AN INNOVATIVE SHAPE MEMORY ALLOY DAMPER FOR PASSIVE CONTROL OF STRUCTURES SUBJECTED TO SEISMIC EXCITATIONS

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ABSTRACT :

An innovative re-centering damping device is presented. Being configurated simply, the device comprises two functional groups of superelastic SMA strands, i.e. the un-pre-tensioned strands and the pre-tensioned strands, resulting in a perfect energy dissipation compatible with a negligible residual displacement. Extensive experiments are carried out to investigate the influence of displacement amplitude and loading frequency on the mechanical behaviors of the device. While increasing the displacement amplitude, the secant stiffness reduces considerably, the energy loss increases, and the equivalent damping exhibits the maximum value at moderate displacement amplitude. The energy dissipation and the equivalent damping decrease with the increasing frequency, but the secant stiffness seems not much sensitive to frequency. Shaking table tests of a two-story steel frame demonstrate that the device not only can reduce the inter-story displacement of the structure subjected to earthquakes, but also can eliminate the residual displacement after excitations.

KEYWORDS: shape memory alloy, superelasticity, re-centering damping device, mechanical tests, shaking table tests

1. INTRODUCTION

Passive protection using special devices, such as isolators and dampers, is widely acknowledged as a very effective anti-seismic technique for civil structures. Several types of seismic devices are available, such as visco-elastic devices, elasto-plastic hysteretic devices, friction devices and viscous devices, which present some inherent limitations related to ageing and durability, maintenance, substitution and geometry restoration after strong earthquakes. Shape memory alloys (SMAs) known as smart materials with unique superelastic properties have many interesting characteristics which can be utilized in structures aimed at eliminating the aforementioned limitations (Motahari *et al*., 2007).

Superelastic SMAs are unique metallic materials which possess the ability to undergo large strain of the order of 10% and return to their original shape after removal of the load, associated with the energy dissipating capacity and the extraordinary fatigue and corrosion resistance. In passive control of structures, the dissipating capability decreases the demand on the main structural systems and decreases the plastic deformations of the structure members, and the re-centering ability causes the structures to return to its original geometry at frequent times during the excitation and thus prevents the structure from the accumulation of inelastic deformations (Motahari *et al*., 2007). However, the re-centering property presents not much dissipating capacity, especially in high rate loadings, SMAs almost remain linearly elastic. In order to offset the above incompatible capabilities of SMAs, Dolce *et al.* (Dolce *et al*., 2000; Cardone *et al*., 2004; Dolce *et al*., 2005) proposed Nitinol-based devices with full re-centering and good energy dissipation capabilities. The kernel component of such a device consists of two groups of Nitinol wire loops, i.e. re-centering group of superelastic Nitinol wires and energy dissipating group of Nitinol wires, which are mounted on two concentric tubes. Their full-scale brace, being designed for a maximum force of 200kN and a 20mm displacement amplitude, can be used as a bracing element in framed structures. Shaking table tests have shown that the SMA braces can provide performances at least comparable to those provided by steel braces, while having an additional re-centering feature. Dolce's idea exploits the great potential of SMAs in the field of passive seismic protection of structures (Li *et al*., 2006), however the SMA brace seems a little complicated and coiled wire loops are stressed inconsistent. Zhu and Zhang (Zhu and Zhang, 2007) presented a special reusable hysteretic brace with re-centering and energy dissipation capacities, but associated with inevitable friction effect due to asymmetric assemble of SMA wires.

This paper presents an innovative re-centering damping device (RDD) for use in seismic design and retrofit of structures. The RDD has such prominent performance characteristics as inherent self-centering behavior, enhanced energy dissipation capacity, simple configuration and survival during severe earthquakes. Extensive tests are taken to investigate the influence of displacement amplitude and frequency on the RDD's mechanical behaviors. Shaking table tests of a 2-story steel frame with/without the devices are carried out to assess the abilities of the RDD to control the seismic response of structures.

