PASSIVE SEISMIC DEVICES BASED ON SHAPE MEMORY ALLOYS

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SUMMARY

The MANSIDE (Memory Alloys for New Seismic Isolation DEvices) project was aimed at exploiting the great potential of Shape Memory Alloys (SMA) in the field of passive seismic protection of structures, through comprehensive experimental and theoretical studies. It has lead to the conceptual design, implementation and testing of two families of energy dissipating/recentring devices for seismic isolation of buildings and bridges and for braces of framed structures. They can provide a wide range of performances, from full re-centring to high energy dissipation capabilities, as well as high resistance to large strain cycle fatigue and great durability. In this paper the conceptual design and implementation of devices based on SMA is described. The experimental behaviour of such devices and of SMA in general, are described in companion papers presented at the same congress

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INTRODUCTION

The passive protection of constructions against seismic vibrations with the use of special devices is widely accepted as a very effective technique, both for new constructions and for the retrofitting of existing ones [Dolce 1994]. Several types of devices have been implemented and used, however the increasingly demanding performance requirements push towards the development of new devices, exploiting the peculiar characteristics of new advanced materials [Aiken et al. 1993, Graesser and Cozzarelli 1991, Whittaker et al. 1995]. Indeed the present 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).

The present achievements in quantity production of shape memory alloys (SMA), to date applied mainly in medical sciences, electrical and mechanical engineering, can open a new application field in civil engineering, specifically in the protection of constructions against seismic vibrations. SMA's show the potential to eliminate some limitations involved in present technologies, allowing a broader application. This is achievable thanks to a combination of behaviour and maintenance advantages, connected to a more reliable and constant behaviour over time.

The MANSIDE (Memory Alloys for New Seismic Isolation Devices) project, funded by the European Commission within the BRITE-EURAM framework, was aimed at the conceptual design, implementation and testing of devices for passive control of buildings, bridges and other structures based on SMA [Nicoletti et al. 1997].

In this paper the conceptual design and the implementation of a family of devices based on SMA are described. They are capable to provide a wide range of performances, which realise, alternately or simultaneously, two main objectives:

- the full recover of the deformation of the devices and/or of the structure at the end of an earthquake (re-centring capability),
- a good energy dissipation,

together with a high resistance to large strain cycle fatigue and a great durability when corrosion-free alloys (such as Nickel-Titanium) are used.

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The description of the conceptual design process starts from the knowledge of the properties of SMA's. Then the basic performances are established and optimised, taking account of the target seismic behaviour of structural systems embodying seismic devices. The design concepts are described and the potential applicability is examined in economic terms. The experimental behaviour of the devices, instead, is described in a companion paper presented at the same Conference [Dolce et al. 2000].

SELECTION OF THE SMA TYPE AND OF THE SMA-ELEMENTS FOR THE DEVICES

SMA's are special alloys which can be made of various metals (Copper, Zinc, Aluminium, Nickel, Titanium, Manganese, etc.). All of them have some peculiar properties in common, which are generally referred to as *Shape memory effect* and *Superelasticity* (or *Pseudoelasticity*) [Van Humbeeck 1994]. These two effects occur, alternatively, depending on the phase, martensite or austenite, in which the alloy is stable at ambient temperature.
In view of possible applications in the field of the passive control of vibrations, the most interesting features of SMA's are:

- the capability to undergo large strains (up to 8-10%) without damaging,
- the capability to recover the initial shape spontaneously upon unloading (superelasticity) or by heating after unloading (memory effect),
- a high corrosion resistance, for some alloys.

