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Implementation and testing of passive control devices based on shape memory alloys

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SUMMARY

Two families of passive seismic control devices exploiting the peculiar properties of shape memory alloy (SMA) kernel components have been implemented and tested within the MANSIDE project (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices). They are special braces for framed structures and isolation devices for buildings and bridges. Their most important feature is their extreme versatility, i.e. the possibility to obtain a wide range of cyclic behaviour — from supplemental and fully re-centring to highly dissipating — by simply varying the number and/or the characteristics of the SMA components. Other remarkable properties are their extraordinary fatigue resistance under large strain cycles and their great durability and reliability in the long run. In this paper, the working mechanisms of the SMA based devices are outlined and the experimental tests carried out to verify the above-mentioned properties are extensively described. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: passive seismic control; energy dissipation systems; isolation systems; smart materials; shape memory alloys; superelasticity

INTRODUCTION

It is widely accepted that it is not economically acceptable to design and build conventional structures to undergo strong earthquakes in the elastic range. As a consequence, the current design philosophy [1] accepts heavy damage under strong earthquakes, provided that the structure is 'ductile' enough to undergo important plastic deformations without collapsing.

Alternative design strategies, commonly referred to as 'Passive control' techniques [2, 3, 4] have been recently conceived. They are aimed at reducing — and possibly eliminating — plastic deformations of structures under strong earthquakes, by exploiting a pre-determined favourable behaviour of special devices inserted in the structural system. Current passive control applications are based on the following two techniques: (1) seismic isolation; and (2) energy dissipation.

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Seismic isolation techniques introduce one or more discontinuities along the height of the structure to be isolated, so that the structure is divided into two or more parts, i.e. the sub-structure, which is rigidly connected to the foundation structures, and the super-structure(s). The isolation system is basically made up of 'isolators', i.e. bearing devices which are installed between sub-structure and super-structure and allow them to move relatively with large horizontal displacements (typically of the order of 100–200 mm). They constitute a horizontally uncoupling system, or filter, which reduces the transfer of seismic energy to the superstructure, thus also limiting forces on the substructure. In order to limit the extent of such displacements, an isolation system must be provided with energy dissipation (and/or re-centring) capabilities. This can be achieved either by using isolators with these intrinsic properties or by embodying additional dissipating (and/or re-centring) elements, or even by providing separate dissipating (and/or re-centring) devices.

Energy dissipation techniques rely upon the absorption and dissipation of big amounts of energy by devices connecting different parts of a structure, which move reciprocally during earthquakes. Relative displacements and, consequently, stresses in structural elements are significantly reduced. A classical application of this concept is made in framed building structures, where energy dissipating braces are installed to connect different storeys and dissipate energy in the relative interstorey displacements. The devices used for this technique are, in principle, similar to the ones used for energy dissipation in seismic isolation systems. The main peculiarity is the displacement amplitude, which is one order of magnitude smaller (10–20 mm instead of 100–200 mm).

A classification of the isolation devices can be made according to the technology used to achieve the above said uncoupling properties and the energy dissipating mechanism. Basically four kinds of isolators can be considered [4]: (1) rubber isolators; (2) sliding isolators; (3) rolling isolators; and (4) isolators with added dissipation. Four types of energy dissipation devices can also be identified among the currently used ones [4]: (1) visco-elastic devices; (2) elasto-plastic hysteretic devices; (3) friction devices; and (4) viscous devices.

At present several applications of passive seismic protection exist all over the world, both in new and in existing constructions. Some recent destructive earthquakes (Northridge, 1995; Kobe, 1996) definitively proved their effectiveness. However, the increasingly demanding performance requirements push towards the development of new devices, exploiting the peculiar characteristics of new advanced materials. Indeed, current technologies present some limitations, such as problems related to ageing and durability (e.g. for rubber components), to maintenance (e.g. for those based on fluid viscosity), to installation complexity or replacement and geometry restoration after strong events (e.g. those based on steel yielding or lead extrusion), to variable performances depending on temperature (e.g. polymer-based devices).

Shape memory alloys (SMAs) [5, 6], to date mainly applied in medical sciences, electrical and mechanical engineering, can open a new application field in civil engineering, specifically in the seismic protection of constructions, since they show the potential to eliminate the limitations involved in current technologies.

Shape memory refers to the ability of certain alloys (Ni–Ti, Cu–Al–Zn, etc.) to undergo large strains (up to 10 per cent), while recovering their initial configuration at the end of the deformation process, spontaneously or by heating, without any residual deformation. The particular properties of shape memory alloys (SMAs) are strictly associated to a reversible solid–solid phase transformation, which can be thermal 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 characterized by four transformation temperatures [7]: M_s and M_f during cooling, A_s and A_f during heating. M_s and M_f indicate the temperatures at which the transformation starts and finishes, respectively. A_s and A_f indicate the temperatures at which the inverse transformation starts and finishes, respectively.

When a unidirectional stress is applied to a SMA sample in the austenitic state, a transformation from austenite to martensite starts at a critical stress value, which depends on temperature. As deformation increases, under isothermal conditions [8], stress remains almost constant until the material is fully transformed. Further straining causes the elastic loading of martensite. Upon unloading, since unstressed martensite is unstable at such temperatures, a reverse transformation occurs. However, since the inverse transformation takes place at a lower stress level, a hysteresis occurs.

If the material temperature is greater than A_f, the large strain attained on loading (even 8–10 per cent) 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 *superelasticity* (or *pseudoelasticity*) [6].

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 the martensitic state), but it may be recovered by heating above A_f. This phenomenon is generally referred to as *memory effect* [6].

Other important features of some SMAs are: high resistance to large strain cycle fatigue, great durability, owing to an exceptional corrosion resistance, and no degradation due to ageing [6, 9, 10].

It is easy to imagine which are the possible advantages resulting from the use of SMAs in seismic devices: no lifetime limits (no problem of maintenance or substitution, even after several strong earthquake), good control of forces, self-centring capability.

Some experimental and theoretical studies have been performed in recent years [11–15] to exploit SMAs in seismic devices. However a more comprehensive research was needed in order to fully explore the possibilities of applying SMAs in the passive control of structural vibrations. With this aim, the European Commission funded the MANSIDE project (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices), within the IV Brite-Euram program. Its main scope was the design, the implementation and the experimental testing of SMA-based devices for passive control of buildings, bridges and other structures. In this paper the conceptual design process, the functioning mechanism of the devices and the results of an extensive experimental investigation are described. Detailed information, on aspects that cannot be treated herein in detail, can be found in the proceedings of the final workshop of the MANSIDE project [16–18].

SELECTION OF THE ALLOY AND OF THE KERNAL COMPONENTS

Three fundamental preliminary steps in the conceptual design process of SMA-based devices are: (1) the selection of the most suitable alloy for the SMA kernel components; (2) the selection of the shape of SMA kernel components; and (3) the selection of the stress mode of SMA kernel components.

Five different alloy types were considered, comparing their mechanical and durability properties: NiTi (nickel–titanium), CuAlNi (copper–aluminium–nickel), CuZnAl (copper–zinc–aluminium), FeMn[Si] (iron–manganese–[Silicium]), MnCu (manganese–copper). Owing to their better superelastic properties, lower sensitivity to temperature, higher resistance to corrosion and fatigue, nickel–titanium alloys, with near equiatomic composition, subjected to cold working and annealing treatments, were selected as the most suitable SMAs for passive control devices.

Considering the limited workability of the material, kernel components for devices can only be drawn from wires or bars. They differ from each other for the diameter (up to 2 mm for commercial wires, up to 8 mm for commercial solid bars, up to 50 mm for special production bars), as well as for the stress state they can be subjected to in practical applications (tensile stress for wires, bending and/or torsion and/or shear for bars). NiTi wires can only be used in their austenitic phase, as superelasticity allows them to undergo loading–unloading cycles without any residual strains. On the contrary, NiTi bars can be employed either in their martensitic or in their austenitic state, according to the requirements to be fulfilled by the SMA-based device.

The optimal stress mode was selected, after an extensive experimental investigation on SMA elements, looking both at the mechanical behaviour of the SMA-elements and at the practical difficulties related to the device construction.

The mechanical performances of several NiTi elements were carefully examined through experimental tests, as well as through accurate numerical finite element simulations, in order to find the best way to exploit the peculiar SMA properties [16]. Different shapes (wires and bars), physical characteristics (alloy composition, thermomechanical treatment, material state) and stress states (tension, torsion, bending and shear) were considered. All the experimental tests were carried out by applying cyclic sinusoidal deformations. For each group of tests, different strain levels, strain rates and temperatures were considered.

As far as austenitic elements are concerned, the mechanical behaviour found with the cyclic tensile tests on wires is characterized by (see Figure 1(a)):

(a) Rather low-energy dissipation capability, being the equivalent damping of the order of 4–5 per cent in the range of interest for seismic applications (i.e. for frequency of loading greater than 0.2 Hz);
(b) zero residual strain at the end of the action (*superelasticity*);

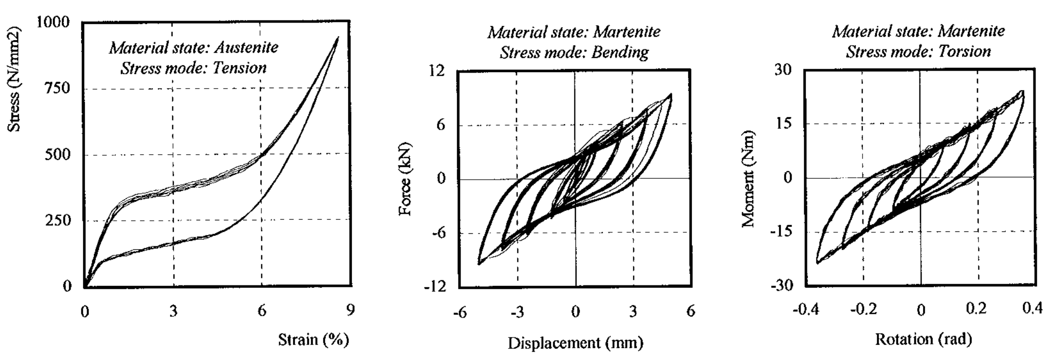


Figure 1. Mechanical behaviour of SMA elements under different stress conditions: austenite wires in tension (a); martensite bars in bending-shear (b); martensite bars in torsion (c).