2. DEVICE CONFIGURATION AND MECHANICS

2.1. Configuration of the Device

Figure 1 symmetrically shows a schematic for the typical mechanical configuration of the RDD, which consists of a rigid frame and a sliding frame. Rigid frame comprises the steel plates 1 and 4 fixed to struts 6, and sliding frame is made of the steel plates 2 and 3 fixed to the center rod 5, with a sleeve 7 spacing the two plates. The sliding assembly slides on the guides provided by the struts 6. To minimize the friction effect, polishing axle can be used as the struts. The core component of the RDD is made of stranded superelastic Nitinol wires with different length and pre-strain level. Strands 9 are pre-tensioned to the middle of the yielding plateau of austenite SMA , arranged like in a double counteracting system of springs, i.e., two strands couple the plate 1 to the plate 3, and the opposing strands couple the plate 2 to the plate 4. Strands 8 are un-pre-tensioned, some attached to the plates 1 and 2, others to the plates 3 and 4. When the two frames move mutually, the two pairs of pre-tensioned strands work in opposition to one another to provide a full hysteretic loop with large energy dissipation capacities, and at the same time, some un-pre-tensioned strands experience tension while others experience compression, which provides a spindle shaped hysteretic loop to eliminate residual displacement of the device. By adjusting the volumes of un-pre-tensioned and pre-tensioned wires, RDD can be used to achieve flexibility in tuning for a broad range of hysteretic behavior and obtain a nearly re-centering hysteretic behavior with an enhanced energy-dissipating capability, as shown in Figure 2. In addition, to ensure all wires play their full roles, the length of the pre-tensioned wires is approximately twice of the length of the un-pre-tensioned ones.

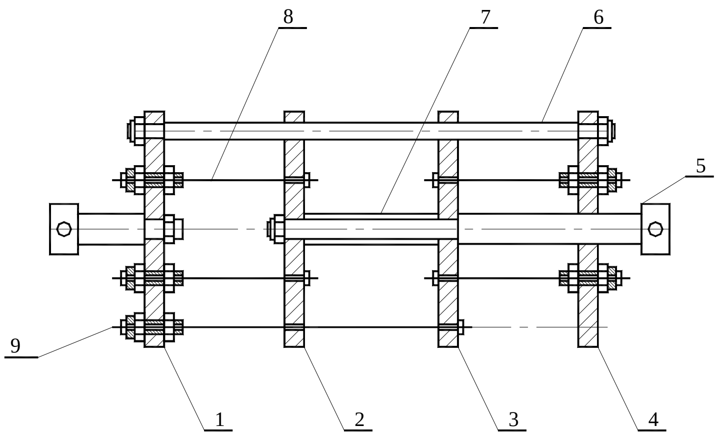


Figure 1 Configuration of the RDD

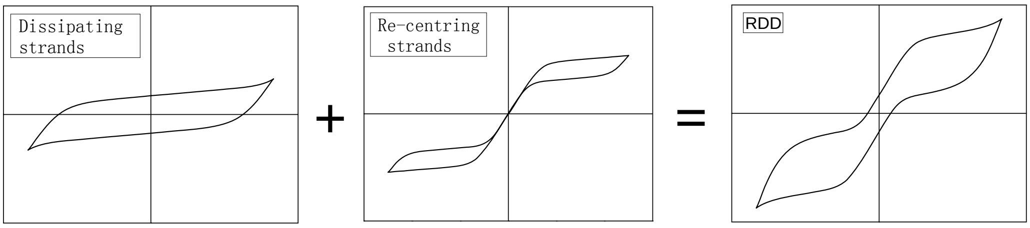


Figure 2 Mechanical behavior of the two functional groups of SMA elements

2.2. Mechanical tests of the Device

To validate the mechanical behaviors of the RDD, cyclic testing of the device is conducted. Figure 3 shows the experimental setup. The superelastic Nitinol wire has a diameter of 0.8mm, the transformation temperature A_f is 0^oC, and thus the wire exhibits superelastic behavior at a room temperature of 24^oC (Ren *et al.*, 2006). Each wire strand of the device is comprised of one superelastic Nitinol wire, one-third being pre-tensioned to a strain level of 3% with a length of 215mm, while the remaining being not pre-tensioned with a length of 115mm. Cyclic tests are carried out on an MTS servo-hydraulic test machine. The device are cyclically loaded at varying frequencies in four sequences of increasing displacement amplitudes; in each sequence, the frequency and maximum displacement are kept constant. Before the formal test, the device is pre-loaded cyclically in order to stabilize the hysteretic behavior.