In the light of what said, it is easy to imagine which are the possible advantages of a seismic device based on SMA: to exhibit, at the same time, an infinite lifetime (no problem of maintenance or substitution, even after several strong earthquakes), a good control of force and an exceptional re-centring capability.
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. A bibliographical investigation on the properties of various alloys was carried out, considering five different alloys, 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 were selected among others as the best candidates for passive control devices, owing to their better superelastic properties, low sensitivity to temperature, higher resistance to corrosion and to fatigue.
Taking into account 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, from 6 to 8 mm for commercial solid bars, up to 50 mm for special production bars), as well as for the stress distribution they will be subjected to in practical applications (tension for wires, bending and/or torsion and/or shear for bars).
Austenitic elements can provide the devices with some energy dissipation capability but also with full re-centring capability, thanks to 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, thanks to their superelasticity that makes them undergo loading-unloading cycles without any residual strains. On the other hand, bars can be employed either in martensite or in austenite phase, according to the desired device behaviour.
Against these characteristics, the mechanical properties of SMA's, in 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 to limit its variability when varying temperature in the practical range.

REQUIREMENTS AND CONCEPTUAL DESIGN OF DEVICES

The main scope of the MANSIDE project was the design and implementation of two families of engineered devices based on SMA: (i) seismic isolation devices for buildings, bridges and other structures, (ii) special braces for framed structures.
The re-centring and the energy dissipation capabilities, were chosen as the main objectives of the design. It must be emphasised, however, that these requirements are somewhat conflicting in a hysteretic-type device. As a matter of fact, the maximum energy dissipation is obtained in a rigid-plastic behaviour, while re-centring necessarily requires the force-displacement cycle to pass through the axis origin. Therefore, the cycle shape shall be optimised to get maximum energy dissipation, compatibly with the latter condition.
Functional simplicity, no maintenance, i.e. durability and fatigue resistance, limited encumbrance and compatible costs were selected as additional objectives.

After verifying that the re-centring and dissipating functions cannot be played by the same component, and taking into account the results of experimental and theoretical studies on the behaviour of bars subjected to torsion, bending, shear and of austenitic wires subjected to tension [Cardone et al 1999], the conceptual design was especially focused on the possibility of achieving the two main objectives (re-centring and energy dissipation capacities) by means of two separate groups of SMA elements.
The re-centring capability is obtained by using austenitic wires. The energy dissipation capability is provided either by martensitic bars subjected to bending or torsion, or by austenitic superelastic pre-tensioned wires, acting as a double counteracting system of springs. A hybrid solution, which appears suitable from many points of view, relies upon the energy dissipation capabilities of compact and low-cost steel elements. From the technical point of view, the advantages of this solution come from the high energy dissipation capability of steel, its very low hardening and independence from temperature, with the only drawback of the eventual need of substituting the elements after very strong earthquakes.
In order to better understand the conceptual design and the actual behaviour of such devices, it is worthwhile to refer to a simplified scheme, in which the self-centring SMA group has a nonlinear elastic behaviour, while the energy dissipating group has a perfectly plastic behaviour, as shown in Figure 1. In order to improve the re-centring capability of the first group, some pre-strain shall be applied. As a consequence, an initial theoretical infinite stiffness is obtained.
If these two behaviours are combined together, just summing up the forces of the two components relevant to the same displacement, the resultant cycles of Figure 1 are obtained. The energy dissipation can be varied according to the number of elements in the energy dissipating group. However in order to keep the re-centring feature, the maximum force corresponding to the zero displacement value must be not greater than the pre-stress force of the re-centring group.