(c) considerable fatigue resistance, of the order of hundreds of cycles at 6–8 per cent strain levels;
(d) not negligible dependence on temperature and on strain rate.

As far as martensitic elements are concerned, the mechanical behaviour found with cyclic torsional and flexural tests on bars is characterized by (see Figures 1(b) and 1(c)):

(i) good energy dissipation capability, with equivalent damping of the order of 15–20 per cent;
(ii) large residual strains after removing the external force, mechanically or thermally recoverable;
(iii) extraordinary fatigue resistance, of the order of several hundreds of cycles even at very large strain amplitudes;
(iv) independence from temperature and on strain rate.

As the bars subjected to torsion and shear/bending presented similar behaviours, 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. As a matter of fact, torsion needs a cumbersome mechanism to transform displacement into rotations and large clamping lengths.

CONCEPTUAL DESIGN AND IMPLEMENTATION OF THE DEVICES

Full re-centring and good energy dissipation were chosen as the main targets of the conceptual design of SMA-based devices. Functional simplicity, no maintenance need, limited encumbrance and compatible costs were selected as additional objectives in their implementation. It must be emphasized that the two main targets (re-centring and energy dissipation capability) are somewhat conflicting. As a matter of fact, the maximum energy dissipation for a given maximum force is obtained in a rigid–plastic behaviour, while re-centring necessarily requires the force–displacement cycle to pass through the axis origin. Therefore, the loop shape has to be optimised to get maximum energy dissipation compatibly with the second condition. Regarding costs, the high unitary cost of SMAs, particularly of nickel–titanium, calls for a full exploitation of the kernel components. This requires the optimisation of the stress condition — uniform stress obviously being the most favourable condition — and the minimization of the clamping length needed to apply stresses to the SMA components.

The experimental performances of SMA elements suggested that the optimal manner to provide self-centring capability requires (pre-tensioned) austenitic superelastic wires to be arranged in the device in such a way as to be always stressed in tension. It is also clear, however, that they must be supplemented with an additional dissipating mechanism, in order to provide the devices with the necessary energy dissipation capability. At this end, either martensitic bars stressed in bending or pre-tensioned austenitic superelastic wires, arranged like in a double counteracting system of springs, can be utilized. The former solution can use either straight bars stressed in double bending, when the device is subjected to small displacements (i.e. for braces), or U-shaped bars stressed in roller bending, when the device is subjected to large displacements (i.e. for isolation systems). An excellent hybrid solution can be realised by relying the energy dissipating function upon steel elements. The advantages of this solution come from the high

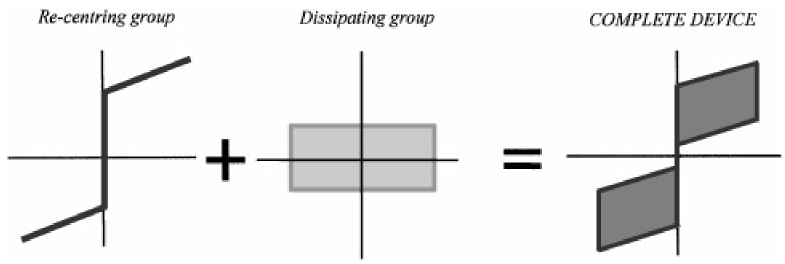


Figure 2. Idealized behaviour of the two functional groups of SMA elements.

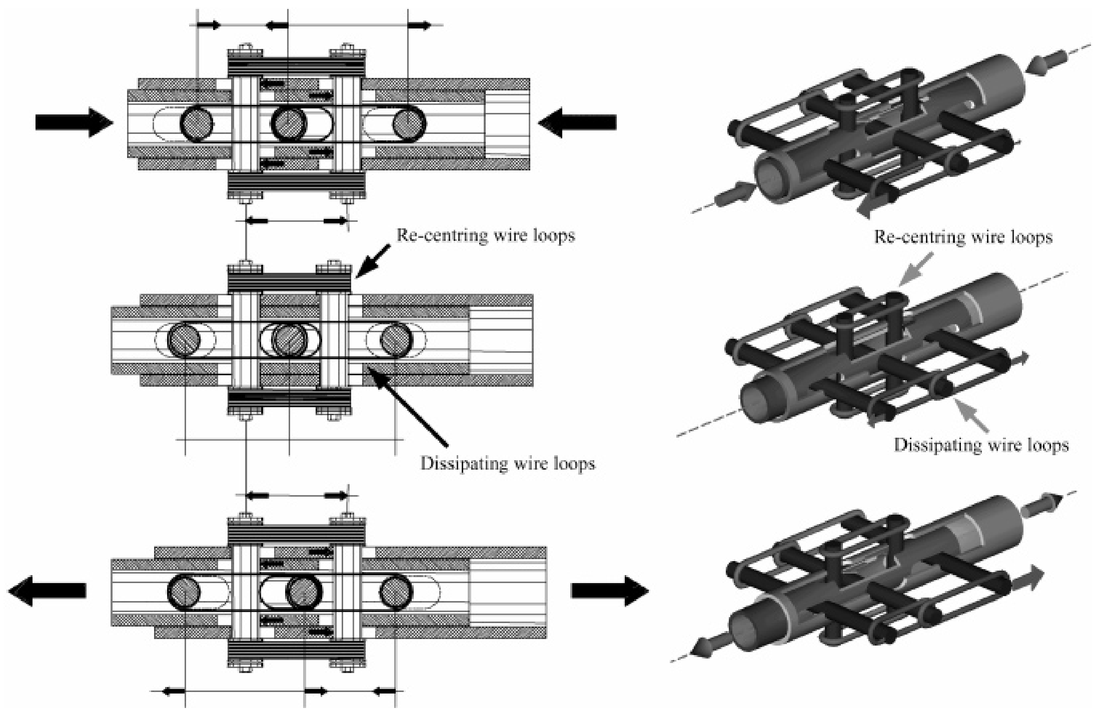


Figure 3. Functioning scheme of a complete device, including both functional groups of SMA-wires.

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.

In order to understand better the conceptual design and the actual behaviour of such devices, it is worthwhile to refer to an idealized scheme, in which the re-centring group has a non-linear rigid–elastic behaviour, while the energy dissipating group is perfectly rigid–plastic, as shown in Figure 2. If these two behaviours are combined together in a parallel system, the resultant cycles also shown in Figure 2 are obtained.

The rigid–linear behaviour of the first group is obtained by pre-tensioning the superelastic wires. The initial infinite stiffness is conditioned upon the infinite rigidity of the other parts of the

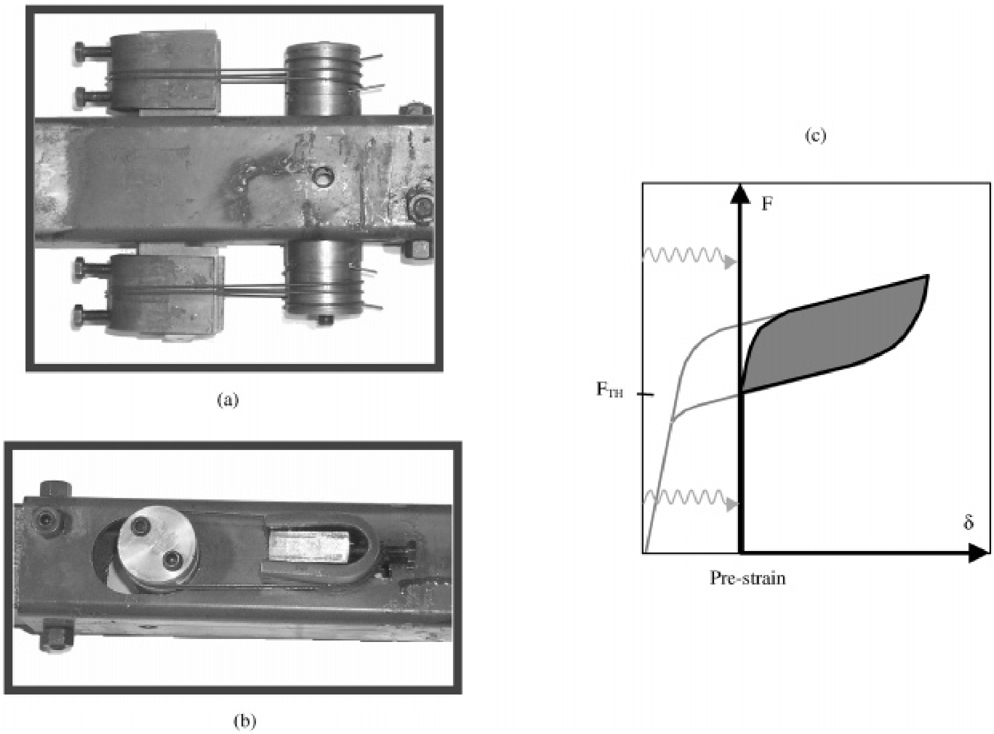


Figure 4. Re-centring group based on austenite superelastic wires: top view (a); lateral view (b); effects of pre-strain (c).

device. If this is not true, the initial stiffness will be finite, but normally very high. The pre-stress force, i.e. the ordinate from which the linear branch starts, represents the force available to dissipate energy in the dissipating group and/or to re-centre the structural system. It can be calibrated by varying the number of wires and their pre-stress level.

