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An algorithm to simulate the one-dimensional superelastic cyclic behavior of NiTi strings, for civil engineering applications

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ABSTRACT

An algorithm to model the one-dimensional cyclic behavior of NiTi strings is addressed. The NiTi alloy belongs to the shape memory alloy class of materials, therefore it presents both shape memory effect, for thermally-induced cycling, and superelasticity, for stress-induced cycles. The superelastic property has been the basis of some devices designed to mitigate the earthquake hazard level in structures. Throughout this paper the implementation of a one-dimensional cyclic behavior algorithm to model the NiTi constitutive relation is presented, supported by the thermomechanical formulation developed by Lagoudas and co-workers. The model was set up in MatLab environment and it accounts for isothermal superelastic behavior, incorporating minor hysteretic transformation loops. The definition of the transformation hardening function allowed for a better adjustment of the numerical model weighted against experimental results. Especial emphasis was given to the process of calibration of the model, regarding the definition of material parameters. The validation process consisted of the comparison between the results achieved with this algorithm and experimental tests performed at the Pacific Earthquake Engineering Research Center at the University of California at Berkeley. Quasi-static tensile tests and shake table tests of a small-scale steel structure with NiTi cross-bracing systems were used as reference. The model was able to simulate the experimental performance. This formulation can be implemented in more robust finite element analysis software, in order to perform studies in more elaborate structures.

1. Introduction

Shape memory alloys (SMAs) are a class of materials, which possess particular thermomechanical, thermochemical or thermoelectric properties, which allows for the phase transition between two solid phases. The Nickel–Titanium (NiTi) alloy is one example of such materials and it has specific properties, which justify its usage in civil engineering applications. Amongst other properties, this alloy has the capacity of undergo large strain deformation and recover its original shape, through stress or temperature induced cycles. Energy dissipation is also associated with this hysteretic cyclic behavior.

This paper intends to develop an algorithm that models the uni-dimensional behavior of NiTi wires, based upon the thermomechanical formulation of Lagoudas and co-workers [1]. Its accuracy was tested against experimental results of works performed at the Pacific Earthquake Engineering Research Center in the University of California at Berkeley [2].

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2. Properties

Although there are several different alloys with shape memory properties, the Nickel–Titanium (NiTi) alloy is the one that presents the best performance for civil engineering applications, due to its capacity to recover from significant strain, hysteretic energy dissipation and resistance to corrosion higher than most iron based metals.

The shape memory alloys may exist in two different crystal configurations, the austenitic and the martensitic. The austenitic phase is stable at higher temperatures and it is stiffer. The martensitic phase is stable for lower temperatures and it is more deformable.

A stress-induced deformation of a material in its martensitic state leads to a change from a detwinned form of its crystals to a twinned configuration associated with large strain, which is mostly nonrecoverable. This phenomenon is designated as pseudoplasticity (Fig. 1). In order to recover the undeformed shape, energy has to be introduced in the system through heating. This causes the shape memory effect, where the SMA regains its original austenitic configuration (Fig. 1). At higher temperatures where there is only the austenitic phase for zero stress loading, stress-induced deformation occurs associated with a phase transformation from austenite

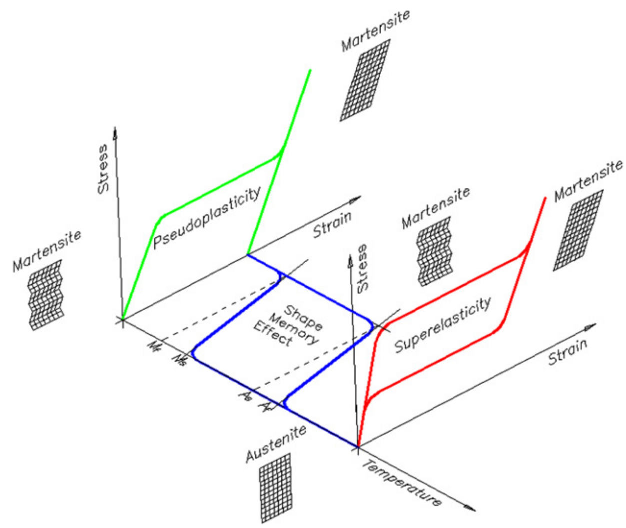

Fig. 1. Representation of three shape memory alloy behaviors: superelasticity, shape memory effect and pseudoplasticity.
Source: Adapted from http://department.fzu.cz/ofm/sma/.

