Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

SUPERELASTIC SHAPE MEMORY ALLOY DAMPER EQUIPPED WITH A PASSIVE-ADAPTATIVE PRE-STRAINING MECHANISM

P. Terriault[1], V. Torra[2], C. Fischer[3], V. Brailovski[1] and A. Isalgue[2]

ABSTRACT

The damping property of shape memory alloys (SMA) can be used in passive damping devices in which there is no moving part. Some of these dampers were designed to work in the martensitic regime of SMA while others operate in the superelastic regime. The superelastic regime dissipates less energy per cycle than the martensitic one, but it offers a better structural stability as well as a re-centering capability. Also, the performances of a superelastic SMA damper are improved if a pre-strain is applied. However, some temporal effects related to the application of a pre-strain compromise the long-term stability of the damper.

This article discusses the design of an SMA superelastic damper intended for small residential buildings. For economical reasons, such buildings cannot be equipped with a classical active or semi-active control damping technology. The innovative aspect of the SMA damper presented here is its capacity to operate in a pre-strain state only when the earthquake occurs. Before the earthquake, no force is applied to the damper in order to avoid the undesirable temporal effects. Such a damper can then be classified as a passive-adaptative technology, even if the shape memory components always remain passive. The damper is made of a series of SMA wires assembled in series with an unattended length reduction mechanism activated by the energy supplied by the earthquake during the first oscillations of the structure. A reduced-scale prototype of the damper has been manufactured and tested with a conventional tensile testing machine. The first results clearly show the advantages of the autonomous pre-straining mechanism.

Introduction

As described in (Soong and Spencer 2002), a wide variety of damping technologies have been developed to enhance the safety of structures subjected to seismic loading. The main idea is to reduce the displacements of the structure by absorbing and dissipating a certain amount of energy supplied by the earthquake. According to (Casciati et al. 2006), all these technologies can be grouped into three categories:

---

[1] Professor, LAMSI, École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, Québec, Canada, H3C 1K3

[2] Professor, CIRG-DFA-ETSECCPB, Polytechnical University of Catalonia, C/. Gran Capita s/n, CAMPUS NORD B4-B5, Barcelona, Catalonia, Spain, E-08034

[3] Undergraduate student, LAMSI, École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, Québec, Canada, H3C 1K3

- Passive energy dissipation: These devices, such as frictional sliding, yielding of material, phase transformation in metals, viscoelastic solids, etc., change the structure's stiffness or damping without requiring any external energy.

- Active control: An active control system (a series of hydraulic actuators for instance) adds substantial forces to the structure in a prescribed manner. A significant amount of external energy must be supplied to the computer-controlled actuators to ensure the efficiency of the system.

- Semi-active control: This category of devices also needs an external energy supply, but this energy is not used to feed an actuator. Instead, it is used to modify the intrinsic property of a component and the energy requirement is significantly reduced when compared to active systems. The viscosity variation within the fluid of a magneto-rheological damper is a good example of a semi-active system. Nevertheless, such systems must operate in conjunction with a computer and sensors in a close-loop algorithm in order to be efficient.

All these technologies have a bright future in many types of large-scaled structures (skyscrapers, bridges, etc.) for which a periodic maintenance can be scheduled in order to keep the devices up-to-date and fully functional. Unfortunately, for small buildings such as residential houses, many of these technologies cannot be applied. Indeed, the ideal technology for this type of building would have to be maintenance-free, meaning that the device should be completely autonomous for its entire life (several decades). Therefore, the active and semi-active control technologies do not represent good candidates for this application because they require continuous monitoring. Software and hardware components of computer-based technologies must be updated periodically in order to ensure the long-term reliability of the system. Passive energy dissipation technologies seem to be the best solution for small residential buildings. Among them, shape memory alloys (SMA) represent a good alternative since they are compact (they can be easily inserted inside the walls) and simple (no moving parts). The reliability of SMA rests on a solid-solid phase transformation that occurs inside the material. Their intrinsic hysteresis (different path during loading and unloading – see Fig. 1), their ability to sustain large reversible strains (theoretically up to 8%) and their good corrosion resistance (at least for Ni-Ti alloys) are the main characteristics that favour SMA.