The amount of energy dissipation can be modified by varying the number of elements of the energy dissipating group. Obviously, in order to keep the re-centring feature, the maximum force corresponding to the zero displacement value must not be greater than the pre-stress force of the re-centring group.

A straightforward and easy implementation of a device with the above-described behaviour can be realized by using two concentric pipes that move mutually when inserted in a structure subjected to seismic actions, their ends being connected to relatively moving parts of the structural system. The functioning principle of the devices is the same as for bracing as well as for isolation systems. They only differ for the order of magnitude of displacements — a few millimetres for the former, several tens of millimetres for the latter — and, as a consequence, in some constructional details. Here, for simplicity, the attention will be especially focused on the dissipating braces, which have been subjected to more extensive tests.

Figure 3 shows the functioning scheme of a complete device, including the two functional groups, both made of SMA wires. To realize the SMA wire re-centring group, two studs are

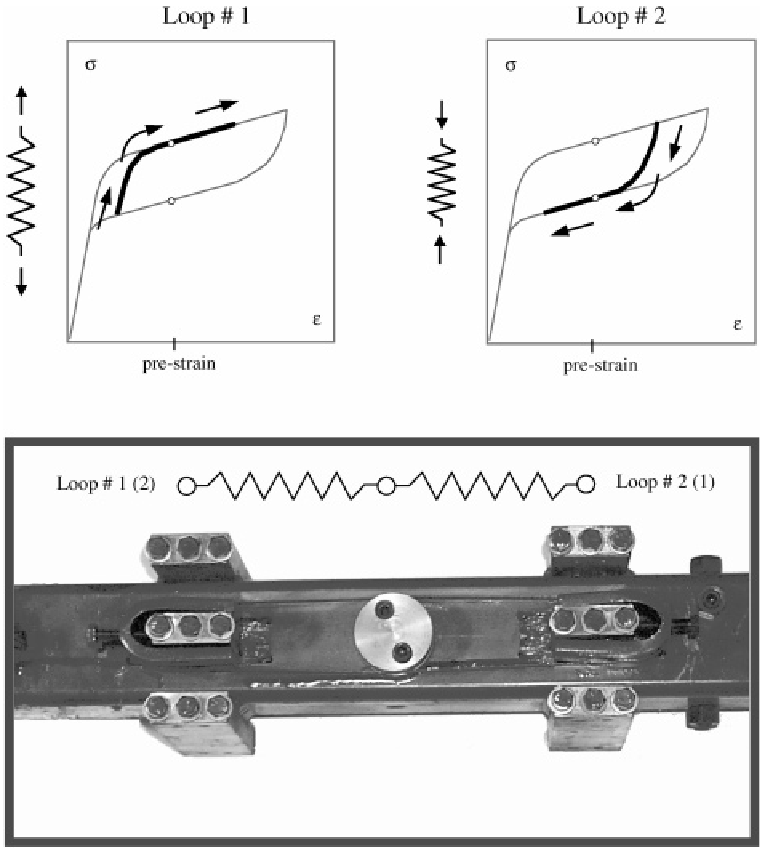


Figure 5. Dissipating group based on pre-tensioned austenite wires loops acting as two counteracting springs.

inserted transversely in the two tubes, into oval-shaped holes. An adequate number of superelastic wires are wound around the studs, which also have a mechanism to apply and calibrate pretension (see Figures 4(a) and 4(b)). The special arrangement of studs and holes is such that, for any positive or negative mutual movements of the tubes, the wires are always subject to elongation, thus increasing the initial tensile strain. Because of pre-strain, a threshold force to elongate wires is defined. Up to that force value, no relative movement of the pipes occurs and, then, a high initial stiffness is obtained, which is only conditioned upon the axial flexibility of the steel pipes (see Figure 4(c)). Since the maximum allowable displacement depends essentially on the length of the SMA wires, a very high value of the ductility of the device can be easily obtained, by suitably calibrating the stiffness of the pipes and the length of the wires of the re-centring group.

The SMA-wire dissipating group is characterized by pre-tensioned austenite superelastic wires wound around three studs, in such a way that two independent groups of wire loops are obtained (see Figure 5). The lateral studs move with the internal tube, the central stud with the external one.

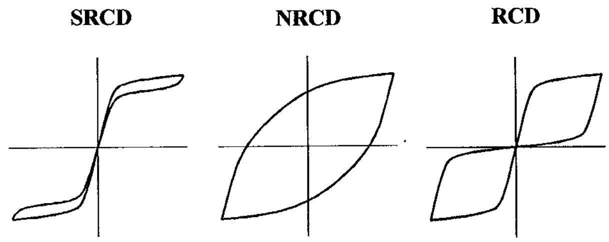


Figure 6. Types of device based on SMA.

When the two pipes move mutually, one loop is stretched, while the other is shortened, thus increasing and decreasing tensile stress, respectively. To assure an optimal behaviour, the imposed pre-strain must be calibrated carefully with respect to the foreseen maximum displacement, in order to avoid the buckling of a wire loop, on the one hand, and the completion of the phase transformation, on the other. From this point of view, the best choice is a pre-strain equal to about half the strain at which the forward martensitic transformation ends. In this case, while one loop goes along (in upward direction) the branch of the stress–strain diagram relevant to the forward martensitic transformation, the other loop goes along (in downward direction) the branch relevant to the inverse martensitic transformation (see Figure 5). The total force is the difference between the tension forces of the two springs. Since the two branches of the diagram present similar slope and translate upwards in the same way while increasing temperature, the resulting cyclic behaviour will be characterized by a considerable energy dissipation capability, a clear threshold value of force and a substantial independence from temperature.

A wide range of mechanical behaviours can be obtained with the same device, by simply varying the number and/or the characteristics of the SMA elements of both groups, as well as the pre-tensioning levels of the re-centring wires. The resulting device can be classified into one of the three following categories (see Figure 6), depending on the residual displacement at the end of the action or the eventual supplemental recovering force:

(1) *supplemental re-centring devices* (*SRCD*): Typically based on the re-centring group only, they present zero residual displacement 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, such as friction of bearings (for isolation systems) or plastic forces of structural elements (for bracing systems);
(2) *not re-centring devices* (*NRCD*): Based on the dissipating group only, they present large dissipation capabilities but also large residual displacement at the end of the action;
(3) *re-centring devices* (*RCD*): Including both re-centring and dissipating group, they present zero or negligible residual displacement, but are not capable to recover the initial configuration if reacting forces external to the device exist.

The main results of the experimental investigation will be examined separately for the above listed types in the following paragraph.

DEVICE TESTING

Several SMA-based devices were designed and constructed by TIS S.p.A. within the activities of MANSIDE, namely:

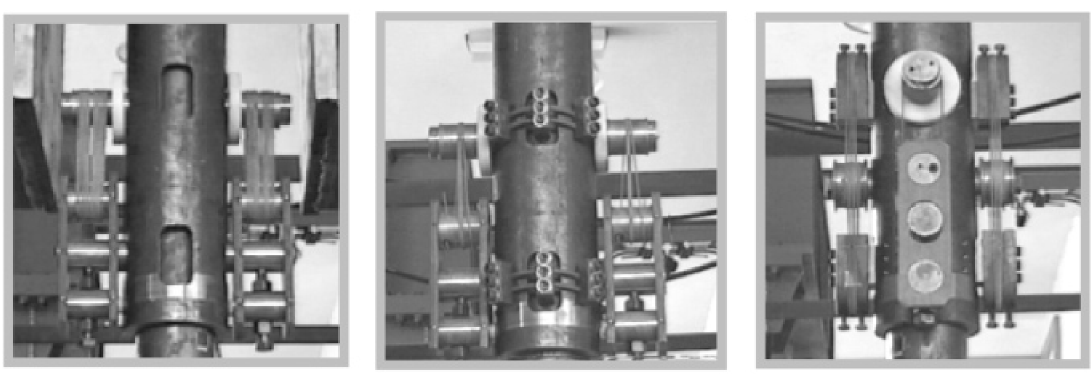
1. one full-scale brace prototype, designed to carry up to 200 kN and to reach 20 mm displacement,
2. three 1/3.3-scale braces, designed to provide up to 80 kN force and to reach 10 mm displacement,
3. one 1/3.3-scale device for isolation system, designed to provide 30 kN force and to reach 100 mm displacement,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

Figure 7 shows the full-scale prototype of brace, equipped with, respectively, re-centring austenite wire loops only (SRCD), re-centring austenite wire loops and martensite bars (RCD), re-centring and dissipating austenite wire loops (RCD).

The reduced-scale devices were especially designed and realised to be installed into the 1/3.3-scale r/c frame models, that were subsequently subjected to simulated earthquakes on the shaking table of the Laboratory of Earthquake Engineering at the Technical University of Athens. Figure 8 shows the arrangement of the SMA brace in the frame model. Figure 9 illustrates the reduced-scale isolation system, also used in the shaking table tests. It includes a SMA wire re-centring and/or dissipating device and three steel–teflon sliding bearings. These latter can incorporate U-shaped SMA bars or steel plates as alternative energy dissipating groups.

Figure 10(a) shows the full-scale isolation device ready to be tested. It acts as a unidirectional device and is equipped with the re-centring group only. It is supposed to be used in an isolation system, where steel energy dissipating elements can be easily incorporated into the bearing devices.

Each device, with the exception of the full-scale isolation devices, was purposely realized to incorporate the re-centring group and both types of dissipating group, with a variable number of



(a) (b) (c)

Figure 7. Full-scale special brace with re-centring austenite wires only (a); with re-centring austenite wires and martensite bars (b); with re-centring and dissipating austenite wires (c).

