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Semi-active Damping Device Based on Superelastic Shape Memory Alloys

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ABSTRACT

Repair costs of structures subjected to intense seismic activity are influenced by the maximum and residual displacements they experience. As a result, the relevance of re-centring in seismic protection has been highlighted in recent research involving new materials, of which shape memory alloys stand out, opening up new possibilities in the field of motion control of structures. In this paper, the concept of a new semi-active damping device based on superelastic shape memory alloys, developed in order to surpass some limitations presented by other control solutions, is introduced. Analytical implementation made it possible to assess the new device for control of a single-degree-of-freedom oscillator, simulating the longitudinal behaviour of a bridge, and of a similar model with added fuse, for evaluating its re-centring capacity. The proposed device is capable of significant energy dissipation, similar to linear derivative solutions, and it is also capable of re-centring. The results obtained indicate that the new semi-active device is efficient for seismic protection of structures with nonlinear behaviour. The effects of time-delay on the response of the proposed damper were also evaluated, showing that, for expected values of time-delay, response degradation is not significant.

1. Introduction

For structural damage control purposes, judiciously implemented high-ductility regions may be complemented by additional dissipative devices. From an economic perspective, the energy dissipation properties of the structure and the implementation and maintenance of the protective dissipation devices should be taken into account for the prediction of damage repair costs. As the structure experiences damage, even though localized, in order to mitigate residual displacements as well as repair costs, re-centring capable devices are preferable, as indicated in numerous research reports. Dolce et al. [1], considering the re-centring capabilities of superelastic shape memory alloys (SMAs), advocated that larger inelastic deformations of RC members with SMA based protecting systems may be allowed when compared to the more common steel brace solution. This is because the property of superelasticity helps the structure to resume its initial position, in which case seismic retrofitting can become economically more attractive [1]. Elasto-plastic, fluid viscous dampers and friction devices lack the re-centring capability, whilst the efficiency of visco-elastic dampers is highly dependent on the seismic frequency content, thus they are not adequate for a significant range of input characteristics [2].

SMA applications in civil engineering are scarce [3,4]. Nevertheless, significant research has been produced on this matter and some interesting damping and re-centring solutions have been proposed. Dolce et al. [5] developed a SMA based isolation device, with some re-centring capability and good energy dissipation characteristics, based on the principle of prestressing. This made it possible to increase the equivalent damping from values of approximately 4% to 6%, corresponding to the raw SMA element, to values close to 40%. Other variations with martensitic bars in bending and with steel elements were also considered. McCormick et al. [6] compared the behaviour of SMA based braces prevented from buckling with conventional steel braces allowed to buckle. Auricchio et al. [7] analysed the same structure with buckling restrained steel chevron braces and compared them with SMA based braces. Speicher et al. [8] proposed SMA bracing devices in the form of helical springs and of Belleville washers. The dampers were designed so that the NiTi elements are compressed when the device is tensioned or compressed. Wilde et al. [9] developed a new base isolation device consisting of elastomeric bearings with two SMA bars working in tension and compression. Attanasi and Auricchio [10] proposed a base isolation device composed of a flat sliding bearing and eight SMA helical springs in a radial configuration. A theoretical damping ratio of approximately 9% was indicated. Passive SMA elements in the form of bars used as restrainers to limit the relative displacements of decks of simply-supported bridges at the piers and abutments and avoid unseating were studied by DesRoches and Delemont [11]. Comparisons were made with steel restrainer cables. The same problem was studied in more depth by Andrawes and DesRoches [2], who considered SMA restrainers and compared the efficiency of this solution with steel cables, metallic dampers and visco-elastic dampers. In general, SMA based solutions showed favourable performance with regard to the

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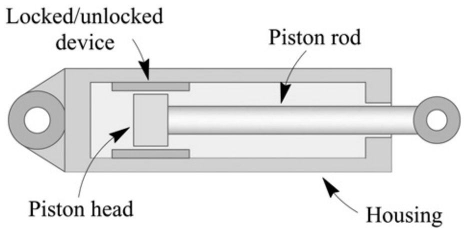

Fig. 1. General scheme of the SMA based semi-active device.

mitigation of residual displacements, influenced by its re-centring properties.

Cismaşiu and Santos [12] proposed a semi-active vibration control solution with superelastic wires, based on the passive device developed by Dolce et al. [5]. With locked/unlocked type supports, the displacements of the structure are used to prestress the wires, avoiding ageing problems occurring in permanently prestressed SMAs. In this device, the utilization of the material is not optimized, because, as in the previous solution, only part of the tension zone of the SMA constitutive relation is mobilized.

