by other dissipating elements or exploited through some particular mechanism in order to provide the devices with a good energy dissipation capability.

Generally speaking, the devices are made of two concentric pipes that move mutually when inserted in a structure subjected to seismic actions, as their ends are connected to mutually moving parts of the structural system, e.g. two consecutive stories in a frame, the pier and the deck in a bridge, the base and the superstructure in a building.

The self-centring and energy dissipation capabilities are relied upon two different groups of SMA elements: the re-centring group and the dissipating group. The re-centring group is characterised by pre-tensioned austenitic superelastic wires winded around two studs inserted transversally in the pipes, into oval-shaped holes. The special arrangement of studs and holes is such that the wires are always subjected to tension increments for any positive or negative relative movement of the pipes. The dissipating group is characterised by either martensitic bars stressed in double bending (only for braces) or U-shaped martensitic bars stressed in roller bending (only for isolators) or pre-tensioned austenitic superelastic wires winded around three studs and arranged in such a way to act as a double counteracting system of springs (both for braces and isolators). An excellent hybrid solution can be realised by relying the energy dissipation function upon steel elements. The advantages of this solution come from the high energy dissipation capability of steel, its very low hardening and its low cost. The only drawback is the eventual need for substitution of the steel elements after strong earthquakes.

Several devices were realised and tested at the laboratory of the University of Basilicata:

- one full-scale special brace prototype, designed to carry up to 200 kN and to reach 20 mm displacement (Fig. 2),
- three 1/3.3-scale special braces, designed to carry up to 80 kN and to reach 10 mm displacement,
- one 1/3.3-scale device for isolation system, designed to carry up to 30 kN and to reach 100 mm displacement,
- two full-scale devices for isolation system, designed to carry up to 600 kN and to reach 180 mm displacement.

The 1/3.3-scale devices were especially realised to be installed into 1/3.3 R/C frame models which were tested on shaking table at the laboratory of the Technical University of Athens for MANSIDE [Brancaleoni et al. 2000].

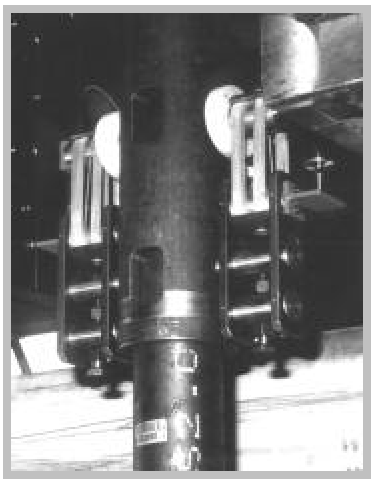
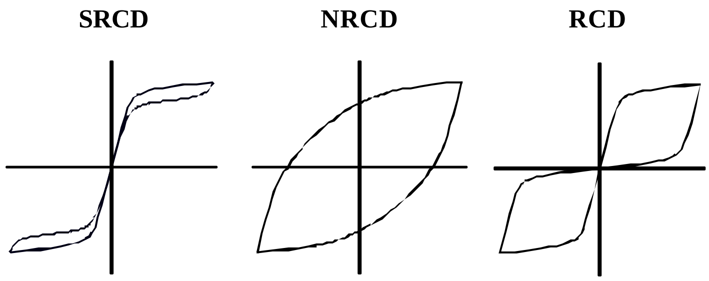


Figure 2. Full-scale brace with re-centring austenite wire loops.



The isolation system is completed by sliding steel-teflon bearings which support the total weight of the superstructure. These latter can incorporate U-shaped SMA bars or steel plates as energy dissipating group, alternative to the SMA wire dissipating group.

Actually, each device was realised to incorporate the re-centring group and both types of dissipating groups, with a variable number of elements. It was thus possible to test a great deal of different configurations, obtaining a wide range of mechanical behaviours by simply varying the characteristics and/or the number of SMA elements of both groups. By applying the previous concepts, several types of SMA-based devices were conceived, which can be classified into the three following categories (see Fig. 3), according to the residual displacement at the end of the action and the possible supplemental recovering force:

- *Supplemental Re-Centring Devices* (*SRCD*): typically based on the re-centring group only, they present zero residual displacements at the end of the action and further capability to provide an auxiliary re-centring force which compensates possible reacting forces external to the device;
- *Not Re-Centring Devices* (*NRCD*): based on the only dissipating group, they present high dissipation capability but also large residual displacements at the end of the action;
- *Re-Centring Devices* (*RCD*): including both re-centring and dissipating group, they present zero or negligible residual displacements, but are not capable of recovering the initial configuration in presence of reacting forces external to the device.