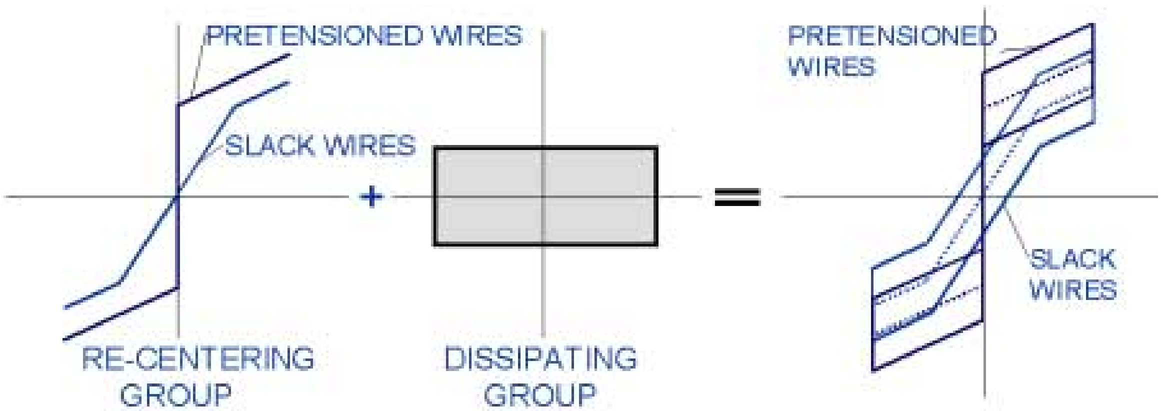

Figure 8. Idealised, separated and joint, behaviour of the two groups of SMA elements

The target behaviour is then obtained by calibrating the number and the characteristics of the elements of both groups, as well as the level of pre-stress. According to the supplemental recovering force or the residual displacements of the force-displacement cycles, the devices derived from the above explained concepts, though belonging to the same family, can be subdivided into the three following categories:

- Supplemental Re-Centring Devices (SRCD): a supplemental recovering force is available to re-centre the structural system, even in presence of parasite forces external to the device (e.g. friction in devices, plastic forces in structural elements, etc.),
- Re-Centring Devices (RCD): the device recover the initial position at the end of the action, but no supplemental force is available,
- Not Re-Centring Devices (NRCD): a high energy dissipation capability is available, but large residual displacements occur at the end of the action.

The actual behaviour of austenitic and martensitic SMA elements, in the practical frequency range, are somewhat different from the idealised ones. Superelastic wires give some energy dissipation (which is in any case favourable), martensitic elements are initially elastic (not rigid) and show some strain hardening. However the main behavioural features are maintained and the above explained working principles, with some approximation, are still valid.
Devices performing as in Figure 1 can be obtained by combining different kinds of re-centring and energy dissipating SMA groups, as shown in Table 1. For some applications, however, devices having either re-centring or energy dissipating capability only are needed, so that just one group of SMA elements must be used.

Table 1. Combination of re-centring and energy dissipating SMA groups to realise braces and isolators

	Bracing Device	Isolating Device
RE-CENTERING GROUP	• Pretensioned superelastic austenite wires arranged to be always stressed in tension	• Pretensioned superelastic austenite wires arranged to be always stressed in tension
ENERGY DISSIPATING GROUP	• Martensite bars in double bending • Pretensioned superelastic austenite wires • Steel hysteretic bars in double bending	• Martensite bars in roller bending • Pretensioned superelastic austenite wires • Steel hysteretic bars in roller bending

The design efforts were mainly focused on the arrangement of the re-centring SMA group. Then the arrangement of an energy dissipating SMA group based on pre-tensioned wires, in the same device including the SMA re-centring group, was studied. The resulting complete device works according to the scheme shown in Figure 2, which is valid for both the bracing and the isolating devices.

Basically, 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 systems.

To realise the SMA wire re-centring group, two studs are inserted transversely in the two tubes, into oval-shaped holes. An adequate number of superelastic wires are winded around the studs, which also have a mechanism (not shown in Figure 2) to apply and calibrate pretension. The special arrangements 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 tensile strains.

Similarly three studs, two of which move with the internal tube and the other with the external one (or vice versa), as well as the wire looped around the studs and the mechanism to calibrate pretension, constitute the energy dissipation group. When the two tubes move reciprocally, one loop elongates and the other shortens, thus acting as a double counteracting system of springs and exploiting the austenitic wires to dissipate energy in an optimal way.