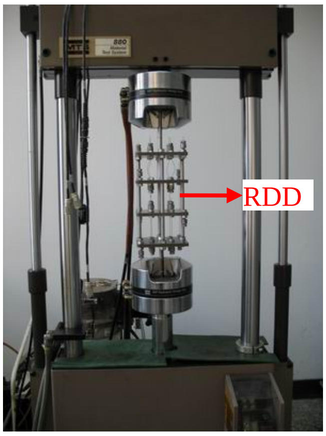
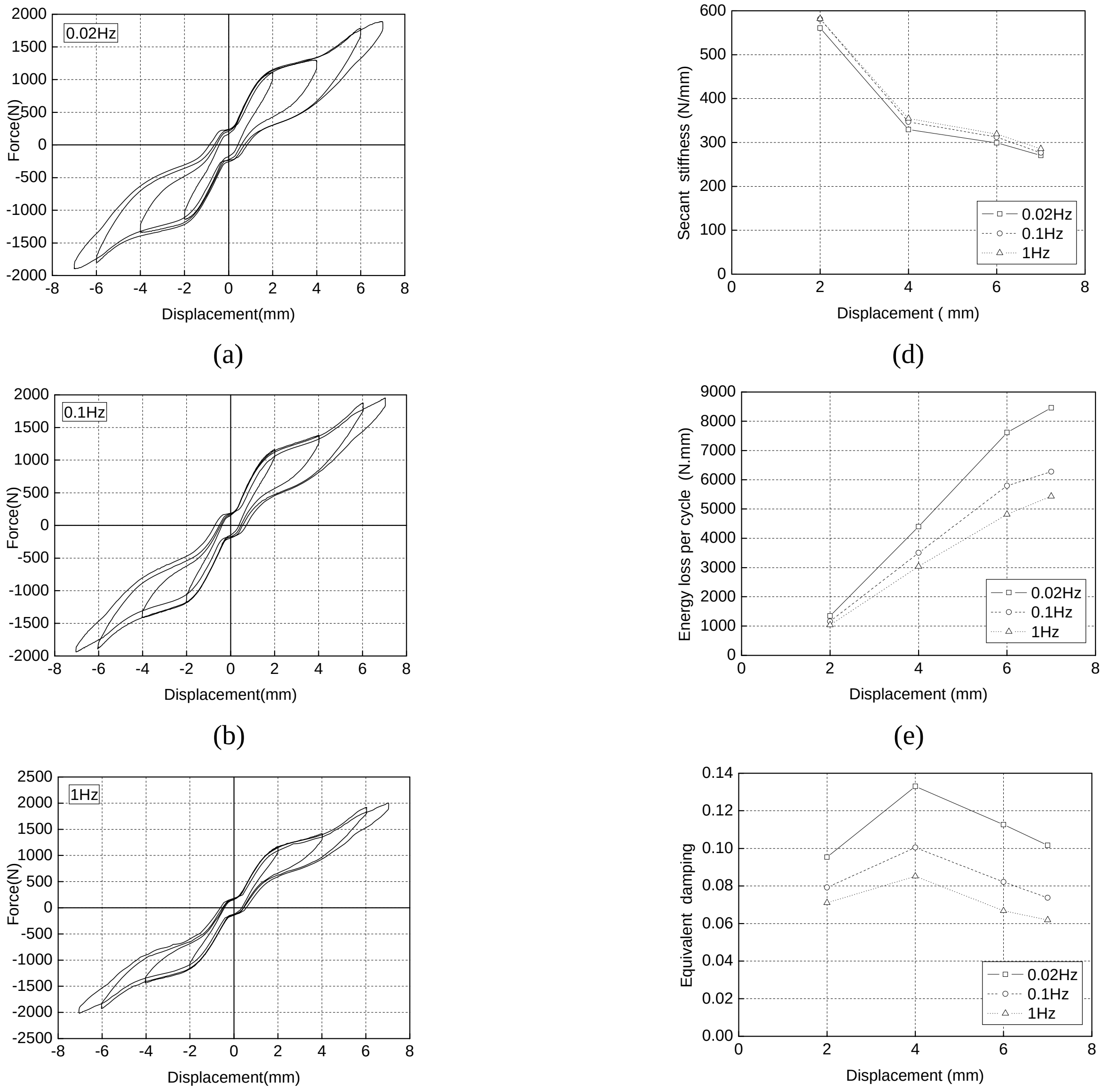