It's worthwhile to emphasise that all of this is done with the same structural components and can be decided at the point of installation, as required for each situation. Therefore, it can be said that a first important feature of these passive seismic control devices is their extreme versatility, i.e. the possibility of calibrating the shape of the hysteresis loops according to any particular individual need.

In the next subparagraphs, the experimental mechanical behaviour of the aforesaid three categories of SMA-based devices is described. For simplicity, the attention is especially focused on the tests conducted on the braces. More detailed and comprehensive information are reported in [Cardone et al. 1999b].

Tests on Supplemental Re-Centring Devices

Several re-centring groups, differing in alloy features, and/or wire diameter, and/or pre-strain levels (0-5%), and/or number of wires were tested. As a matter of fact, more than 200 tests were carried out, both at room temperature and under temperature control (between 0 °C and 50 °C), at frequency of loading ranging from 0.02 to 4 Hz and displacement amplitude up to 13 mm, corresponding to about 11% maximum strain in the wires.

In Fig. 4 there are shown three typical force-displacement diagrams relevant to three different pre-strain levels, namely 1.2%, 2% and 4%. As can be seen, the greater the pre-strain of wires, the greater the supplemental re-centring force and the stiffness at small displacements. In fact, because of pre-strain, a threshold force to elongate wires is defined. When increasing pre-strain the threshold force increases and the loops translate

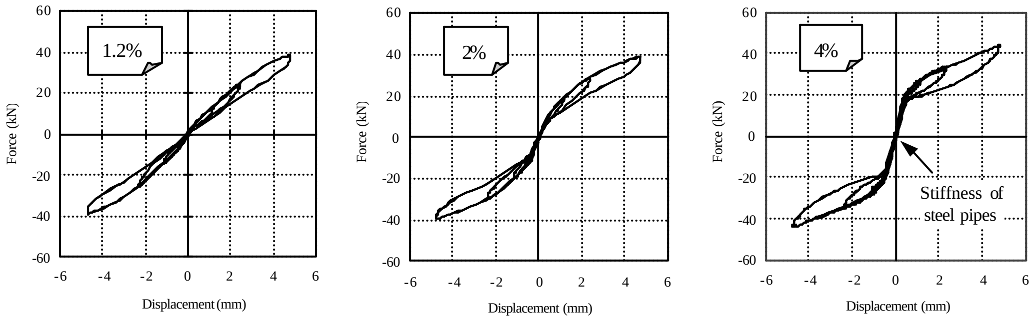


Figure 4. Supplemental Re-centring Device (*12 re-centring 2mm diameter austenite wire loops*): Mechanical behaviour as a function of pre-strain (1 Hz frequency, 25 °C temperature).

upwards. Actually, the initial stiffness of the devices is simply the axial stiffness of the steel pipes.

The effectiveness of a device in damping vibrations is generally measured in terms of the equivalent viscous damping, which is commonly defined as:

where W_D is the energy loss per cycle, equal to the area within the hysteresis loop, K_s the secant stiffness and δ the maximum cyclic displacement under consideration.

$$\zeta_{eq} = \frac{W_D}{4 \cdot \pi \cdot W_s} = \frac{W_D}{2 \cdot \pi \cdot K_s \cdot \delta^2} \qquad \text{(Eq. 1)}$$