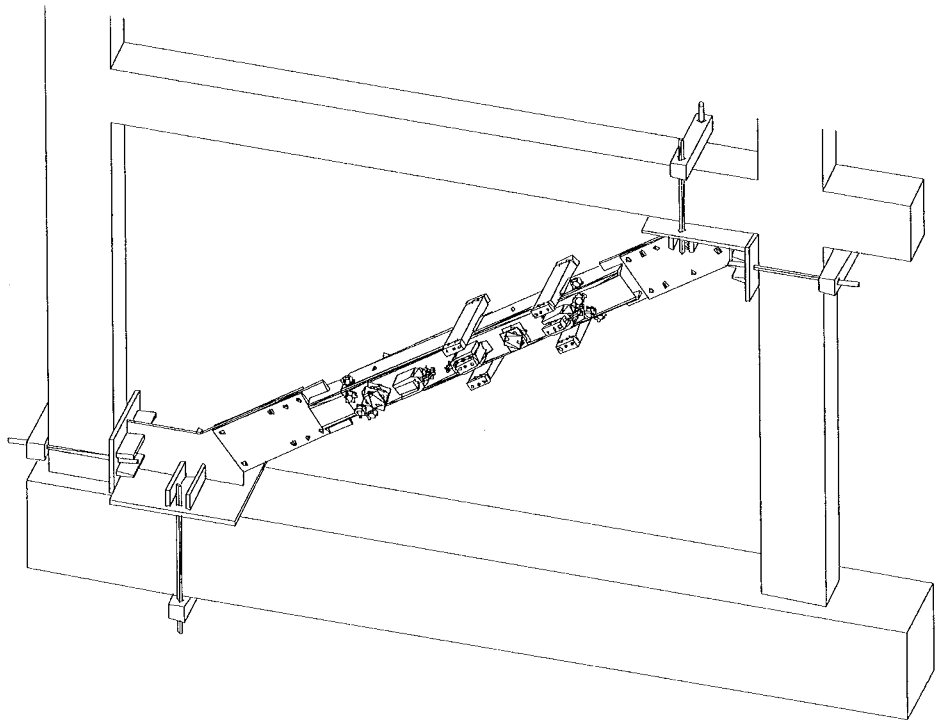


Figure 8. Arrangement of the SMA brace in the scaled frame model.

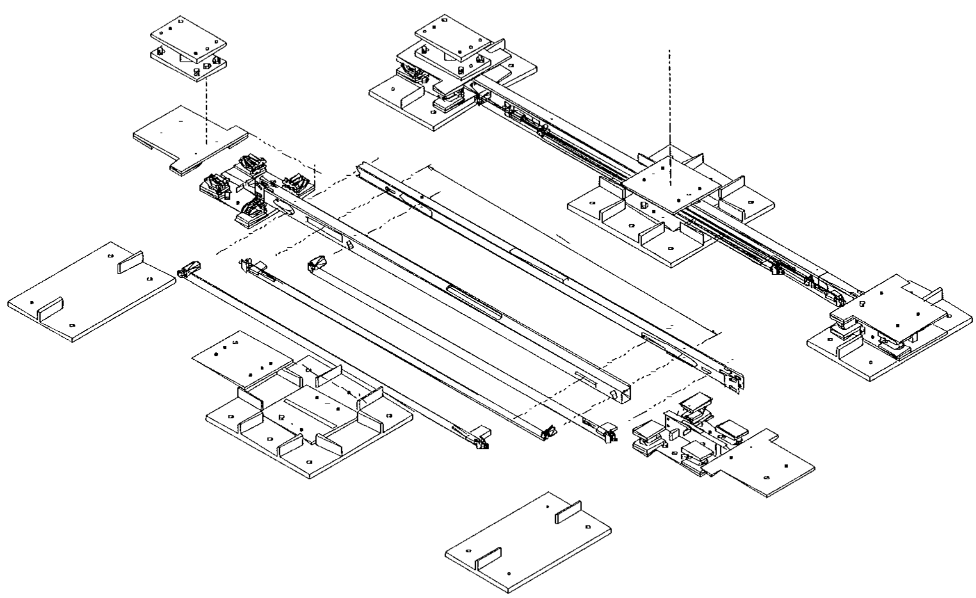


Figure 9. Arrangement of the reduced scale isolation system.

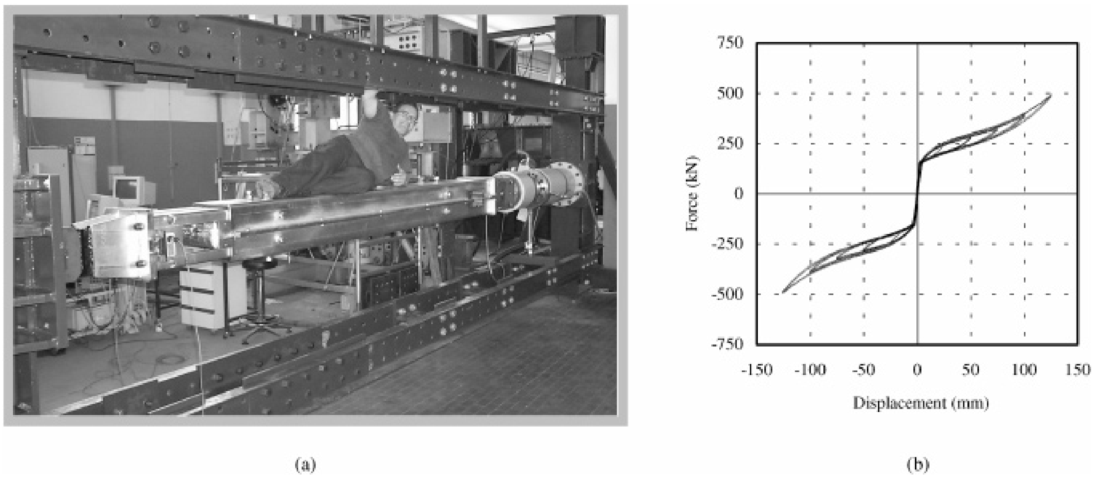


Figure 10. Full-scale isolator device ready to be tested (a) and the relevant hysteresis loops (b).

elements. It was thus possible to test different device configurations, obtaining different mechanical behaviours, like those idealized in Figure 6.

All the devices were tested at the Laboratory of the Department of Structures, Geotechnics, Applied Geology of the University of Basilicata, at Potenza, Italy. Cyclic sinusoidal displacements were applied to the devices, in order to investigate their actual behaviour, and their dependence on displacement amplitude, frequency of loading, temperature and number of cycles. The values of the test parameters were selected taking into account the respective ranges of interest for seismic devices, namely: 1–10 mm displacement amplitude for braces and 10–200 mm for isolation devices; 0.5–4 Hz frequency of loading for braces and 0.3–1 Hz for isolation devices; 0–40°C temperature; 10–20 consecutive loading cycles.

Two different apparatuses were used to test the devices, according to their size and the forces required. For the first three types the testing rig shown in Figure 11(a) was used. It was equipped with a Hydropuls Schenck hydraulic jack, able to apply 250 kN maximum force and ± 125 mm maximum displacement (250 mm stroke). This rig was conceived to test either rubber isolators or uniaxial devices, like the ones described in the present paper. For the last type of device the testing rig shown in Figure 11(b) was used. It was equipped with a Hydropuls Schenck hydraulic jack, able to apply 640 kN maximum force and ± 125 mm maximum displacement (250 mm stroke). This apparatus was purposely conceived and realized to test the uniaxial SMA based devices described in the present paper. Both hydraulic jacks were served by a couple of Schenck hydraulic units, providing 160 l/min of oil at 280 bars.

In the next subparagraphs, the mechanical behaviour of the three categories of SMA-based devices is described. Starting from the experimental results, some significant mechanical quantities have been calculated: (1) the secant stiffness K_s; (2) the energy loss per cycle W_D; (3) the energy loss per unit weight $W_d = (W_D/w)$, where w is the weight of the SMA components; and (4) the equivalent viscous damping $\xi_{eq} = W_D/(4\pi W_s) = W_D/(2\pi K_s \delta^2)$, where δ is the displacement amplitude of the cycle under consideration. Their trends as a function of some internal