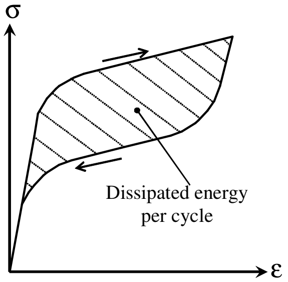

Figure 1. Schematisation of a SMA superelastic cycle.

Several researchers have studied SMA as structural dampers. For example, (Ocel et al. 2004) developed SMA tendons in the martensitic phase of the alloy for a steel beam-column connection. During an earthquake, the large deformations of the structure are absorbed by the SMA tendons instead of the steel structure itself. After an earthquake, the tendons must be heated to reset their behaviour for the next earthquake. Others used instead SMA in their superelastic (or austenitic) phase. Compared to a martensitic cycle with the same strain amplitudes, a superelastic cycle dissipates less energy, but offers a better structural stability and a re-centering capability. Also, superelastic SMA components do not need to be heated between earthquakes since they automatically recover their initial state after the unloading (see Fig. 1). With this in mind, (DesRoches and Delemont 2002) designed a superelastic SMA restrainer bar to reduce the seismic vulnerability of bridges. The SMA bars have a large diameter so that they can work in tension as well as in compression. Similarly, (Isalgue et al. 2006) and (Torra et al. 2006) developed a damper for family houses made of superelastic SMA wires in CuAlBe alloy (see Fig. 2), but instead of using a single bar having a large diameter, they have decided to use several smaller wires. These wires, installed as braces within the walls of the structure, can only work in tension (due to the buckling of the wires on compression). On the other hand, the heat generated by the hysteresis (work to heat) and the latent heat (released and absorbed) during the phase transformation can be extracted from several wires more easily than with a single bar having the same total cross-section. Therefore, the risk of SMA degradation due to overheating is minimized and the heat treatment of smaller wires is much more uniform than that of bulky bars.

Figure 2. Damper made of several SMA wires developed for family houses (Torra et al. 2006).

Since the damper is made of several tiny wires that work only in tension, it is efficient only one half of the time when the structure oscillates during an earthquake. To improve the efficiency of such dampers, (Lafortune et al. – In press) as well as (Dolce et al. 2000) showed that pre-straining the SMA wires is beneficial. Unfortunately, (Torra et al. 2006) pointed out that some undesirable temporal effect could affect the long term stability of the alloy when stressed (or pre-strained) during a long period of time. Fig 3. shows such a temporal instability, which is in this case an elongation of a copper-based SMA wire subjected to a constant stress for three days. Also, in NiTi some evolution in pre-strained state is observed under the stress and temperature yearly actions. Thus, at the present state of the art, if a pre-strain is applied to the SMA damper in order to improve its performances during an earthquake, it becomes impossible to guaranty its behaviour after a very long period (many years or even many decades) of inactivity in a pre-strained state.

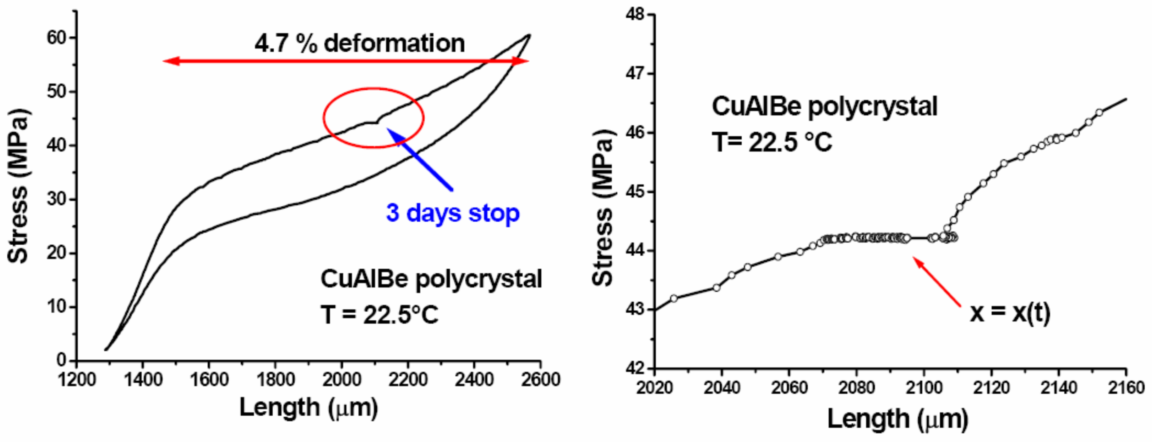

Figure 3. Temporal instability of a copper-based SMA (Torra et al. 2006).