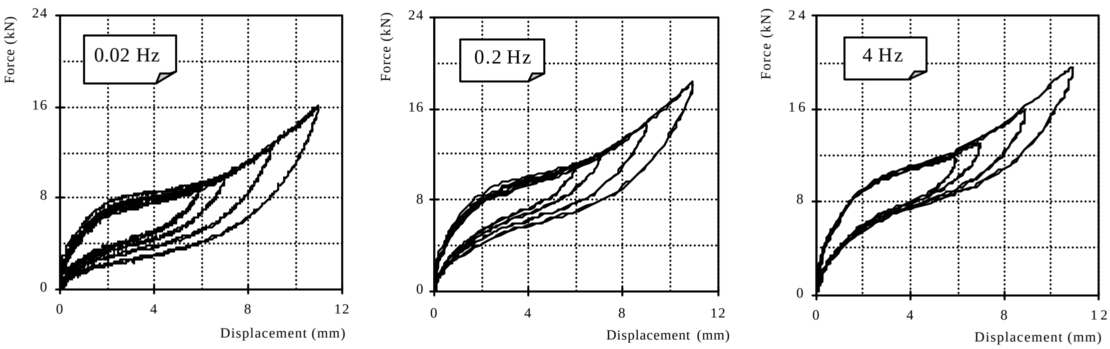


Figure 5. Supplemental Re-centring Device (*4 re-centring 1.84mm diameter austenite wire loops*) : Mechanical behaviour as a function of frequency of loading (25 °C temperature, 1% pre-strain).

The SRC devices exhibited an equivalent damping of the order of 4-5%, independently from pre-strain. It appears rather low if compared with that of other common devices. But it should be noted that energy dissipation capability is not the primary requirement for the SRC devices. As a matter of fact, they were conceived to provide an auxiliary re-centring force to allow the structural system to recover its initial configuration at the end of an earthquake, even in presence of parasite non conservative forces external to the device, such as friction of bearings (for the isolation systems) or plastic forces of structural elements (for the bracing systems).

The mechanical behaviour of the SRC devices was found to be substantially insensitive to frequency (see Fig. 5), at least in the range of interest for seismic applications (i.e. for frequencies greater than 0.2 Hz). One favourable feature is that their strength increases as large displacements are attained (see again Fig. 5). Therefore if the predicted earthquake excitation were exceeded, the structural system would stiffen rather than soften.

Tests under thermal control, with temperature varied between 0 and 50 °C (step 5 °C), revealed a linear dependence on temperature (see Fig. 6), with increases of force of the order of 10% every 10 °C, and decreases of equivalent damping the order of 13% every 10 °C.

The sensitivity to temperature, though not negligible, appears to be compatible with the typical applications in the field of civil engineering, also considering that similar and even stronger dependence on temperature can be found in other devices for passive control, especially those based on polymers (rubber and other visco-elastic materials). In any case it's important to check the compatibility of the mechanical variability due to temperature of the device as a component of a structural system. At worst, in particular situations, the devices could be protected, as far as possible, from temperature changes.

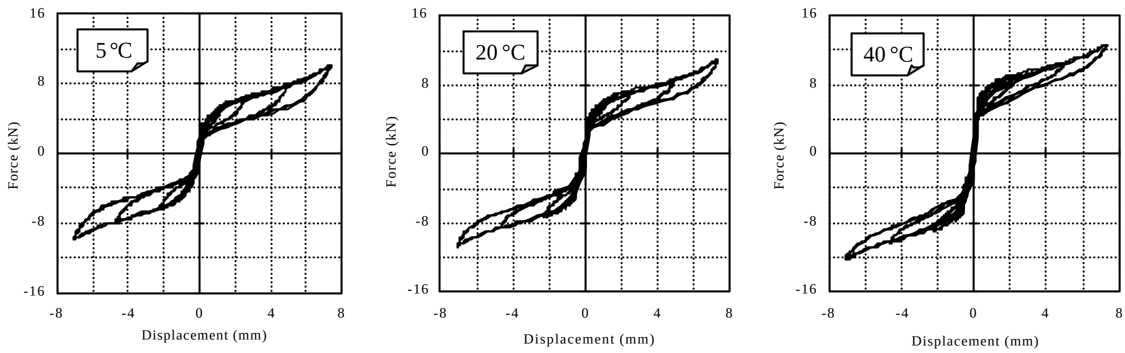


Figure 6. Supplemental Re-centring Device (*12 re-centring 1mm diameter austenite wire loops*) : Mechanical behaviour as a function of temperature (1 Hz frequency, 3% pre-strain).

It must be observed that if an earthquake occurs when temperature is very low, the supplemental re-centring force could not be fully available, since it reduces when temperature decreases. Thus a residual displacement could occur at the end of the earthquake. As soon as temperature increases, however, the structure would be automatically re-centred, as tests carried out at variable temperature, under constant force, demonstrated (see Fig. 7).