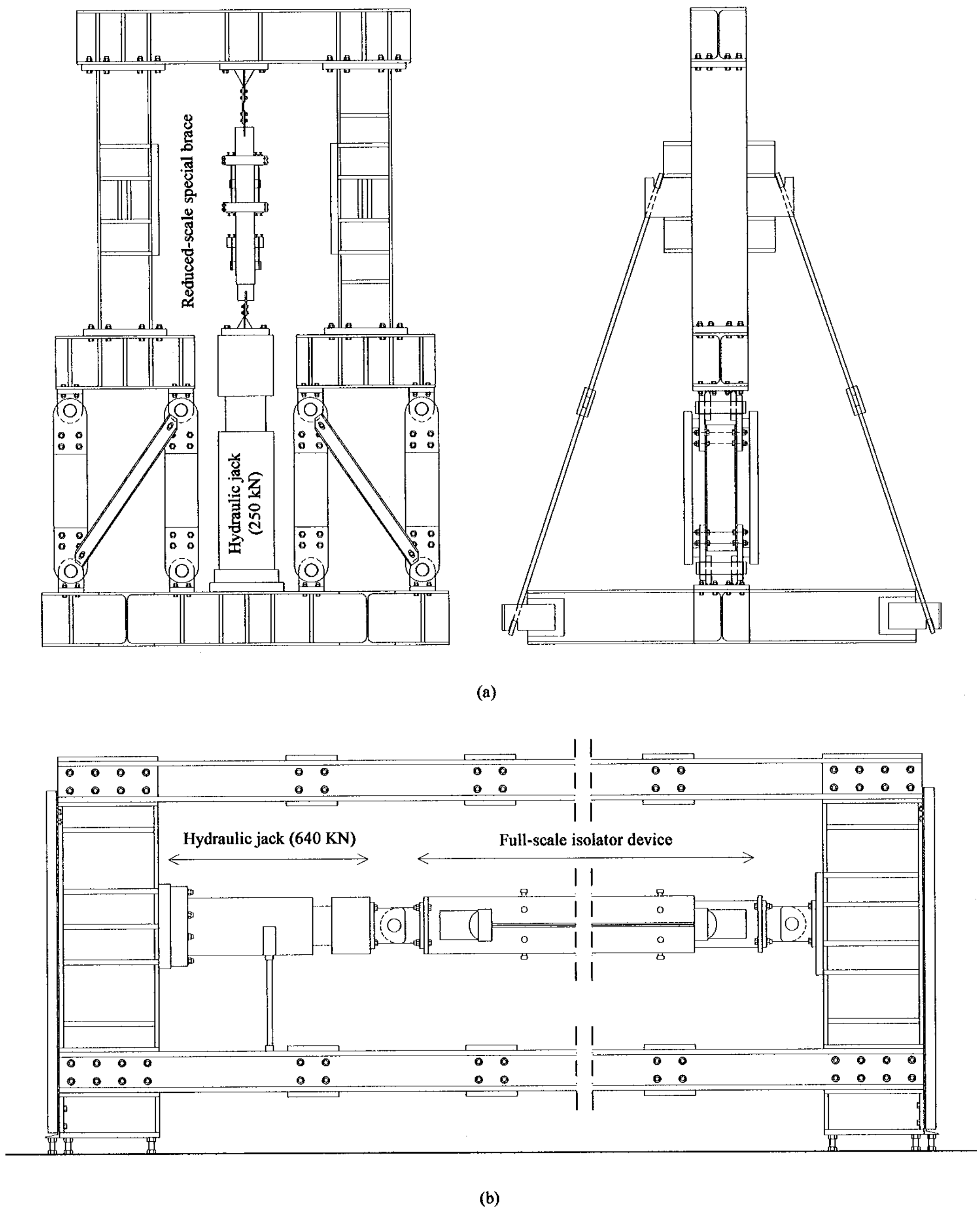


Figure 11. Experimental set-up for cyclic testing of SMA-based special braces (a) and SMA-based isolator devices (b).

parameters (such as pre-strain) and external parameters (such as displacement amplitude, frequency of loading and temperature) are illustrated in summary diagrams.

Experimental tests on the supplemental re-centring devices

Several re-centring groups, differing in alloy characteristics and/or wire diameter and/or pre-strain levels (0–5 per cent) and/or number of wires were tested. As a matter of fact, more than 200

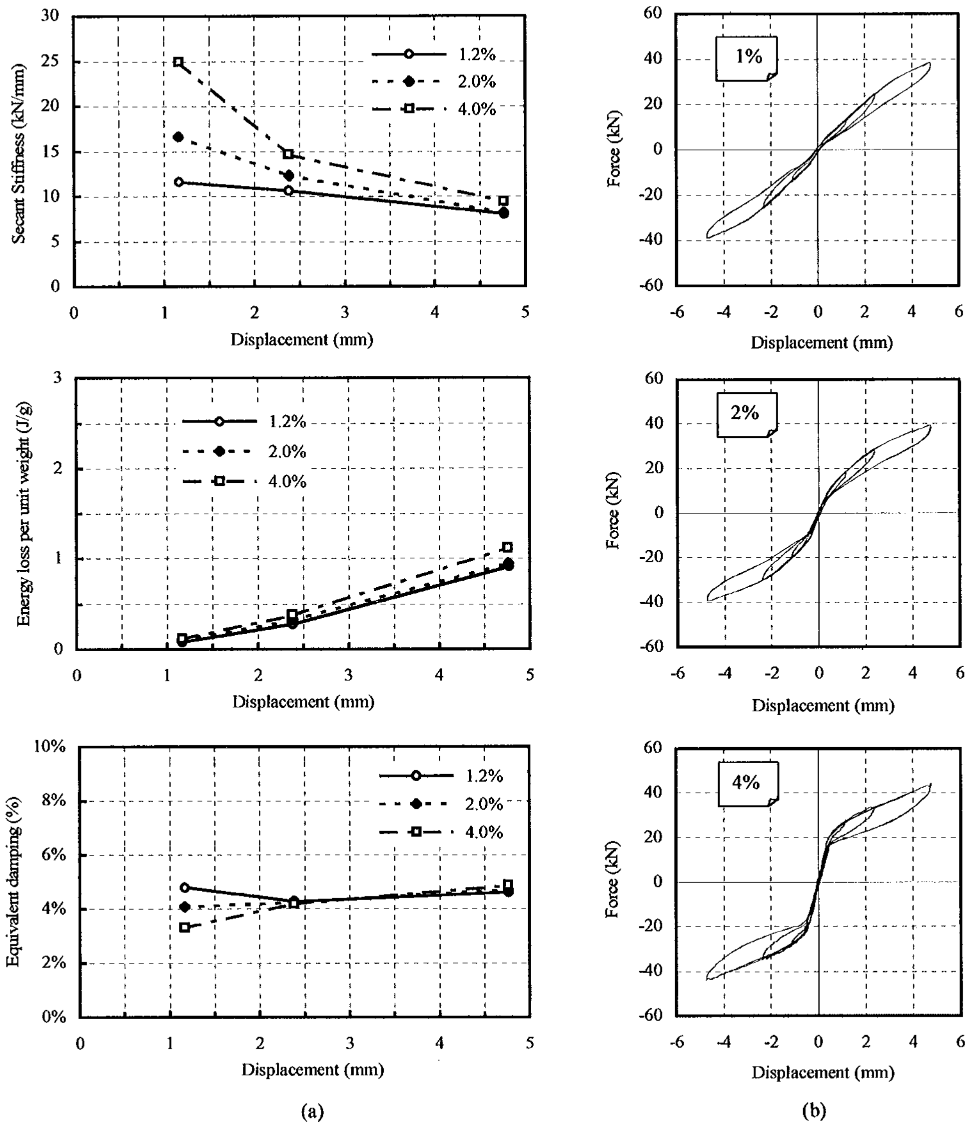


Figure 12. Mechanical behaviour of a supplemental re-centring device as a function of pre-strain (1 Hz frequency, 25°C temperature).

tests were carried out, both at room temperature and under temperature control (between 0 and 50°C), with cyclic frequency ranging from 0.02 to 4 Hz and displacement amplitude up to 13 mm, corresponding to about 11 per cent total strain in the wires.

Figure 12 shows the mechanical behaviour of a SRC device as a function of pre-strain and displacement amplitude. The tests were carried out at room temperature ($\approx 25°C$) and 1 Hz frequency, on a device having 12 re-centring 2 mm diameter wire loops pre-strained at, respectively, 1, 2 and 4 per cent. Three cyclic displacement amplitudes were considered: 1.2, 2.4 and 4.8 mm, approximately corresponding to 1, 2 and 4 per cent additional strain.

As can be seen, the greater the pre-strain of wires, the greater the supplemental re-centring force and the stiffness at small displacements are. By increasing pre-strain, threshold force increases and is better defined, while loops translate upwards. The secant stiffness at 1.2 mm displacement increases by about 30 per cent, when pre-strain rises from 1 to 2 per cent, and 35 per cent, when pre-strain rises from 2 to 4 per cent.

The energy loss increases slightly while increasing pre-strain, because of the higher strain levels induced in the wires for the same displacement. Moreover it increases more than linearly with the displacement amplitude (see also Figures 13 and 14), because the unloading force levels reduce while increasing the cyclic displacement.

The effectiveness of a device in damping vibrations is generally measured by the equivalent viscous damping. The SRC devices exhibited an equivalent damping of the order of 4–6 per cent, practically independent from pre-strain, except for very small displacements. It is rather low, if compared to other common devices, not being energy dissipation the primary task of SRC devices in a passive control system. If necessary, supplementary energy dissipating elements, as in RC devices, or energy dissipating devices, like NRCDs, shall be provided.

Figure 13 shows the mechanical behaviour of a SRC device, with four re-centring 1.84 mm diameter wire loops, pre-strained at 1.5 per cent, as a function of cyclic frequency and displacement amplitude. Some typical force-displacement diagrams at different frequencies are also reported. It should be noted that the maximum reached displacement produces about 10.5 per cent total strain in the wires.

The mechanical behaviour of the SRC devices is not much sensitive to frequency, at least in the range of interest for seismic applications (i.e. for frequencies greater than 0.2 Hz).

As SMAs are sensitive to temperature, it was deemed very important to ascertain the behaviour of the devices under different temperature conditions, within the range of interest in practical applications. Figure 14 shows the mechanical behaviour of a SRC device with 12 re-centring 1 mm diameter wire loops, pre-strained at 4 per cent, as a function of temperature and displacement amplitude. Some typical force–displacement diagrams at different temperatures are also shown.

When increasing temperature, an almost linear increase of the force levels occurs upon loading (about 12 per cent every 10°C at low amplitudes, about 8 per cent every 10°C at large amplitudes), and upon unloading (about 12 per cent every 10°C at low amplitudes, about 15 per cent every 10°C at large amplitudes). As a consequence, the secant stiffness also increases linearly, with a growth rate depending on the displacement amplitude. Since the unloading force levels increase more than the loading force levels, the energy loss decreases a little when temperature increases. The equivalent damping, finally, decreases significantly when temperature increases (about 14 per cent every 10°C).