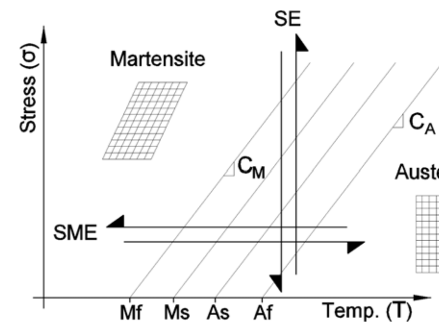

Fig. 2. Shape memory effect (SME) and superelasticity (SE) properties presented in the stress–temperature plan. The *s* and *f* indexes stand for the start and finish temperatures for the forward (*M*) and reverse (*A*) transformations. All temperatures are defined for zero stress conditions.

to martensite (forward transformation). After unloading, the material regains the original austenitic structure (reverse transformation), dissipating energy through hysteretic loops. This behavior is designated as superelasticity (Fig. 1) [2–4]. In Fig. 2 the shape memory effect and the superelastic properties are presented in the stress–temperature plan. For constant temperature the superelasticity occurs for stress-induced deformation (vertical arrows), for constant stress the temperature-induced deformation leads to the shape memory effect (horizontal arrows).

In order to take advantage of these materials for civil engineering applications, its properties should be carefully characterized, especially the properties related to cyclic loading.

Experimental results showed that cyclic loading leads to residual strain due to sliding of the metals micro-structure during the martensitic phase. Another effect is the reduction of the transformation plateau. To improve this behavior, several studies [1,5] point out the need for pre-cycles in order to stabilize the residual strain, despite the consequent reduction in hysteretic energy dissipation. Generally it is possible to obtain 15%–20% equivalent viscous damping in the martensitic phase and 4%–8% in the austenitic phase [6,7].

A series of tests [8,9] were conducted on both SMA bars and wires, in order to access its performance for seismic loading. Parameters such as the strain amplitude, frequency of loading, number of cycles and temperature variation, were analyzed. The results revealed a smaller damping capacity in bars, associated with a smaller residual strain. Presently, due to its higher price and difficult workability, only the use of small section elements, such as wires, is viable. For these elements, bending and shear may be neglected in computation, when compared to the axial forces.

Pre-stressing of SMA wires allows always working in tension, therefore improving their performance. Works conducted on this subject present the optimum pre-strain between 1.5% and 3%. Nevertheless, the material should be kept in the austenitic phase, with a strain level close to the beginning of the austenite to martensite transformation [5,7].

3. Civil engineering applications

In the recent decades, several studies were conducted to test the application of SMA technology to civil engineering structures. Most of the projects developed take advantage of the re-centering capacity and the hysteretic energy dissipation, due to superelasticity, to achieve an improvement in seismic behavior of structures [12–14].

Despite most of the applications are intended to work as passive control, there are a few examples of active control applications to structures. Song and Mo [15] placed SMAs wires inside a concrete beam in order to measure the strains it would be subjected during loading. Through heating of the wires, the cracks could be closed and correct the deflection of the beam, using the shape memory effect in real-time. Rustighi et al. [16] developed an adaptive tuned vibration absorber, which uses the NiTi shape memory effect to change its stiffness and to adapt to different ground motions.

Regarding the passive control of vibration, Liu et al. [17] used superelastic SMA dampers to mitigate the vibration in cables of a cable-stayed bridge. Inaudi and Kelly [18] also tested NiTi elements to improve the performance of a tuned mass damper.

Base isolation is globally accepted as one of the most efficient ways of reducing the earthquake effects in structures. Nevertheless, high residual displacements are usually associated with non-recentering bearings. Therefore, Shook et al. [19] and Dolce et al. [20] used hybrid systems with elastomeric and hysteretic base isolators together with SMA devices to control residual displacements.

Ma and Cho [21] and Dolce et al. [22] explored the re-centering ability and the hysteretic energy dissipation through the design of SMA dampers. Devices composed by pre-stressed austenitic wires, springs and martensitic wires were tested and validated through shake table tests, with good results.

Also with the purpose of controlling the residual displacements after the event of an earthquake, Johnson et al. [23] performed shake table testing combined with numerical models of restrainers to control relative displacements at joints in reinforced concrete bridges. Compared to classical solutions, higher energy dissipation and a reduction of 50% in the maximum openings were achieved.

The earthquakes of Northridge in 1994 and Kobe in 1995 raised some questions regarding the performance of the column to beam connections. With this background, Ocel et al. [24] and Alam et al. [25] used NiTi bars in the connection between steel elements and reinforced concrete elements, respectively. Both studies used the superelastic properties to dissipate energy and to minimize residual displacements.

Another area of research on passive retrofit techniques focused on the possibility of auto-repair concrete beams, as already mentioned for the active control of structures [15]. Otero [26] and Kuang and Ou [27] used NiTi wires encased in the concrete to repair the cracking after rupture on a bending test. After unloading, the NiTi fibers due to its superelastic re-centering ability recovered part of the deflection and partially closed the cracks.

There are only a few case-studies were the SMA technology was implemented in actual retrofits of existing structures [28]. As examples there is the retrofit of the bell-tower of the Church