Figure 3 Experimental test setup

To evaluate the mechanical behaviors of the RDD, some significant mechanical quantities are calculated: (1) the secant stiffness K_s; (2) the energy loss per cycle W_D; (3) the equivalent viscous damping $\xi_{eq} = W_D / (2\pi K_s \delta^2)$, where δ is the displacement amplitude of the cycle (Dolce *et al.*, 2000). Their trends as a function of external parameters, such as displacement amplitude and frequency, are illustrated in Figure 4, and some typical force-displacement curves are also reported.

As can be seen, the hysteresis curves are characterized by double flag-shaped loops, resulting in much energy dissipation compatible with self-centering capability. While increasing the displacement amplitude, the initially high secant stiffness reduces considerably, resulting almost halved at relatively large amplitudes. The energy loss increases more than linearly with the displacement amplitude, because the unloading force levels reduce while increasing the cyclic displacement. The equivalent damping exhibits the maximum values at a displacement amplitude of 4mm.The influence of frequency on the secant stiffness is in general negligible. Since the unloading force levels increase more than the loading force levels, the energy dissipation decreases when frequency increases. The equivalent damping decreases with the increasing frequency, being the order of 10-13 per cent at 0.02Hz, and the order of 6-10 per cent at a frequency greater than 0.1Hz.



(a) (d)

(b) (e)

(c) (f)

Figure 4 Mechanical behaviors of the RDD at different displacement amplitudes and frequencies

3. SHAKING TABLE TESTS

3.1. Instrumentation and Model

Shaking table tests are designed at the State Key Laboratory of Coastal and Offshore Engineering of Dalian University of Technology. The shaking table measures $4\text{m}\times 3\text{m}$ in plane and can support test specimens weighing up to 10t. Simulating seismic motions can be applied in one horizontal direction with a maximum acceleration of $10\,\text{m/s}^2$. The frequency band is over the range of $0-50\text{Hz}$.

A two-story steel frame building is designed as Figure 5. The model is 1.2m long and 0.9m wide. The height of the 1st-story is 1.4m, and the top-story 1.25m. All the columns are all made of angle iron with a constant cross section of $\angle 30\text{mm}\times 30\text{mm}\times 3\text{mm}$, and all the beams are made of square steel tube with a cross section of

□$30mm \times 60mm \times 3mm$. The columns are welded to the strong steel slabs anchored to the earthquake platform which provide the fixed condition, and the beams are welded to the columns. Masses are added, using steel slabs welded to the beams of each floor. The model is intended to work in the longitudinal direction, so steel braces are installed at each story in the transverse direction to avoid torsion. The dampers are installed at each story, being fixed on the steel brackets and bolted to the beams. The steel brackets seems infinite rigid, so the deformation of brackets can be neglected, moreover, the bracket welded to the 1st floor slab can be regarded as the supplementary mass for the 1st-story. The 1st-story weighs 1280N, and the top-story 1090N.

Figure 5 Prototype of the model

Three accelerometers that measure longitudinal accelerations are installed in the model, one on the shaking platform, and the others on the beams of each story. Data are acquired automatically by a digital signal processing system.