Fig. 8 shows the full-scale isolator device (nearly) ready to be tested. In Fig. 9 there is reported the force-displacement diagram recorded during a test (25 °C temperature, 0.2 Hz frequency) on the full-scale isolation device with 118 re-centring 1.84 mm diameter austenite wire loops pre-strained at 2%. As a matter of fact, the device have an elastic non linear behaviour with a supplemental re-centring force of about 160 KN, which can be exploited to counteract the friction of the bearings and the dissipating force of additional components or devices.

Another relevant aspect is the better control of force with respect to other elastic device (e.g. a rubber isolator).

It's worthwhile to underline that, in any case, what is pursed is a re-centring behaviour with as much energy dissipation as possible. However, this behaviour must be referred to the entire isolation system or, for the bracing systems, the entire structural system. As parasite forces are always present in the isolation system, and generally also in the structure, supplemental re-centring devices are needed to achieve the desired aim. In the light of what

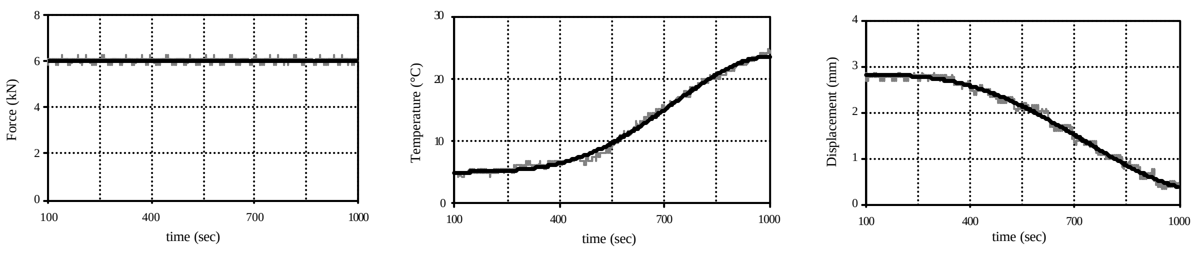


Figure 7. Delayed recovery of the residual displacement.

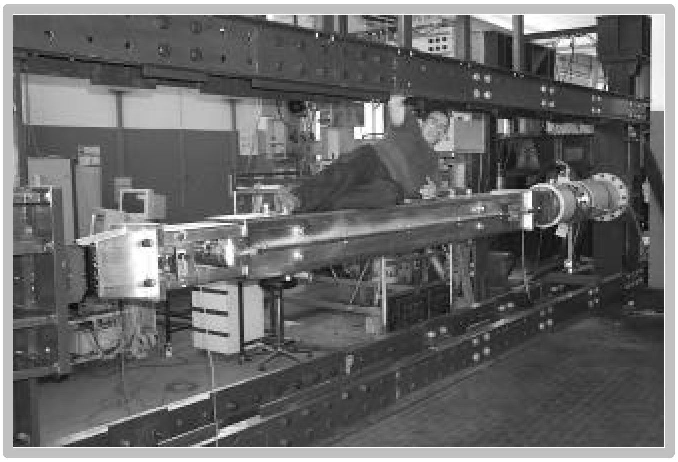


Figure 8. Full-scale isolator device ready to be tested.

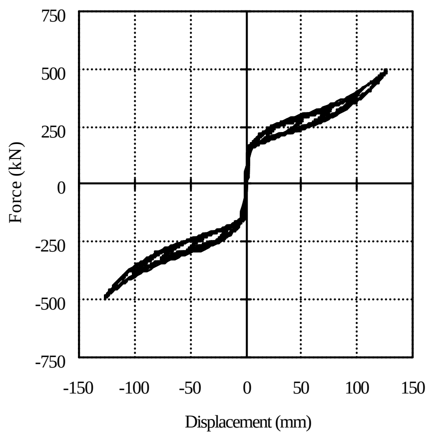
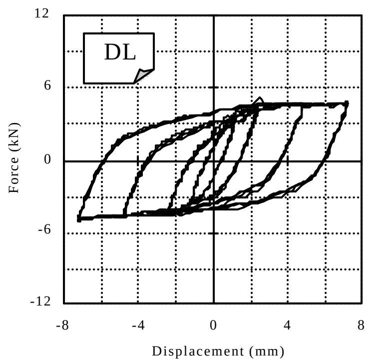


Figure 9. SMA-based isolator device hysteresis loops.

said, the Re-Centring Devices (see point 3.3) can be seen as a particular case of Supplemental Re-Centring Devices, with auxiliary re-centring force equal to zero.