The experimental performances of these devices based on SMA are described in a companion paper presented at the same Conference [Dolce et al. 2000].

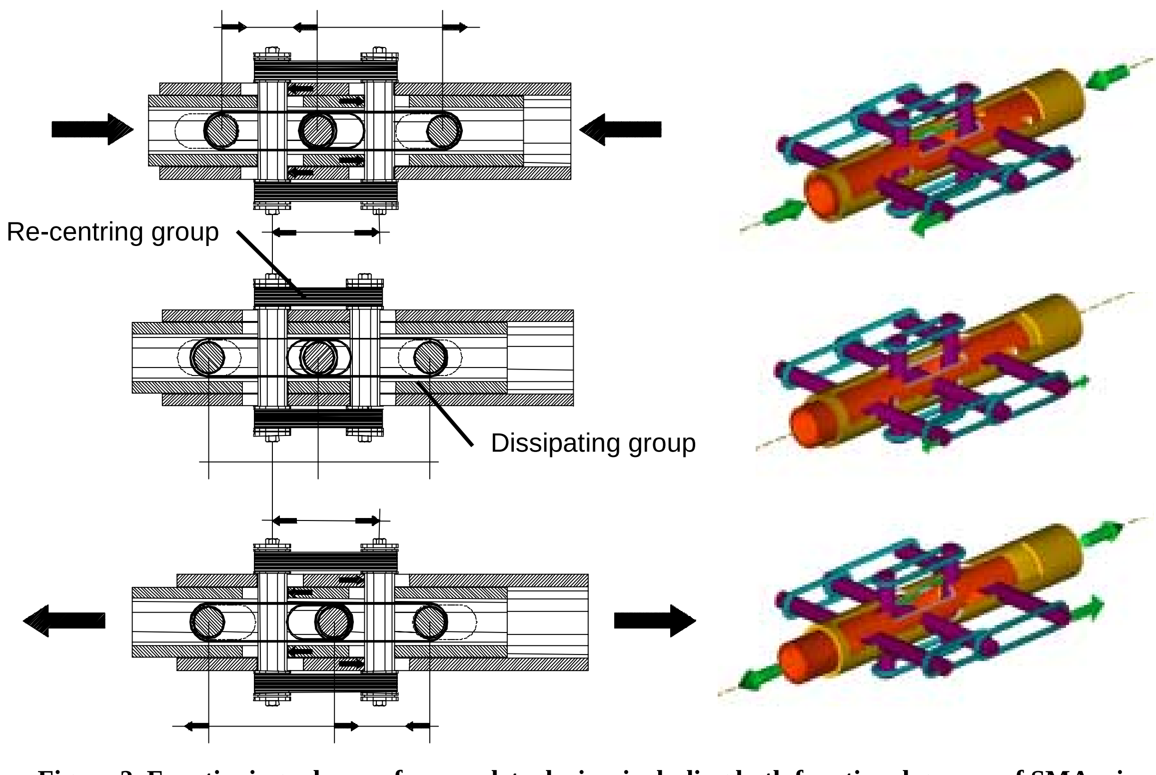

Figure 2. Functioning scheme of a complete device, including both functional groups of SMA wires