The sensitivity to temperature, though not negligible, appears to be compatible with the typical applications in the field of civil engineering, considering that similar and even stronger

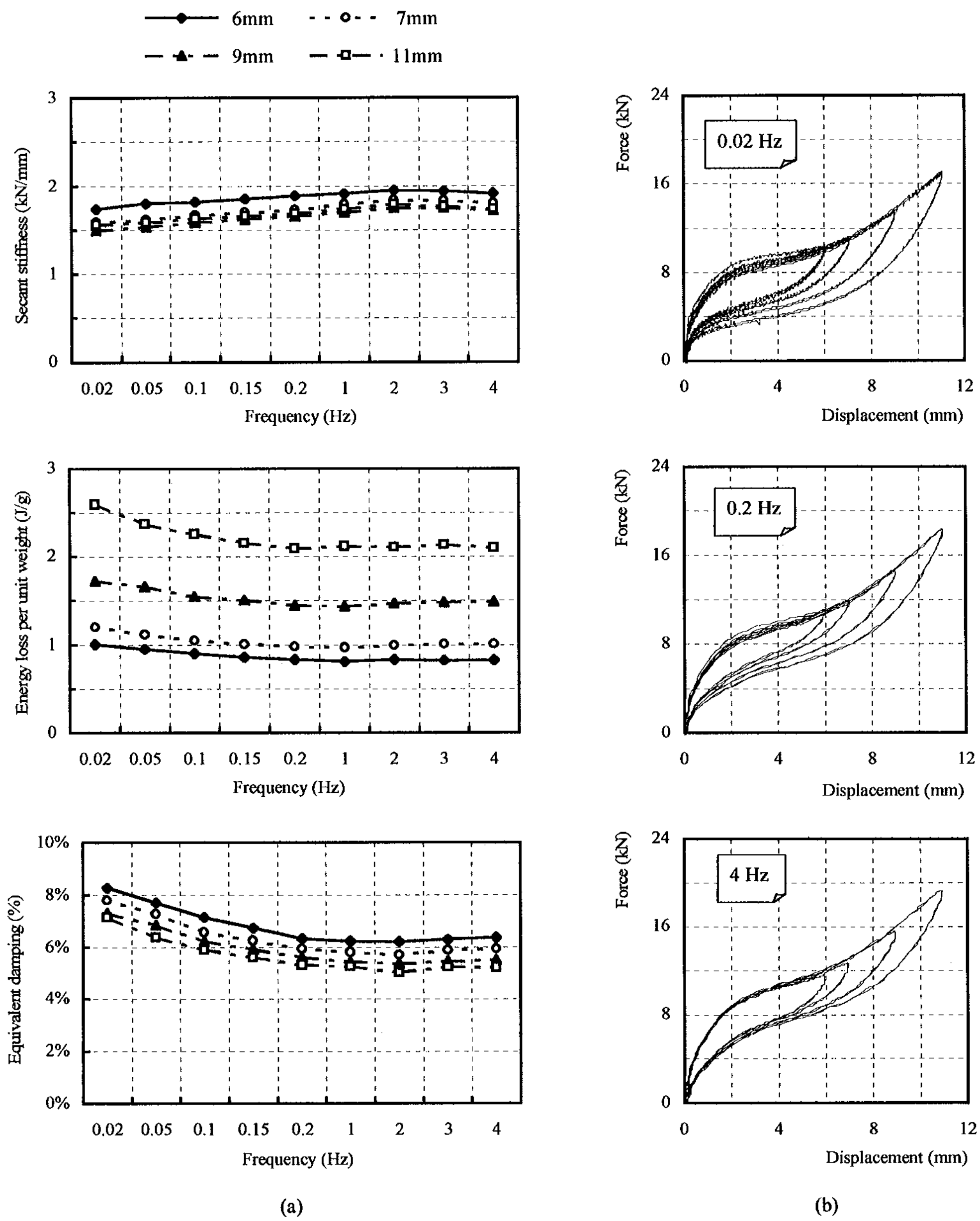


Figure 13. Mechanical behaviour of a supplemental re-centring device as a function of frequency (1.5 per cent pre-strain, 20°C temperature).

dependence on temperature can be found in other devices for passive control. In any case it is important to check the consequences of temperature variations for each specific case, by considering the device as a component of the structural system, where other parallel components

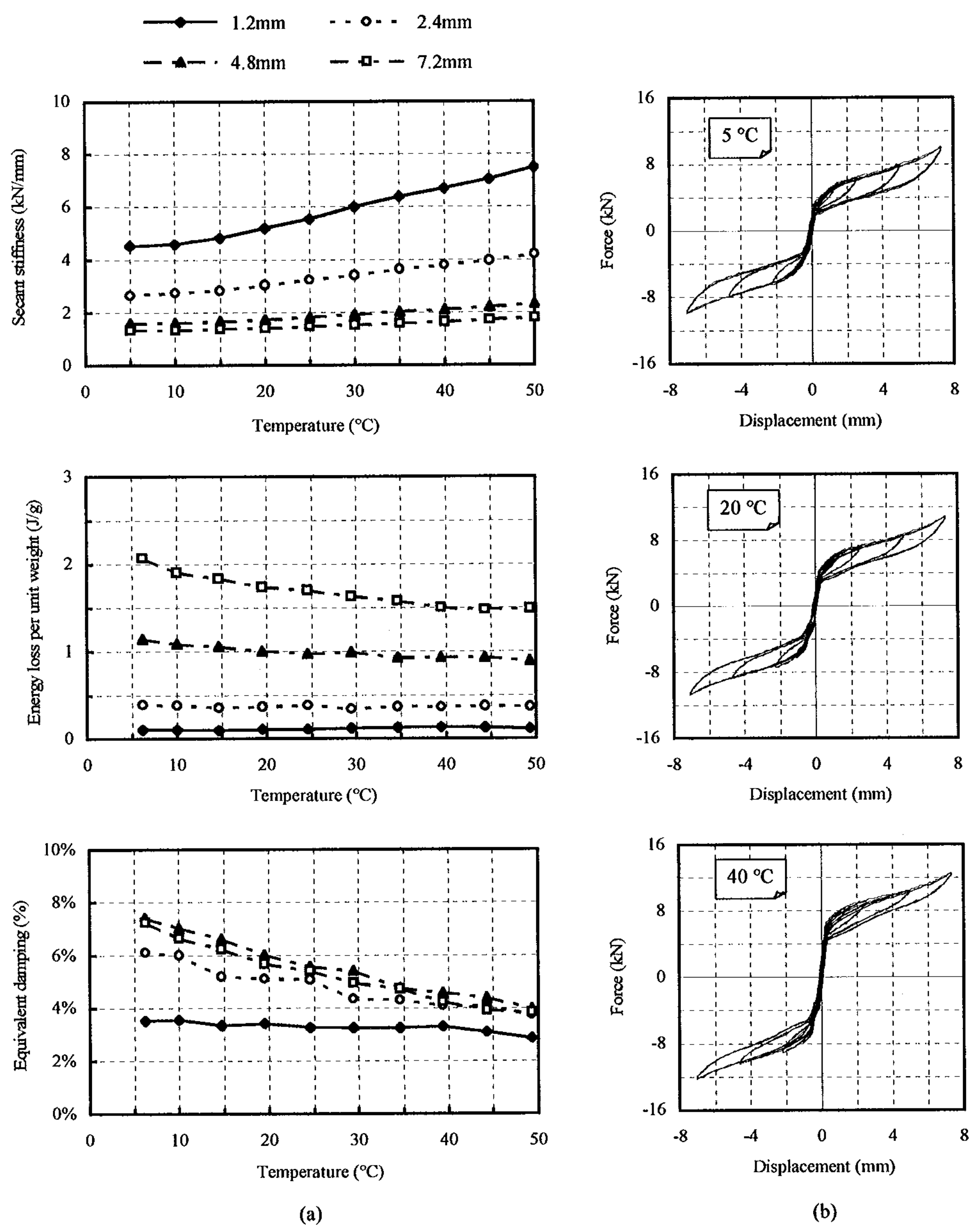


Figure 14. Supplemental re-centring device: mechanical behaviour as a function of temperature (4 per cent pre-strain, 1 Hz frequency).

can exist, which are not affected by temperature changes or show an opposite trend. In this respect, it must be observed that if an earthquake occurs in very cold conditions, the supplemental re-centring force could not be fully available, as it reduces when temperature decreases. Thus,

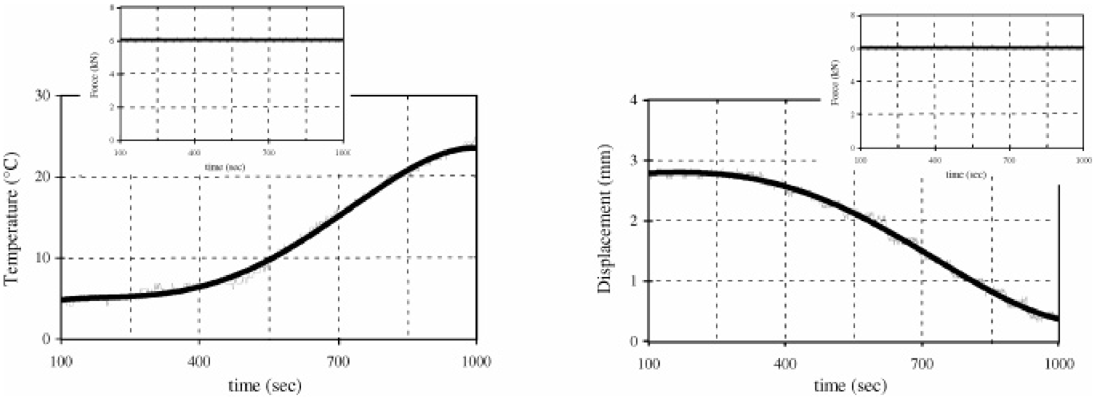


Figure 15. Test at variable temperature while keeping the force constant: delayed recovery of the residual displacement.

a residual displacement could occur, which is, however, totally recovered as soon as temperature increases. Figure 15 shows the results of a specific test carried out by varying temperature, from 5 to 23°C (ambient temperature), while keeping a 6 kN constant force. The 3 mm residual displacement at 5°C is almost totally recovered at 23°C.