Tests on Not Re-Centring Devices

Two versions of Not Re-Centring Devices were considered, differing in the SMA elements used: martensite bars stressed in double bending in the first version (for simplicity type B), pre-strained austenite wires acting as a double counteracting system of springs in the second version (for simplicity type DL). The tests were carried out both at room temperature and under temperature control (0-50 °C), with frequency of loading ranging from 0.02 to 1 Hz and displacement amplitude up to 8 mm, corresponding to about 9% maximum strain in the wires.
As regards the shape of the hysteresis loops (see Fig. 10), deep differences were observed between the two



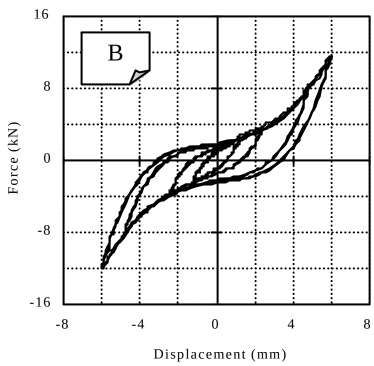


Figure 10. SMA-based Not Re-centring Devices hysteresis loops.

versions of NRC device. In fact, while the type DL devices exhibited an apparent threshold value of force, the type B devices exhibited a strong hardening effect. The softening effect of the type DL devices can be ascribed to the particular arrangement and working conditions of the SMA-austenite wires. The hardening effect of the type B devices, instead, corresponds to the completion, in some zones of the bars, of the detwinning process of the martensitic variants [Duerig et al. 1990].

Both behaviour are interesting for practical applications, though from different point of view. The former would allow the structural system to be designed with respect to a well defined maximum force, according to the capacity design criterion. The latter obtains a better control of displacements, as the device (and as a consequence the structure) would stiffen rather than soften for unforeseen large displacements.
Further remarkable differences were found in the trend and values of the equivalent damping. While for the DL devices the equivalent damping increases while increasing displacement, reaching values of the order of 40% at relatively large amplitudes (7 mm), for the B devices it decreases as displacement becomes quite large (because of hardening), reaching about 20% peak value.
Temperature and frequency of loading do not affect significantly the mechanical behaviour of both devices. For the type B devices this is due to the intrinsic properties of martensite, while for the type DL devices this is a consequence of the working mode of the wire arrangement.

Tests on Re-centring devices

As foreseen, the mechanical behaviour of the Re-Centring devices resulted to be intermediate between those of the two previous families of devices, since they are nothing but a combination of a SRC device with a NRC device.
By calibrating the number and the characteristics of the SMA elements of both groups (including pre-strain of wires), in such a way that the cyclic force of the dissipating group at zero displacement is not greater than the pre-stress force of the re-centring group, the optimal mechanical behaviour is obtained. It is characterised by double flag-shaped hysteresis loops, i.e. by the maximum energy dissipation compatible with the self-centring feature.
Two examples of RC devices are given in Fig. 11. In particular, Fig. 11a refers to a device having 24 re-centring 1mm diameter austenite wire loops pre-strained at 3% and 6 martensite bars with 6.7mm diameter and 30mm frexural length. Fig. 11b, instead, is relevant to a device resulting from the combination of 10 re-centring 1mm diameter austenite wire loops, pre-strained at about 3%, with 6 dissipating 1mm diameter austenite wire loops, pre-strained at about 4%.
As a general remark, it's worth to note that the equivalent damping, starting from quite low values (4%), increases rapidly while increasing the cyclic amplitude, reaching values of the order of 15-20% at relatively large amplitudes (8 mm).
In order to assess the long term reliability of the SMA-based devices, the effects due to the relaxation of the pre-tensioned wires were evaluated by repeating some tests after three weeks on the same devices. It actually resulted to be largely negligible. Considering the nature of the phenomenon, that will be true also in the long term.
Tests under temperature control (0-40 °C) pointed out a lower sensitivity to temperature variations with respect to the SRCD. Increases of the order of 7% every 10 °C in terms of force, and decreases of the order of 8% in terms of equivalent damping were found.