SEISMIC BEHAVIOUR OF STRUCTURAL SYSTEMS

In order to asses the effectiveness of the SMA-based devices in reducing the seismic effects on structures, detailed numerical simulation analyses were carried out on very accurate models of the 1/3.3 scale frames that were subsequently tested by the shaking table at the laboratory of the Technical University of Athens for MANSIDE.
The numerical simulations were performed by means of the non linear finite element program DRAIN-3DX in order to calibrate and optimise the characteristics of the bracing systems and of the seismic isolation systems based on SMA to be installed in the 1/3.3 scale reinforced concrete frames. However, to compare the behaviour of all the passive control systems to be subsequently tested, also seismic isolation and bracing systems based on current technologies (rubber, hysteretic steel dampers, etc.) were analysed. The characteristics of all the devices were drawn from the experimental tests carried out at the laboratory of the University of Basilicata (Dolce et al. 2000).
The seismic action was represented by an artificial accelerogram compatible with the EC8 type B spectrum, suitably scaled in time. Two maximum table accelerations were considered, namely 0.36g and 0.6g.
In Figure 3 there are shown the most significant numerical results relevant to frames equipped with SMA-based isolation systems and rubber isolators, subjected to 0.60g maximum table acceleration. The force-displacement cycles of the isolation systems, the time histories of the displacement of the isolation systems and the maximum interstorey drifts are reported. As can be seen the structural response of the SMA-based system is more favourable than the rubber system. Not only the displacement of the isolation system but also the interstorey displacements are significantly smaller for the SMA-based device. The better control of force of the SMA system plays a fundamental role in limiting the force transmitted to the superstructure and then the interstorey displacements, while the considerable stiffening in rubber isolators under large strains produces the opposite effect. Moreover, the higher energy dissipation of the SMA isolation systems also limits the base displacements and, along with the re-centring capability, stops the vibrations of the structural system immediately after the end of the earthquake. On the contrary, a quite long queue of vibrations is apparent in the rubber system. It is finally to be noticed the considerably low values of the interstorey drift in the frame equipped with SMA based isolation. Drift remains well below 0.1% even for 0.60g acceleration, thus guaranteeing a very high protection level for both the structural and non structural elements.
As far as the bracing systems are concerned, the structural response of the frames equipped with devices based on SMA and devices based on hysteretic steel elements were very similar in terms of interstorey displacements, both guaranteeing a high safety level. Important differences, instead, were found in the residual displacements for 0.6g, which were significant for the steel bracing system while practically zero for the SMA bracing system.
The numerical results were confirmed by the experimental tests carried out on the shaking table of the Technical University of