The main objective of this paper is to present a mechanism that applies a pre-strain to the SMA damper in an autonomous manner only when needed, i.e. at the very beginning of an earthquake. During the long period of inactivity that precedes the earthquake, the SMA damper is kept unstressed in order to avoid any undesirable temporal effect.

Description of the Damper

The functioning of the SMA damper equipped with its autonomous pre-straining mechanism is schematized in Fig. 4. The SMA wire is clamped at one extremity to the mobile end and at the other extremity to the plunger with setscrews. If a tensile force is applied to the SMA wire (Fig. 4a), the plunger's shoulder leans against the threaded cap which is screwed on to the fixed support. In this configuration, the circlips are not activated and no relative displacement is obtained between the parts of the mechanism. By assuming that all the components are rigid compared to the SMA wire, the displacement of the mobile end is then fully converted into an elongation of the SMA wire. If the device is now compressed (Fig. 4b), the plunger freely slides inside the fixed support. Such a design is used in order to ensure that the SMA wire always remains in tension and the compression that could bend and damage the wire by buckling is then avoided. If the displacement is sufficient, one or more circlips move from the larger diameter of the plunger to the smaller one. Note that the circlips have to be initially and manually stretched for their installation on the larger diameter of the plunger. When the device is subsequently loaded in tension (Fig. 4c), the plunger's shoulder now leans against the circlips that are restrained by the threaded cap. This simple mechanism has the same effect of pre-straining the SMA wire prior to the loading. The pre-strain value, that can be easily adjusted by changing the number of circlips used, is given by the ratio of the combined thickness of the circlips over the effective length of the wire. For sake of clarity, only one SMA wire is represented in Fig. 4, but it could be replaced by several wires as shown in Fig. 2.