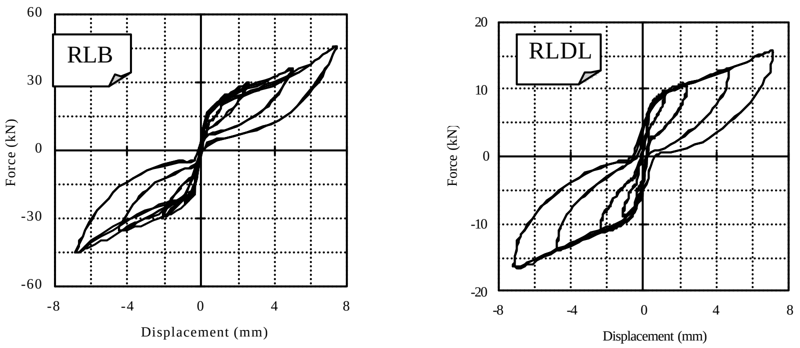


Figure 11. SMA-based Re-Centring Devices hysteresis loops.

To conclude, an important remark has to be made. Several configurations of devices were tested within three different families of SMA-based devices (SRCD, NRCD, RCD). Most of them underwent a great number of cycles (more than 300, on average; up to more than 600, in some cases) at large displacement amplitudes (up to 13 mm) without any failure and with a stable and repeatable cyclic behaviour. As a matter of fact, during each series of tests, it was never necessary to substitute any SMA element, even better, sometimes the SMA elements used in a series of tests were still re-used in the next one. That confirmed the exceptional fatigue resistance properties of SMA's. It is then clear that the SMA-based devices can undergo many destructive earthquakes without any need of substitution or maintenance, guaranteeing always the same mechanical performances.
Another important consequence in terms of reliability is that they can be tested and then mounted in the structure, without changing anything.

CONCLUSIONS

Two families of passive seismic control devices (special braces for framed structures and isolation devices for buildings and bridges) based on Shape Memory Alloys (SMAs) have been realised within the Brite-Euram MANSIDE project. An extensive experimental investigation clearly showed their full suitability and, even better, their great potential in the passive seismic protection of civil structures.
The basic features of these devices are:

- A *great versatility*, i.e. the possibility to obtain a wide range of cyclic behaviours, from fully re-centring to highly dissipating, just by varying the characteristics and/or the number of the SMA components, thus allowing to calibrate the shape of the hysteresis loops according to any particular individual need;

- To have a *very simple functioning mechanism*, even though they are behaviourally sophisticated .

By properly calibrating their design parameters, a mechanical behaviour characterised by double flag-shaped hysteresis loops is obtained. In this case, the devices present, at the same time, three favourable features:

- *Self-centring capability*, with the possibility to provide a supplemental re-centring force to bring back the structural system at its initial configuration when the earthquake is over, even in presence of parasite non conservative forces external to the devices, such as friction of bearing or plastic forces of structural elements;
- *High stiffness for small displacements*, to avoid the structure to move by wind or small tremors;
- *Good energy dissipation capability*, to reduce accelerations and displacements caused by an earthquake.

Further important properties, which are common to all types of devices based on Ni-Ti shape memory alloys are:

- *Extraordinary fatigue resistance*, i.e. the capability to undergo several hundreds of cycles of large amplitude, and therefore many destructive earthquakes, without any need of substitution or maintenance;
- *Long term reliability*, thanks to the largely negligible relaxation of the pre-tensioned SMA wires;
- *High durability,* thanks to an excellent corrosion resistance and no degradation due to ageing;
- *Substantial independence from oscillation frequency* in the range of interest for seismic applications;
- *Rather limited sensitivity to temperature*, compatible with the typical applications of the civil engineering.

These SMA-based devices seem to be really especially suited for seismic isolation. In fact, they are very stiff for small displacements, but become very deformable in the event of strong earthquakes, thus making up a filter between the ground motion and the superstructure. Moreover, with a cyclic behaviour characterised by double flag-shaped hysteresis loops, they combine the best mechanical features of both quasi-elastic devices (e.g. rubber isolators) and elasto-plastic devices (e.g. sliding/roller bearings or devices based on common metals). On the one hand, they re-centre the structure at the end of the earthquake (like the quasi-elastic devices), on the other hand, they assure a good control of the force transmitted to the superstructure (like the elasto-plastic devices).

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