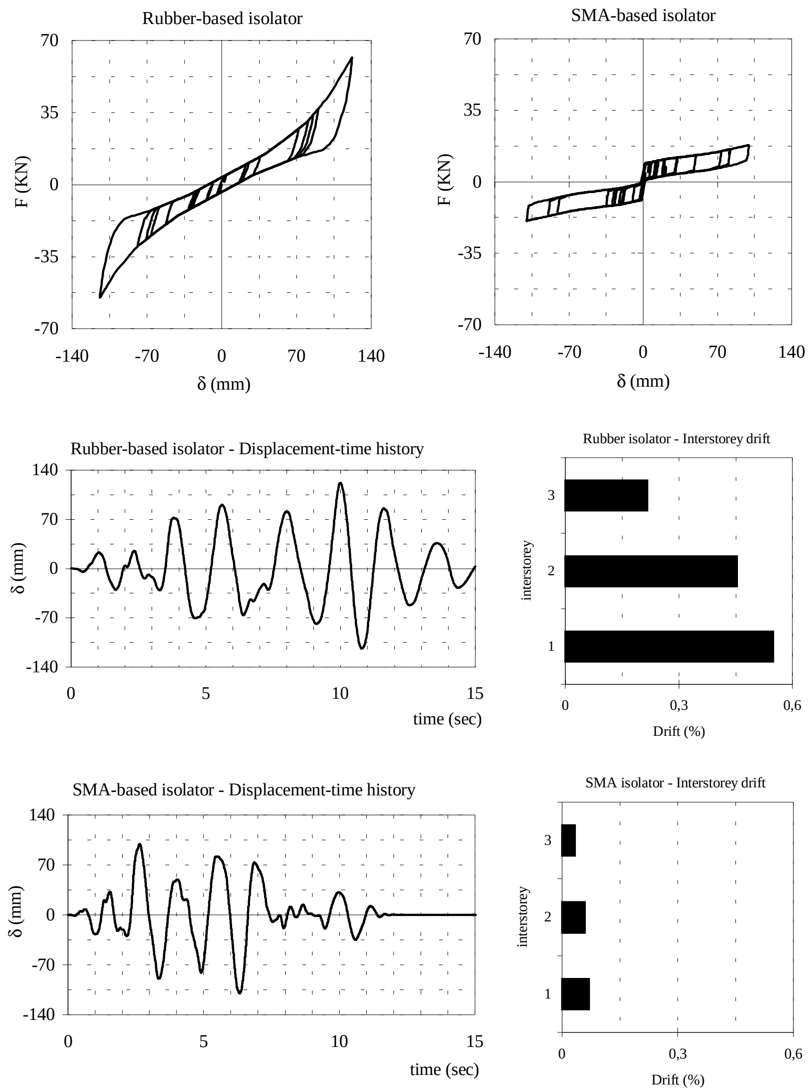

Figure 3. Comparison of the behaviour of structures with rubber-based and SMA-based isolation systems

Athens (Brancaleoni et al. 2000).
The fixed-base structure was severely damaged for a maximum table acceleration 0.48g.. The frames equipped with SMA-based devices had no damage even for intensity practically as big as twice the intensity that damaged the conventional structure. In Figure 4 there is reported an example of acceleration and displacement time histories recorded during the tests, on an infilled frame with SMA-based isolation system, for a maximum nominal table acceleration equal to 0.72g (about 0.6g actual acceleration). The initial position recovering and the de-amplification are apparent.

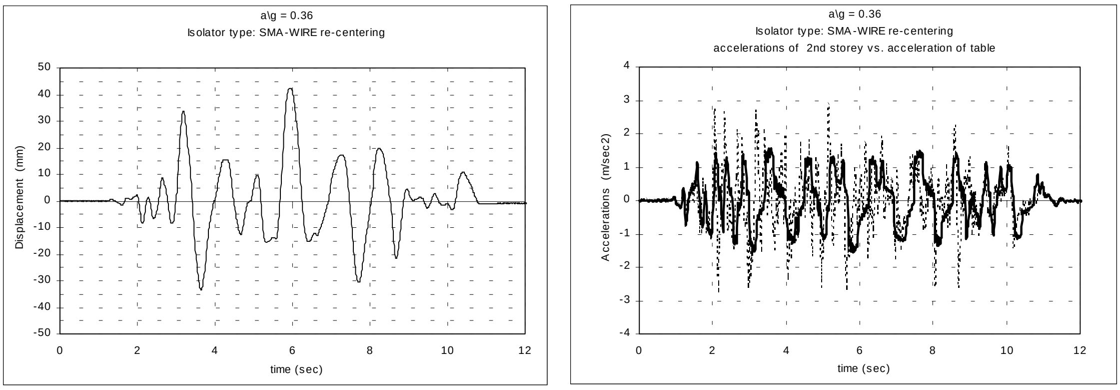

Figure 4. Recorded experimental time history of the displacement of the SMA-based isolation system (left) and of the acceleration of the table (dotted line) and of the 2nd storey (continuous line)

As a general conclusion of the above described results, SMA-based devices for both isolation and bracing system are very promising also for what concerns the seismic response of structural systems. They can provide performances which are at least comparable, but often better, than those provided by current passive control devices, while adding specific features like the re-centring property, the unlimited fatigue resistance, the high durability, which cannot be found all at the same time in the other systems. Among the different behaviours that can be obtained by calibrating the SMA elements in the devices, it seems that the most effective in terms of global structural response is the re-centring behaviour, with as much energy dissipation as possible. It must be reminded that this behaviour must be referred to the entire passive control system or, in case of braces, the entire structural system. To achieve this, supplemental re-centring devices are needed, as parasite forces are always present either in the isolation system or in the structure. Obviously the supplemental force shall be calibrated in order to realise the maximum energy dissipation.