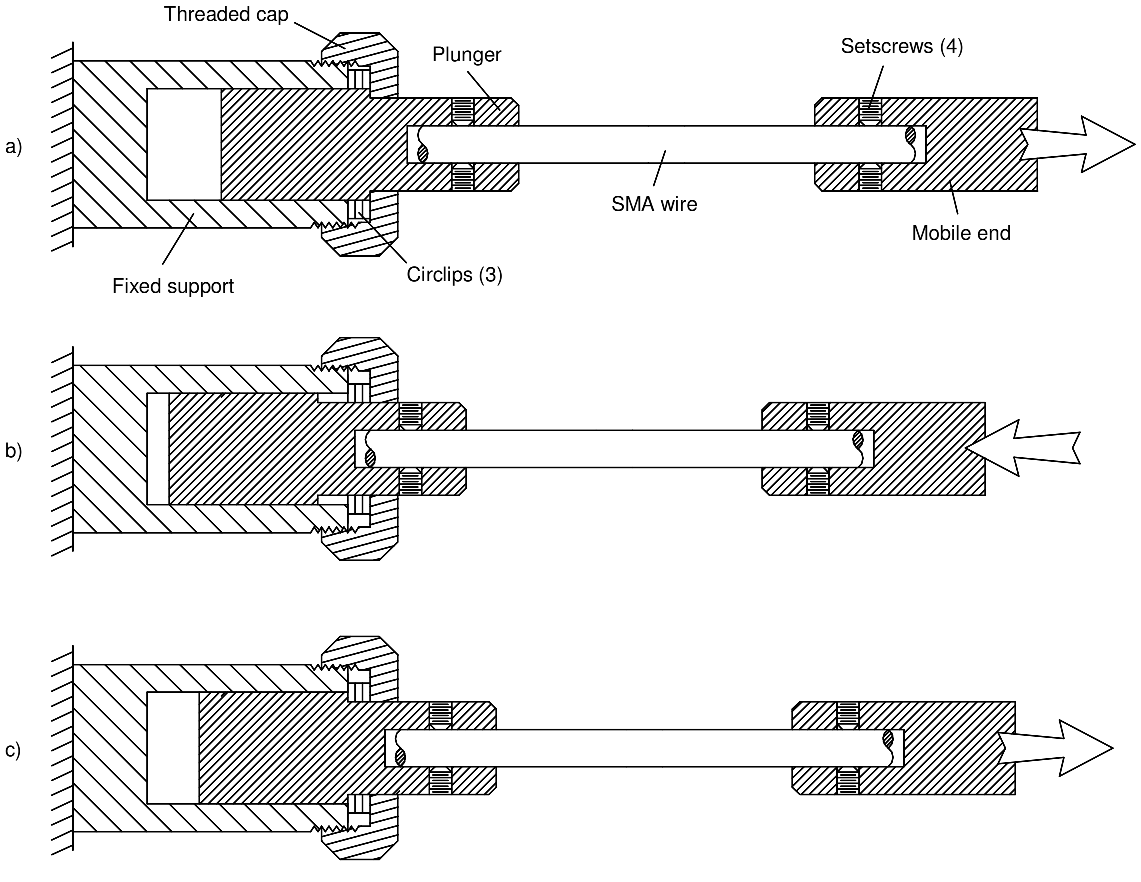

Figure 4. Representation of the autonomous pre-straining mechanism.

The most interesting aspect of this mechanism is its autonomous characteristic. Indeed, there is no sensor or computer to detect the occurrence of an earthquake and no actuator to trigger the pre-straining mechanism. During the inactivity period preceding the earthquake, the SMA wires are unstressed, which favours the long term stability of the shape memory properties. Finally, the energy needed to activate the pre-straining mechanism comes from the earthquake itself so that no external power is needed to operate. Therefore, without any classical (i.e. electrical energy) external energy supplied to the mechanism, the technology cannot be categorized as an active or semi-active control device. It is definitively a passive energy dissipation device but since additional forces are applied to the structure during its functioning (due to the pre-straining mechanism), the term "passive-adaptative" as been chosen to describe the device.

Experimental Validation

To validate the design, a prototype has been built (see Fig. 5 and 6). The fixed support, threaded cap, plunger and mobile end are made of stainless steel. The setscrews and circlips are commercially available parts bought from a supplier. The SMA wire is a 2.46 mm (0.097") pseudoelastic nitinol wire supplied by Special Metals used as furnished. The composition of the alloy is Ti-55.9wt%Ni and the heat treatment has been carried out by the supplier so that the transformation temperatures A_s and A_f are respectively -27°C and -7°C. Therefore, at room temperature, the alloy is superelastic. The effective length of the SMA wire (between the grips) is 130 mm.

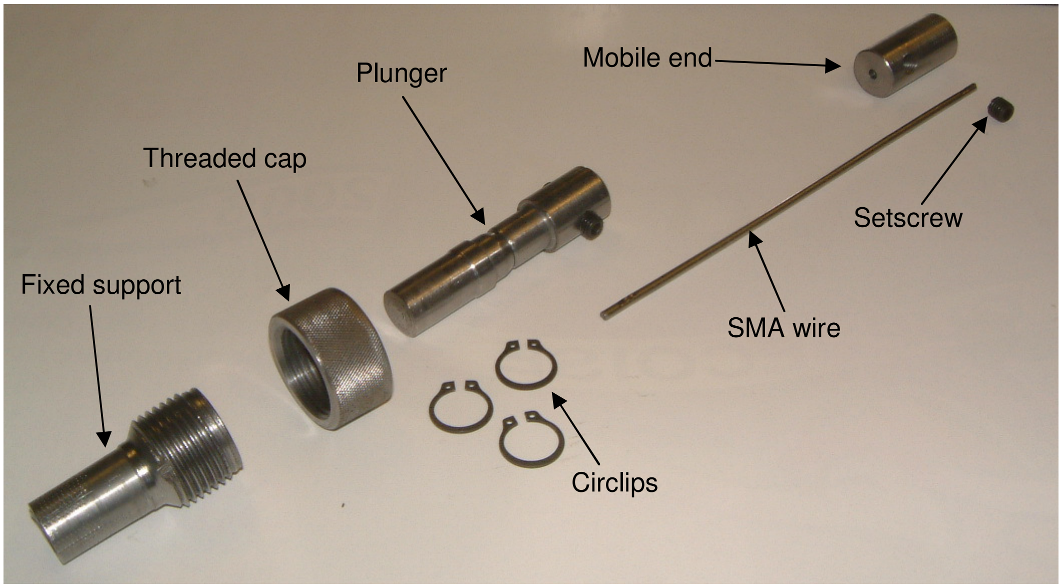

Figure 5. Disassembled prototype of the damper.