Maji and Negret [13] studied the active prestress of concrete beams by means of electrically heating SMA strands embedded in concrete. The same solution was investigated later by Deng et al. [14] using SMAs in the form of wires. In the light of present knowledge, secure permanent prestressing of SMAs lacks research into the effects of ageing, namely the prediction of relaxation as well as of temperature and stress effects on behaviour. Silva [15] studied the active control of the deflection of simply-supported beams subjected to dynamic loadings by means of the shape memory effect of SMA wires. Generally, the heating actuation rates were adequate but the cooling speed was insufficient to satisfactorily track low frequency periodic reference functions. Furthermore, because active control depends on external energy, power failure is a source of concern, thus this type of control is considered unsafe for seismic protection.

2. Shape memory alloys

SMAs are metal alloys with unique thermomechanical behaviour. Nickel–titanium alloys (NiTi) with near-equiatomic composition, subjected to cold working and annealing treatments, is commonly considered the most suitable SMA for control devices, given its better superelastic properties, higher stability under temperature variations and higher resistance to corrosion and fatigue [5,8,16,17].

Macroscopically, the behaviour of SMAs may be defined by the shape memory effect and the superelastic effect. The first is related to the capacity to recover from residual strains after loading and unloading cycles, by raising the temperature of the material. The other is characterized by its recovery from strains as large as 8% or 10%, induced by loading, through hysteresis loops upon unloading [18].

In the stress-free state, SMAs have four transition temperatures, M_f, M_s, A_s and A_f, arranged from the lowest to the highest, in which the M and the A symbols are references to martensite and austenite, the two state phases in which SMAs may be found. The subscripts indicate the starting and finishing temperatures of the so-called transformation strips. If the temperature, T, is inferior to M_f only martensite is stable and if it is superior to A_f only austenite is stable. Between M_s and A_s both martensite and austenite coexist in a stable manner. From M_s to M_f, there occurs the transformation from austenite to martensite, which is called forward transformation. From A_s to A_f martensite is converted to austenite, corresponding to the reverse transformation.

The superelastic effect is characterized by the single-variant martensite transformation from the parent phase (austenitic) due to loading at a temperature superior to A_f. Initially, elastic loading of austenite occurs and, after critical stress is reached, the transformation process into single-variant martensite commences, at which stress remains nearly constant. After the transformation process is completed, elastic deformation of martensite takes place, which, if continued, would lead to the plastification of the material. When unloaded from the elastic martensite branch, as at these temperatures martensite is unstable, the reverse transformation occurs. This follows a distinct path, with lower stress than the one associated to the forward transformation, and the material recovers its initial properties without significant residual deformations.

2.1 Characterization of SMAs

SMAs are highly sensitive to variations in material composition and to thermomechanical treatments. Consequently, safe design implies careful evaluation of the properties of SMAs on a case to case basis.

Residual plastic deformation due to the accumulation of irreversible strain with loading cycles may occur in SMAs. Researchers have come to conclusions related to this matter which, in some cases, are contradictory. Nevertheless, thermomechanical treatments making it possible to stabilize almost perfectly the superelastic behaviour of Ni-rich alloys, reducing residual deformations to negligible values, have been reported [16,19].

Differences in tension/compression behaviour were found in tests on martensitic and austenitic NiTi SMA, due to different microstructural deformation mechanisms [20,21]. Bars of austenitic NiTi were subjected

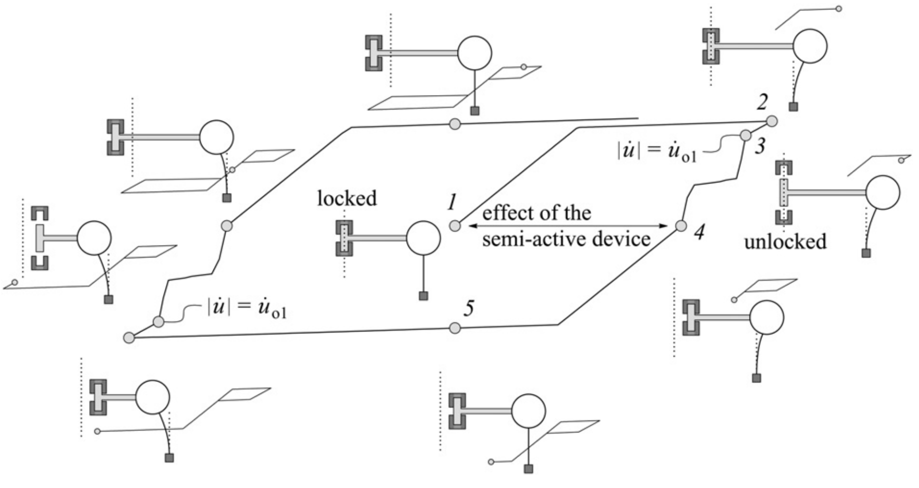

Fig. 2. Functioning scheme of the proposed semi-active SMA based motion control device.