COSTS OF SMA-BASED SYSTEMS

The use of materials with high cost per unit weight, like shape memory alloys, requires some considerations on the costs of passive protection systems based on SMA, in order to asses their practical feasibility and economic convenience. At this end, a cost analysis was carried out for the devices set up within the MANSIDE project. Here the conclusions of the analysis are reported. More detailed information can be found in [Dolce and Marnetto 1999].
The following assumptions were made: (1) devices based on SMA (NiTi) wires working in tension with a stress of 0.5 KN/mm^2 for the maximum strain of 8%; (2) cost per unit weight of SMA equal to 200 EURO/kg; (3) weight density of SMA equal to $7 \cdot 10^{-6}$ kg/mm^3; (4) cost of construction per unit area equal to 600 $EURO/m^2$; (5) weight of construction per unit area equal to 10 KN/m^2.
With the above assumptions, it turns out that, for isolation devices of buildings, the cost of SMA is about 0.7 % of the cost of construction. To make a comparison with current seismic isolation systems, e.g. based on High Damping Rubber Bearings, the total cost of the isolation system must be evaluated, considering also the cost of the devices embodying SMA wires and the cost of steel-teflon bearings. The cost of the complete isolation system is about 3.5% of the cost of construction. This value is comparable to the cost ratio of the most common isolation system based on high damping rubber bearings, which is of the order of 2.5-3.5 %.
With reference to bracing systems for framed structures, it turns out that the cost of SMA is negligible with respect to the cost of the device. Therefore, the cost of dissipating braces based on SMA is practically the same as that of common dissipating braces based on steel.
From the previous considerations, it appears that the use of SMA-based passive control systems, in spite of the better overall performances, does not imply high costs, specifically not higher than those of current passive control systems. Some further remarks can emphasise the convenience of SMA-based systems with respect to the most popular passive control systems.

As far as seismic isolation systems are concerned, the use of a SMA-based isolation system (SMA-BIS) presents the following advantages with respect to a rubber-based isolation system (R-BIS):

- The vertical space needed by a SMA-BIS is of the order of 100-150 mm, while it is of the order of 300-400 mm for the R-BIS, therefore it can better fit architectural and functional needs.
- NiTi shape memory alloys are highly durable and have an extraordinary fatigue resistance. Therefore, no substitution or maintenance interventions are needed along the entire lifetime of the structure, even in the occurrence of one or more strong earthquakes, while the same does not hold for the other isolation systems, based on traditional technologies. As a consequence, by using a SMA-BIS running costs are zero.
- A suitable arrangement of SMA devices along the perimeter of the construction eliminates any risk of modal coupling between translational and rotational vibration modes, which is typical of R-BIS.
- No theoretical limits of displacement and carried weight can be envisaged for SMA-BIS, while buckling phenomena are of great concern for rubber isolators, when large displacements are needed.

As far as bracing systems are concerned, whose employment is generally addressed to existing buildings, the following considerations hold:

- With the same bracing truss, the stiffness of the SMA-BBS is greater than the stiffness of S-BBS, as for this latter the elastic flexibility of the energy dissipating elements plays an important role. Therefore important savings in the truss weight can be obtained using SMA-BBS.
- No maintenance costs, even after strong earthquakes, must be considered for SMA-BBS, as neither permanent residual deformations nor any decay of mechanical features occur.

So far, the comparison of SMA-based passive control systems with the current ones, reference was made to the currently used design criteria, without looking at any possible improvements or change of structural design strategy, that the use of SMA can introduce. As a matter of fact, the peculiar superelastic properties of SMAs and the related supplemental re-centring capabilities of SMA-based devices suggest new criteria in the conceptual seismic design of structures with passive control systems.