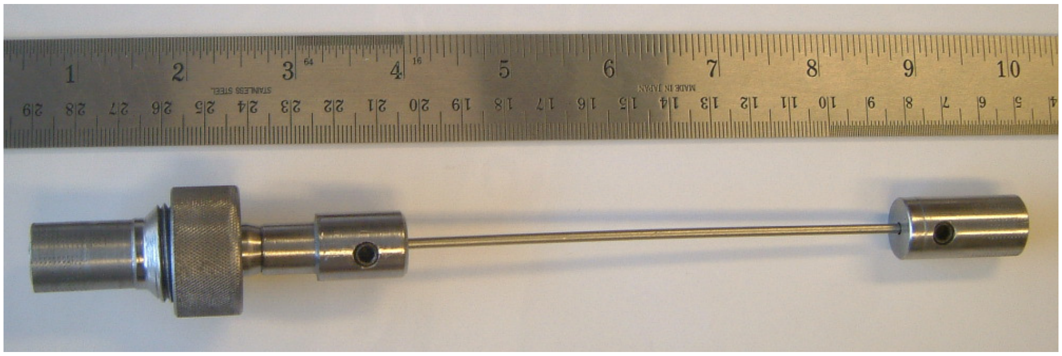

Figure 6. Assembled prototype of the damper.

The prototype has been validated with a MTS-858 Mini Bionix II tensile testing machine. The first experiment is conducted without the prestraining mechanism because no circlips are installed. The device is stretched up to 2.6 mm and compressed down to -2.6 mm at a frequency of 0.1 Hz (10 seconds per cycle) with a sinusoidal command for five consecutive cycles. This displacement value of 2.6 mm has been chosen in order to obtain a maximum strain of ±2% for a 130 mm long nitinol wire. The response of the damper is shown in Fig. 7 where it is clear that the device works exclusively in tension. Indeed, when the displacement (or the strain) becomes negative, the damper offers no compressive reaction.

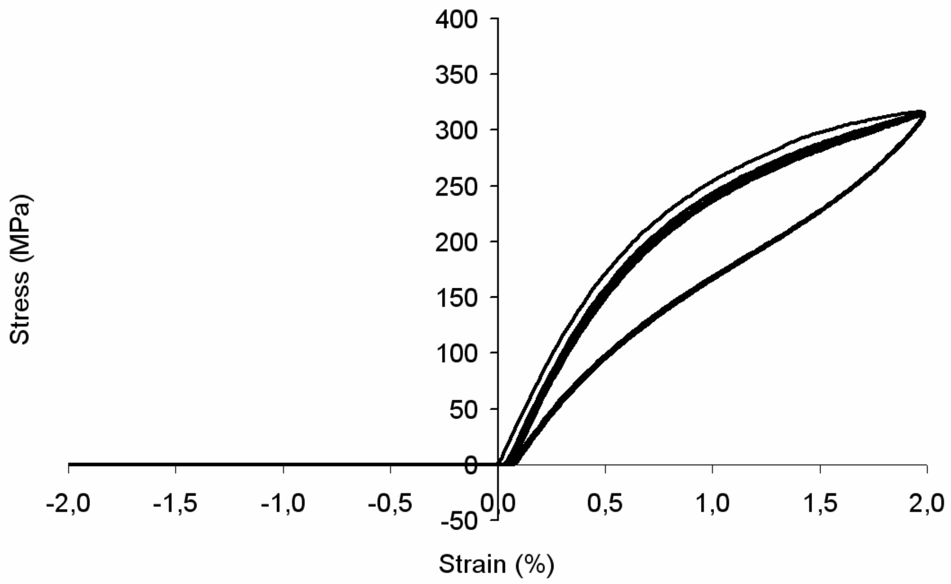

Figure 7. Response of the device without the pre-straining mechanism.

In the second experiment, three circlips are installed in order to obtain a pre-strain value corresponding to 2% of the initial length of the SMA wire. The applied loading consists of six cycles where the elongation of the device is varied between +2.6 mm and -2.6 mm at 0.1 Hz. The device's response is shown in Fig. 8 with the tensile part of the first cycle being practically identical to the one of the previous experiment, which is obvious since the pre-straining mechanism is not yet activated. During the compressive part of the first cycle, the circlips are sequentially engaged (see the peaks in Fig. 8). Afterwards, 5 other cycles are carried out and the SMA wires always remain in tension with a strain amplitude of 4%.