3.2. Test Programme

Shaking table tests are performed using amplitude-scaled records from Qian'an 1976 (N-S), Taft 1952 (N-S), El Centro 1940 (N-S) and Tianjin 1976 (N-S).

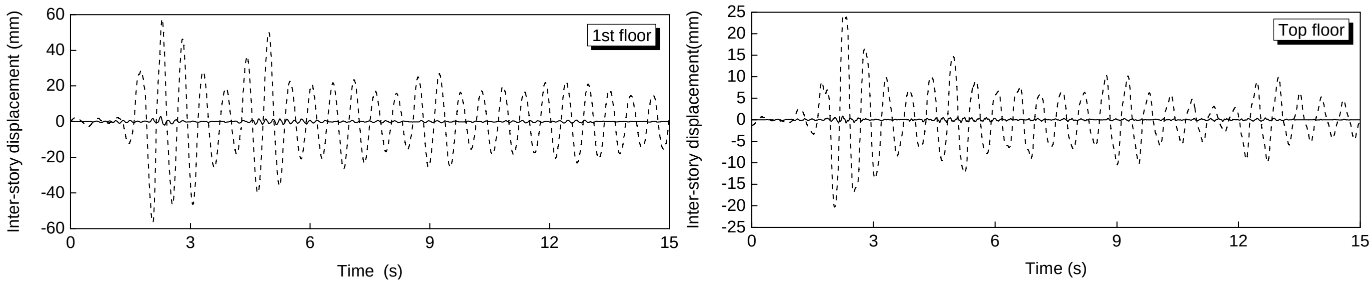
To evaluating the re-centering and energy dissipation capabilities, three models are tested. Model 1 is a bare frame, model 2 is upgraded with the identical RDD on each story, i.e. the ratio of cross-sectional area of un-pre-tensioned wires to pre-tensioned wires in the device is 2, and model.3 is damped with two different energy dissipating devices, the RDD on the top-story and the damping device (DD) with pre-tensioned wires only on the 1st-story.

3.3. Shaking table test results

Table 1 compares peak inter-story displacements in each story for model 1 and model 2 for all applied records. The absolute peak acceleration of records is adjusted to be $4m/s^2$ for Taft, El Centro and Tianjin earthquakes, and $7m/s^2$ for Qian'an earthquake to remain the structure being elastic and the wires' strain not exceeding 7%. Calculation of the inter-story displacements included (Cerda *et al*., 2006) (1) filtering the absolute acceleration records at each floor and shaking platform to eliminate noise, (2) integrating the acceleration records twice, and (3)obtaining inter-story displacements at each story by subtracting the absolute displacement of the nether floor. Table 1 shows significant reductions of the inter-story displacements for the damped model in all cases. To better understand the seismic response behaviors of the RDD frame, Figure 6 draws the time histories of the inter-story displacement of the models subjected to El Centro earthquake, in which the dot line represents the inter-story displacement of model 1, while the solid line represents that of model 2. Figure 6 once again shows the effectiveness of the RDDs in vibration reduction.

Table 1 Comparison of peak inter-story displacements between model 1 and model 2

Earthquake records	1st-story			Top-story		
	Model 1	Model 2	Reduction ratio	Model 1	Model 2	Reduction ratio
Qian'an	19.0mm	6.4mm	66.3%	8.5mm	1.7mm	80.0%
Taft	56.2mm	2.4mm	95.7%	23.1mm	0.8mm	96.5%
El Centro	59.0mm	3.0mm	94.9%	24.3mm	0.9mm	96.3%
Tian jin	62.2mm	1.7mm	97.3%	25.2mm	0.7mm	97.2%



(a) (b)
Figure 6 Inter-story displacement time histories of the models under El Centro earthquake

In shaking table tests, the models are in elastic stage for all cases, so comparisons of the residual displacements between model 2 and model 3 can show the re-centering capability of the RDDs. Qian'an record is applied, with a scaled peak acceleration of 4.7m/s^2, lasting 8 seconds, and then followed by 6 seconds of zero excitation. The long duration free vibration is intended for re-centering evaluation. Figure 7 shows the 1st-story displacement time histories of model 2 and model 3, respectively. The residual displacements are 0.3mm for the DD frame and almost zero for the RDD frame, which demonstrates that the self-centering capability of the RDDs can effectively drive the structure to restore the original shape after earthquakes.