Figure 10(b) reports a typical force–displacement diagram (25°C temperature, 0.2 Hz frequency) relevant to the full-scale isolation device equipped with 118 re-centring 1.84 mm diameter austenite wire loops, pre-strained at 2 per cent. The device shows an elastic non-linear behaviour, with about 160 kN supplemental re-centring force. As can be seen, the behaviour of the full-scale isolation device is the same as that of the reduced and full-scale bracing device, thus confirming that the target of the conceptual design was fully achieved by the engineered implemented devices, both for bracing and for isolation systems.

Experimental tests on non re-centring devices

Two versions of not re-centring devices were considered. The first version uses pre-strained austenite wires acting as a double counteracting system of springs (for simplicity type DL). The second version uses martensite bars stressed in double bending (for simplicity type B).

Tests were carried out both at room temperature and under temperature control (typically between 0 and 50°C, step 5°C), with frequency of loading ranging from 0.02 to 1 Hz and displacement amplitude up to 8 mm, corresponding to about 9 per cent maximum strain in the wires.

Figure 16 shows some significant results of the tests carried out at room temperature. Figure 16(a) refers to a device made of eight dissipating 1 mm diameter austenite wire loops, pre-strained at 4.5 per cent. Figure 16(b) refers to a device made of four martensite bars, with 6.7 mm diameter and 30 mm freely deformable length.

As far as the shape of the hysteresis loops is concerned, considerable differences are observed between the two versions of NRC device. In fact, while the DL device exhibits a clear threshold value of force, the B device exhibits a strong hardening effect. The softening effect of the DL device

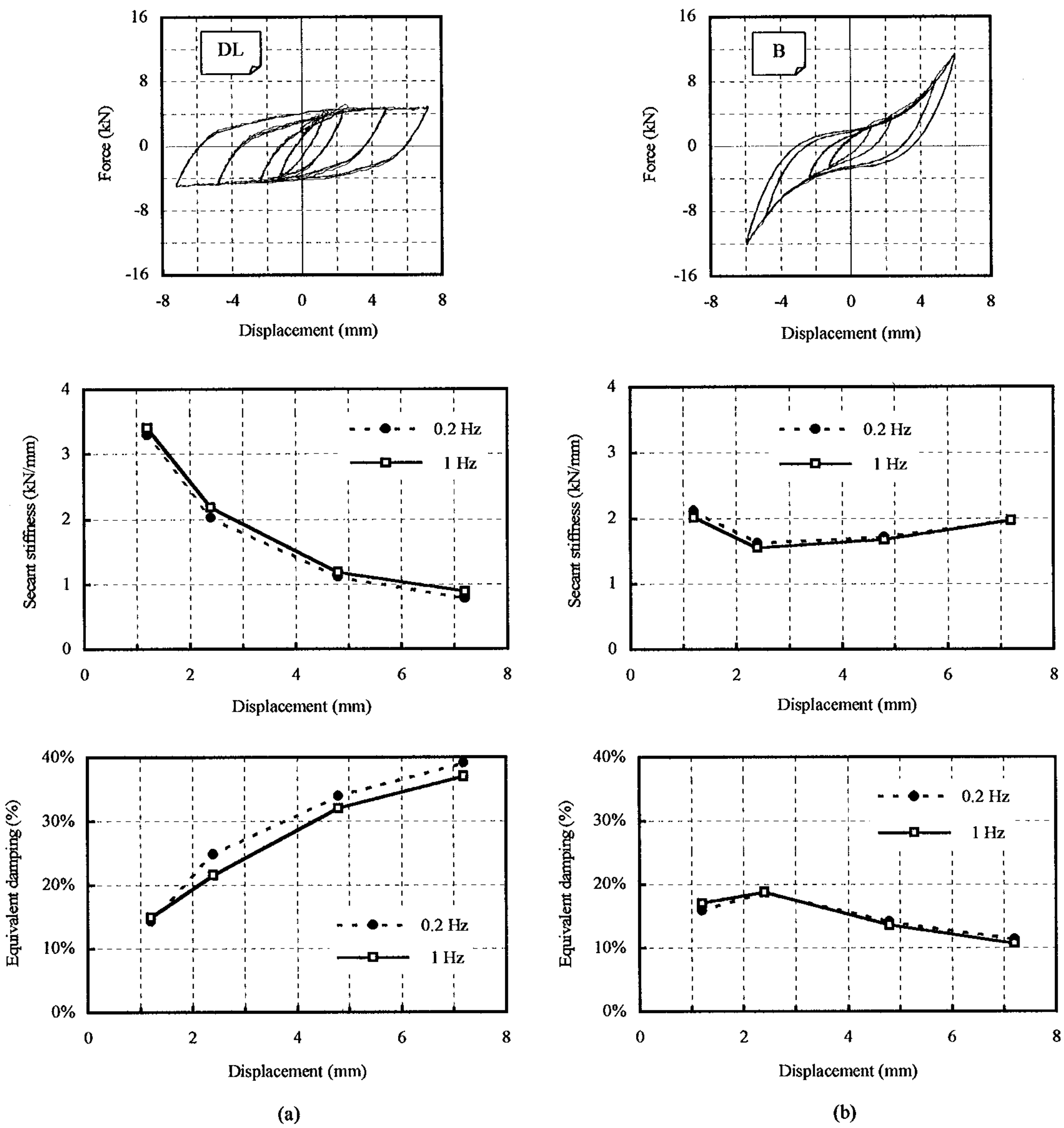


Figure 16. Mechanical behaviour of Not Re-Centring Devices based on pre-tensioned austenite wires acting as two counteracting springs (a) and martensite bars stressed in double bending (b).

can be ascribed to the particular arrangement and working conditions of the SMA-austenite wires. The hardening effect of the B device, instead, is due to the completion of the detwinning process of martensite variants [5] in some zones of the bars. The trend of the secant stiffness as a function of the displacement summarizes the two types of behaviour. While for the DL device it exhibits a marked reduction when increasing displacement, resulting four times less than the initial value at relatively large amplitudes, for the B device it keeps almost constant.

Both behaviour types can be of interest for practical applications, to achieve different objectives. DL devices provide a good control of forces, thus allowing the structural elements to be designed with respect to a known maximum force, according to capacity design criteria [1], while B devices provide a better control of displacements.

Further remarkable differences are found in the equivalent damping. While for DL devices it increases when increasing displacement, up to values of the order of 40 per cent at relatively large amplitudes, for B devices it decreases when increasing displacement, reducing from about 20 per cent peak value up to about 10 per cent. It is worth remarking that by simply varying the arrangement and the functioning scheme of the austenite wires, the equivalent damping passes from values of the order of 4–6 per cent (SRCD) to values even one order of magnitude greater.

Temperature and frequency of loading did not seem to affect significantly the mechanical behaviour of the devices [17]. For B device this is due to the properties of martensite, for DL devices this is a consequence of the special arrangement of the austenite wire groups.

Experimental tests on re-centring devices

Being nothing but a combination of the components of a SRC device and a NRC device, re-centring devices exhibited an intermediate mechanical behaviour. By calibrating the number and the characteristics of the SMA elements of both groups (including the pre-strain levels of wires), the optimal behaviour can be obtained. It is characterized by double flag-shaped hysteresis loops, resulting in the maximum energy dissipation compatible with the self-centring capability.

The behaviour of two types of re-centring devices is shown in Figure 17. Figure 17(a) refers to a device which combines a re-centring group, made of 24 loops of 1 mm diameter wire pre-strained at 4 per cent, with a B energy dissipating group, made of six martensite bars with 6.7 mm diameter and 30 mm freely deformable length. Figure 17(b) refers to a device which combines a re-centring group, made of 10 loops of 1 mm diameter wire pre-strained at 4 per cent, with a type DL energy dissipating group, made of six loops of 1 mm diameter wire pre-strained at 4.5 per cent.

The comparison between the two types of devices emphasises the greater effectiveness of the devices entirely based on austenite wires (RLDL devices) in terms of energy dissipation capability and their lower increase of stiffness.

The influence of frequency is in general negligible. The apparent changes in the mechanical behaviour of the RC devices when frequency varies in the practical range of interest (from 0.2 to 2 Hz), which can be observed in Figure 17, should be ascribed to the stabilization of the material behaviour which occurs during the first loading cycles.

The initially high secant stiffness reduces considerably while increasing the displacement amplitude, resulting more than halved at relatively large amplitudes. The equivalent damping, starting from values rather small (6–8 per cent and 10–12 per cent in RLB and RLDL devices, respectively), increases rapidly while increasing the cyclic amplitude, reaching values of the order of 18 per cent at relatively large amplitudes in RLDL devices.

In order to assess the long-term reliability of the devices, the possible effects of the relaxation of the pre-tensioned wires were evaluated by repeating some tests on the same devices after three weeks. Figure 18 compares the hysteresis loops recorded during the initial test (thin line) to those recorded in a test carried out after 20 days (thick line). The device is the same as in Figure 17(b). The repeated tests confirmed that the effects of relaxation are largely negligible.