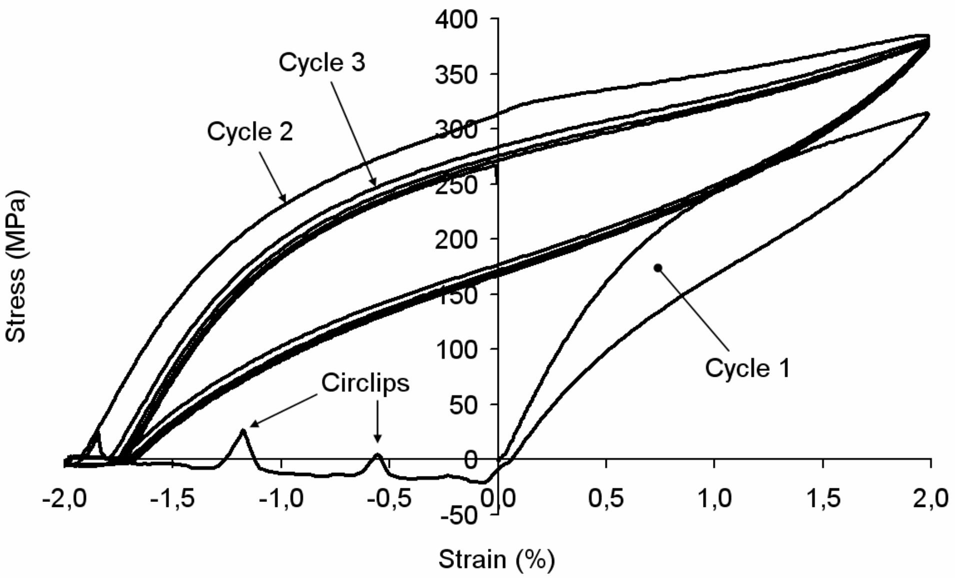

Figure 8. Response of the device with the pre-straining mechanism.

Note that the strain axis reported in Fig. 7 and 8 is not the real strain within the SMA wire. It is in fact the elongation of the entire device over the initial length of the wire. Therefore, in Fig. 7 and 8, even if the behaviour of the device is reported down to -2%, in any case the SMA wire can be loaded in compression due to the displacement of the plunger inside the fixed support. Thus, in Fig. 8, the strain of the SMA wire varies between 0% and +2% for the first cycle and between 0% and 4% for the other five cycles (instead of between -2% and +2%).

Finally, the energy dissipated during each cycle can be calculated by the area inside the corresponding hysteresis loop. Fig. 9 shows the evolution of the energy dissipated per cycle for the two experiments. With this result, it is clear that the pre-strained SMA wire dissipates nearly three times more energy that the non pre-strained wire, except for the very first cycle when the pre-strain mechanism in not activated, and this for the exact same displacement amplitude applied to the device (from -2.6 mm to +2.6 mm).

Of course, different pre-strain values could be studied in order to determine the best one that maximizes the performances of the damping device, but the objective of this paper is to demonstrate the technical feasibility of the autonomous pre-straining mechanism for SMA dampers.