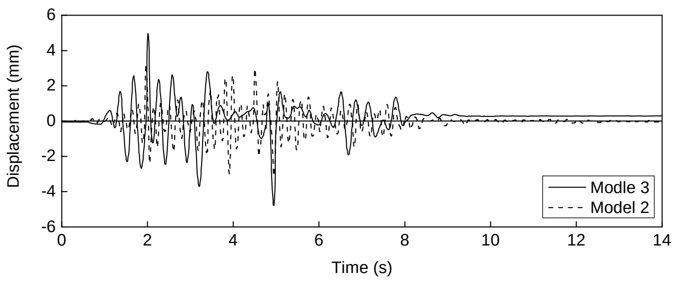


Figure 7 1st-story displacement time histories of the models under Qian'an earthquake

4. CONCLUSIONS

An innovative re-centering damping device based on superelastic Nitinol wires is presented. The functioning principles as well as the extensive experimental investigation are described. The basic features of the device are summarized as follows:

(1) Being configurated simply, the device is composed of two functional groups of SMA wires, i.e. the pre-tensioned strands and the un-pre-centering strands, resulting in a perfect energy dissipation compatible with a negligible residual displacement. In addition, attributed to favorable properties of superelastic SMA, the device has some other advantages for use in the passive seismic control of structures, such as extraordinary fatigue resistance, long-term reliability, high durability and survival during strong earthquakes without repair or replacement.

(2) Mechanical behaviors of the device are influenced by displacement amplitude and loading frequency. As the displacement amplitude increases, the secant stiffness reduces considerably, the energy loss increases, and the equivalent damping exhibits the maximum values at a displacement amplitude of 4mm. When frequency increases, the secant stiffness has a negligible increase, the energy dissipation decreases, so the equivalent damping decreases.

(3) Shaking table tests of a two-story steel frame with/without the devices are carried out. Results demonstrate that the device not only can mitigate structural response effectively, but also can provide supplemental forces to recover the undeformed shape of the structure at the end of the action.

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REFERENCES

Motahari, S.A., Ghassemieh, M. and Abolmaali, S.A. (2007). Implementation of shape memory alloy dampers for passive control of structures subjected to seismic excitations. *Journal of Constructional Steel Research* **63:12**, 1570-1579.

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* **29:7**, 945-968.

Cardone, D., Dolce, M., Ponzo, F.C. and Coelho, E. (2004). Experimental behavior of R/C frames retrofitted with dissipating and re-centering braces. *Journal of earthquake engineering* **8: 3**, 361-396.

Dolce, M., Cardone, D., Ponzo, F.C. and Valente, C. (2005). Shaking table tests on reinforced concrete frames without and with passive control systems. *Earthquake engineering and structural dynamics* **34:14**, 1687-1717.

Li, H., Mao, C.X. and Ou, J.P. (2006). Shape memory alloy-based smart buildings. *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, San Francisco, California, USA.

Zhu, S.Y. and Zhang, Y.F. (2007). Seismic behavior of self-centering braced frame buildings with reusable hysteretic damping brace. *Earthquake engineering and structural dynamics* **36:10**, 1329-1346.

Ren, W.J., Li, H.N. and Song, G.B. (2006). New constitutive model of superelastic shape memory alloy. *Journal of Dalian University of Technology* **46:S**, 157-161.

Cerda, M., Boroschek, R., Farías, G., Moroni, O. and Sarrazin, M. (2006). Shaking table test of a reduced-scale structure with copperbased SMA energy dissipation devices. *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, San Francisco, California, USA.