Referring to the general requirements of an isolated structure under seismic actions, the fulfilment of the serviceability conditions under service actions and short return period (50-100 years) earthquakes calls for a minimum initial stiffness for rubber systems as well as a minimum yielding force for steel hysteretic systems. The former limit is aimed at avoiding sensible oscillations under wind actions, the latter at avoiding permanent deformations under minor earthquakes. The re-centring capability of SMA based systems solves both problems, thanks to the inherent high initial stiffness and the capability of recovering the initial configuration. It is therefore possible to consider a lower threshold value of the force transmitted to the superstructure with respect to an hysteretic system and to have a better control of forces under strong earthquakes with respect to a rubber based system, as sketched in Figure 5. The reduction of the forces transmitted to the superstructure implies the reduction of the structural costs and also an easier applicability of seismic isolation to existing structures.

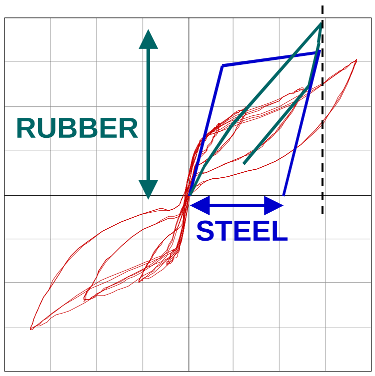

Figure 5. Comparison of steel and rubber BIS with SMA-BIS.

As far as bracing systems are concerned, the supplemental re-centring capability of the SMA-based bracing systems can be fully exploited by changing the design criterion of the structure, which limits the formation of hinges in the structure or the ductility demand. With a re-centring system of forces available all along the structure, even if the structure is totally hinged, working as a truss system, the structural system recover its initial configuration at the end of the earthquake. Although this concept needs some more investigations before being applied, it is clear that, in any case, larger ductility demands in the structure can be accepted. This would simplify greatly the seismic retrofitting of reinforced concrete structures, as the old structure does not need to satisfy any flexural strength or ductility requirement.

Though, until now, only the energy dissipation capacity has been considered as the fundamental feature of bracing systems in passive control, the beneficial effects of the re-centring feature shall be considered in future and a new category of re-centring braces shall be introduced in the panorama of passive control devices.

CONCLUSIONS

The peculiar properties of Shape Memory Alloys (SMA) have been deeply investigated and reconsidered in view of their possible applications in passive control of seismic structural vibrations. The superelasticity and the high fatigue resistance to large strain cycles have turned out to be the properties with the higher potential in this field. A careful conceptual design has lead to the implementation of two families of devices, for seismic isolation and for special bracing of framed structures. Their most important peculiarity is the re-centring capability, which can be improved by pre-stressing, up to provide a supplemental re-centring force. The devices are then capable to reset the structural system at its initial configuration after an earthquake, even in presence of parasite forces, such as friction in bearings or plastic forces in frame elements.

In particular, SMA-based 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 at the end of the earthquake, together with a good control of displacements during the action, on the other hand, they offer, at the same time, a good control of the force transmitted to the superstructure. Moreover, the modularity of the two functional groups of SMA elements (re-centring and dissipating), permit to calibrate the mechanical behaviour of the device to fit any specific need.

The availability of such features permit to improve the design of the structural system, allowing for considerable savings, especially for what concerns the seismic retrofitting of the existing structures.

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 SMA-based devices, which are able to provide supplemental forces to recover the initial configuration 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 re-centring capabilities, consisting in the elimination of any residual displacement, while accepting yielding in structural elements.

In conclusion, the overall performances of the SMA-based devices presented in this paper appear better than currently used devices', not only for their mechanical behaviour, but also for their high durability and fatigue resistance. As a matter of fact, they need no maintenance operations along the entire lifetime of the structure, even in the occurrence of several strong earthquakes. Nevertheless, a simple cost analysis estimates the initial costs of SMA-based systems to be comparable with respect to other currently used systems. The passive seismic protection systems based on SMA result, after all, more convenient than the systems based on traditional technologies, even without considering the important savings that can be obtained by introducing the new design concepts related to their re-centring features.

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