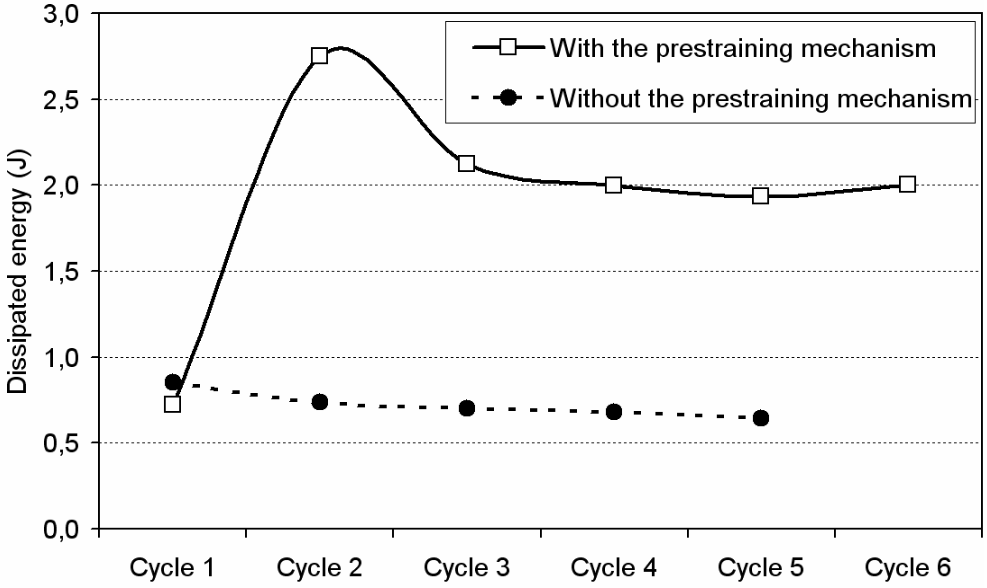

Figure 9. Comparison of the energy dissipated by each cycle.

It is interesting to note that the energy dissipated per cycle (for the pre-strained case) drops from the 2nd to the 3rd cycle and then stabilizes for subsequent cycles. This particular behaviour is caused by the significant residual strain (approximately 0.2%) that is created during the 2nd cycle, this cycle being indeed the 1st cycle with 4% strain amplitude. For this cycle, in opposition to the subsequent cycles, the hysteresis behaviour does not form a close loop, meaning that another mechanism contributed to the energy dissipation, namely the creation of plastic deformations. For the subsequent cycles, the material is practically stabilized and the energy dissipated par cycle remains fairly constant.

Conclusions

Shape memory alloys can be used as dampers for small residential buildings subjected to earthquakes because they are compact and reliable without requiring a periodic maintenance. In order to dissipate more energy per cycle, pre-straining the alloy is beneficial, but long term stability is then questionable. The autonomous pre-straining mechanism represents an economical approach that can be used to pre-strain the SMA wire only when required (i.e. at the very beginning of an earthquake) without needlessly keeping the SMA wires loaded.

The only drawback with this technology is the need to reset the mechanism after an earthquake. Indeed, for the next use, the circlips must be relocated on the larger diameter of the plunger, but this minimal maintenance must be carried out after an earthquake and this action can be done during the inspection of the house's structure following an earthquake.

Finally, the exact same mechanism can be used to eliminate the residual strain accumulation that is generally observed with SMA subjected to cyclic loading in tension only (see Fig. 7 for instance). The trigger point at which the residual strain is fully recovered is determined by the ratio of the thickness of the circlips over the length of the SMA wire. This application is currently under investigation by the authors. Also, other systems, which have to damper scarce events, and which have strained material as damper might have profit from this idea, as in some cases (e.g. rubber dampers) the life of the damper depends also on the continuous stress it has to support.

References

Casciati, F., Magonette, G. and Marazzi, F., 2006. "Technology of Semiactive Devices and Applications in Vibration Mitigation", John Wiley & Sons, ISBN: 0-470-02289-2, 268 p.

DesRoches, R. and Delemont, M., 2002. "Seismic retrofit of simply supported bridges using shape memory alloys", Engineering Structures, 24, 325-332.

Dolce, M., Cardone, D. and Marnetto, R., 2000. "Implementation and testing of passive control devices based on shape memory alloys", Earthquake Engineering and Structural Dynamics, 29, 945-968.

Isalgue, A., Lovey, F.C., Terriault, P., Martorell, F., Torra, R.M. and Torra, V., 2006. "SMA for dampers in civil engineering", Materials Transactions, 47, 3, 682-690.

Lafortune, P., McCormick, J., DesRoches R. and Terriault, P., In press. "Testing of superelastic recentering pre-strained braces for seismic resistant design", Journal of Earthquake Engineering, accepted for publication in December 2005.

Ocel, J., DesRoches, R., Leon, R., Hess, W.G., Krumme, R., Hayes, J.R. and Sweeney, S., 2004. "Steel Beam-Column Connections Using Shape Memory Alloys", Journal of Structural Engineering, 130, 5, 732-740.

Soong, T.T. and Spencer Jr, B.F., 2002. "Supplemental energy dissipation: state-of-the-art and state-of-the practice", Engineering Structures, 24, 243-259.

Torra, V., Isalgue, A., Martorell, F., Terriault P. and Lovey, F.C., 2006. "Built in dampers for family houses via SMA: an Ansys computation scheme based on mesoscopic and microscopic experimental analyses", Article in press in Engineering Structures, Available online since 28 November 2006 at http://www.sciencedirect.com/science/journal/01410296.