Tests under temperature control (between 0 and 40°C, step 5°C) were also carried out and the results compared to those relevant to SRCD [17]. A lower sensitivity to temperature variations

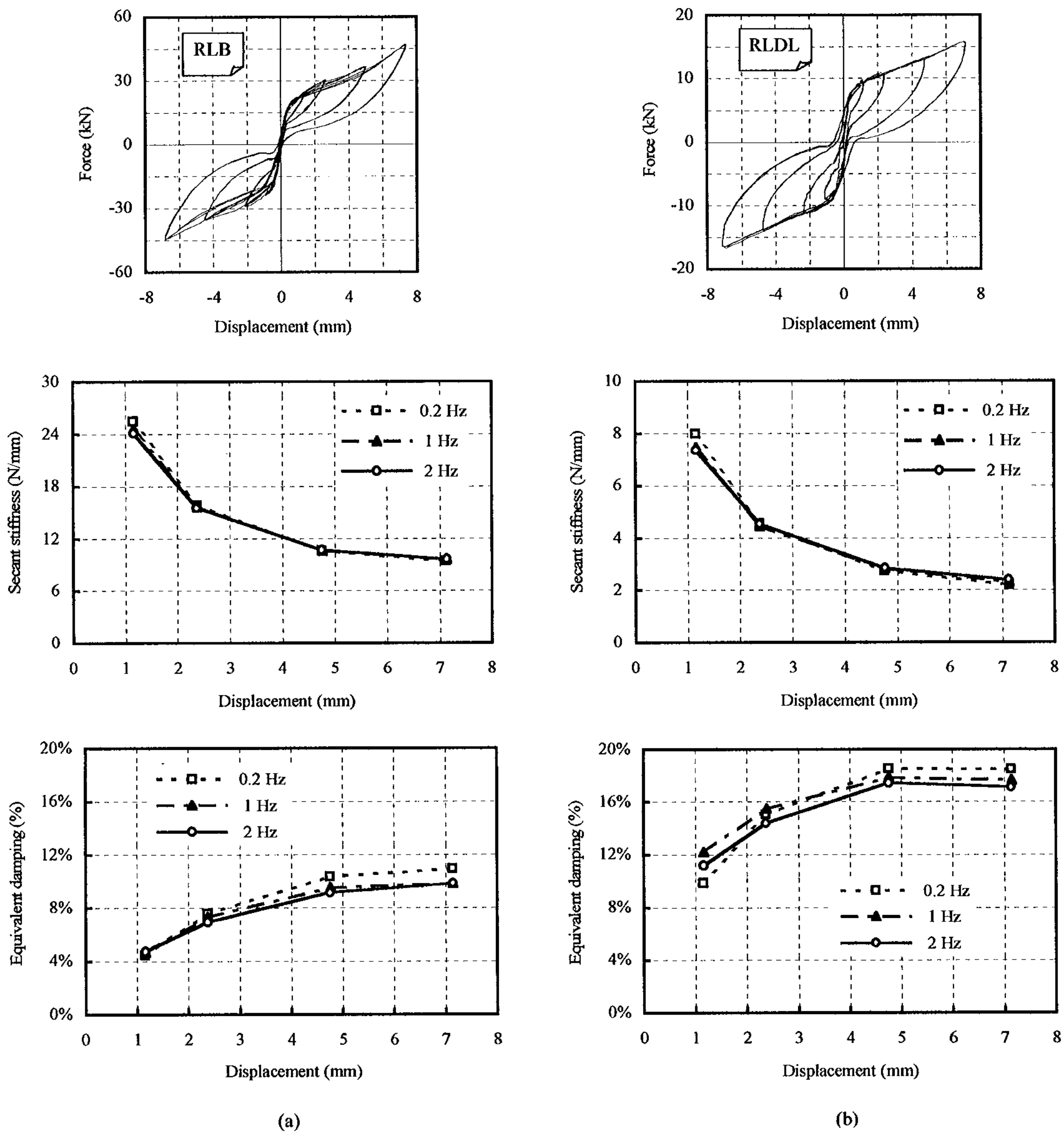


Figure 17. Mechanical behaviour of Re-Centring Devices realized by combining re-centring austenite wire loops and martensite bars (a) or re-centring and dissipating austenite wire loops (b).

with respect to the SRCD was found, as shown in Figure 19. Increases of the order of 7 per cent every 10°C in terms of force, and decreases of the order of 8 per cent in terms of equivalent damping can be observed.

To conclude, a further important remark is to be made. Several configurations of SMA-based devices were tested, belonging to three different types (SRCD, NRCD and RCD). Most of them

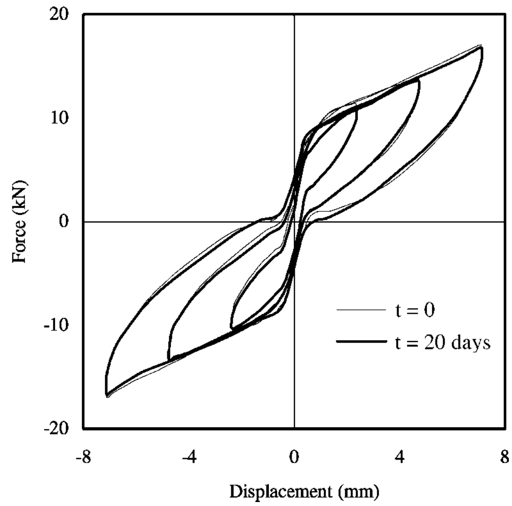


Figure 18. Changes in the hysteresis loop shape due to relaxation of wires.

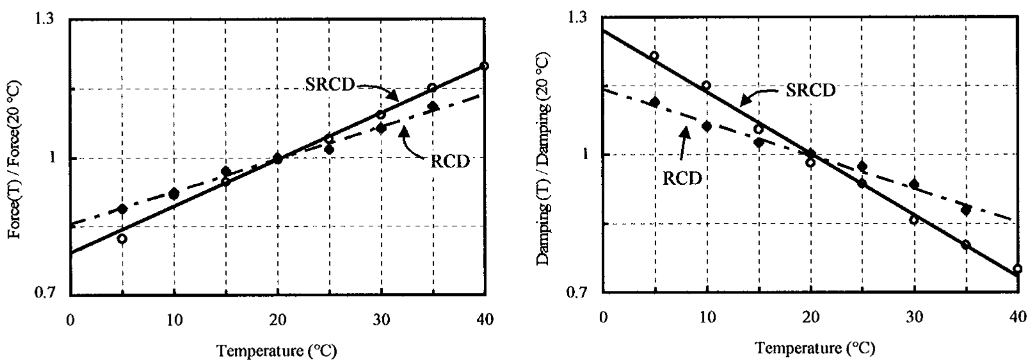


Figure 19. Sensitivity to changes in temperature for RC devices (broken lines) and for SRC devices (continuos lines).

underwent a great number of cycles (on average more than 300, but in some cases even more than 600), implying large strain in the SMA kernel components, 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. Moreover, sometimes the SMA elements used in a series of test were still re-used in the next one. This confirmed the extraordinary fatigue resistance properties of SMAs, as well as the capability of SMA-based devices to undergo many destructive earthquakes without any need of substitution or maintenance, always guaranteeing the same mechanical performances.

CONCLUSION

Two families of passive seismic control devices (special braces for framed structures and isolation devices for buildings and bridges) based on nickel–titanium shape memory alloys (SMAs) have been presented. Their functioning principles as well as the extensive experimental investigation carried out to calibrate and validate them have been exhaustively described. A full suitability of the devices and a great potential of SMAs in the passive seismic control of civil structures resulted from the present study.

The basic features of the SMA devices described in this paper resulted to be:

(a) *Great versatility*, i.e. the possibility to obtain a wide range of cyclic behaviours, from fully re-centring to highly dissipating, by simply varying the number and/or the characteristics of the SMA components, thus allowing to calibrate the shape of the loops according to any particular individual need.
(b) *Simplicity of the functioning mechanism*, in spite of their sophisticated behaviour.

By properly calibrating the number of SMA elements and their pre-stress level, a double flag-shaped hysteresis loops is obtained. In this case, the devices present three favourable features, at the same time.

(c) *Self-centring capability*, with also 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.
(d) *High stiffness for small displacements*, to avoid the structure to be moved by wind or small tremors.
(e) *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 NiTi shape memory alloys herein shown are:

(i) *Extraordinary fatigue resistance*, i.e. capability to undergo several hundreds of cycles with large amplitude, and therefore many destructive earthquakes, without any need of substitution or maintenance;
(ii) *Long-term reliability*, thanks to the absolutely negligible relaxation effects of the pre-tensioned SMA wires;
(iii) *High durability*, thanks to an excellent corrosion resistance of NiTi alloys [19] and no degradation due to ageing [6];
(iv) *Substantial independence from oscillation frequency* in the range of interest for seismic applications;
(v) *Rather limited sensitivity to temperature*, compatible with the typical applications of civil engineering.

Re-centring seismic isolation devices gain the best mechanical characteristics of both quasi-elastic devices (e.g. rubber isolators) and elasto-plastic devices (e.g. steel hysteretic dampers). On the one hand, they recover the initial position of the structure, with a good control of displacements, on the other hand, they put a threshold to the force transmitted to the superstructure, thus well controlling forces. The full possibility of designing the mechanical behaviour, thanks to the modularity of the two groups of elements governing the two aspects (re-centring and energy dissipation), permit to calibrate the desired features and fit the specific needs. The availability of such features opens considerable room for improvement of the structural system design, allowing for considerable savings. A specific concern is relevant to existing structures, for which SMA-based isolation systems appear to be optimal candidates.

As far as bracing systems are concerned, until now all the applications and the research studies on this technique were focused on the energy dissipation capability. The availability of SMA-based devices, which are able to provide supplemental forces to recover the undeformed shape of the structure at the end of the action, suggest new design concepts, especially useful for seismic retrofitting. In existing structures, in fact, particularly when they were designed without any seismic provision, the energy dissipation can turn out to be insufficient to limit damage to structural elements. It would be then necessary to strengthen some elements to fully achieve the design objectives. Local strengthening would imply expensive works, also involving non-structural parts. Retrofitting could turn out to be economically inconvenient, and, yet some residual displacement could occur in case elasto-plastic devices are used. An alternative strategy can be pursued by using SMA devices having supplemental force to recover the undeformed structural configuration, resulting in the elimination of any residual displacement, while accepting yielding in structural elements.

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