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Ni-Ti SMA bars behaviour under compression

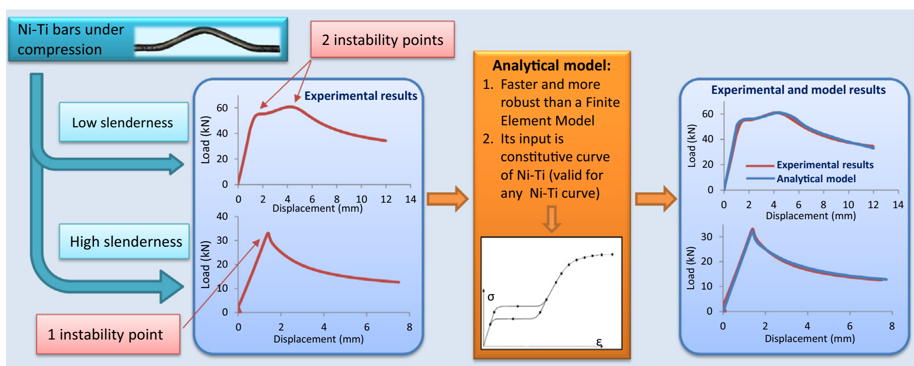
Javier Pereiro-Barceló [a], José L. Bonet [b,*]

[a] Instituto de Ciencia y Tecnología del Hormigón (ICITECH), Universitat Politècnica de València, C/Vera unnumbered, Valencia 46022, Spain
[b] Instituto de Ciencia y Tecnología del Hormigón (ICITECH), Universitat Politècnica de València, Valencia 46022, Spain

HIGHLIGHTS

- Ni-Ti bars with low slenderness can present two instability points.
- Slender Ni-Ti bars show only one instability point.
- Instability in compression of Ni-Ti bars depends on tension-compression asymmetry.
- The proposed model determines Ni-Ti bars behavior with instability in compression.
- The proposed model is faster and more robust than a finite element model.

GRAPHICAL ABSTRACT



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ABSTRACT

SMA (Shape Memory Alloys) is a type of material suitable for using in civil engineering as concrete reinforcement because of their shape memory effect or superelasticity and their high ductility and damping capacity. However, Ni-Ti alloys Young modulus could be 3 or 4 times lower than steel (200 GPa) depending on the composition and thermal treatment, which can cause the instability of compressed bars. The main objective of this work is to provide a modified constitutive model of SMA bars, particularized for Ni-Ti bars, that considers instability in compression. The inclusion of this effect in the constitutive equation allows for simulating Ni-Ti bars under compression in a simple way as if they were perfectly straight bars. To achieve this, six 12-mm diameter SMA bars made of Ni-Ti were tested under compression. The mechanical slendernesses of the six Ni-Ti samples were: 28.33, 38, 48, 66, 82 and 108.33. Thirty steel specimens were tested beforehand to validate the experimental setup and to calibrate the subsequent Abaqus finite element model. This model aims to conduct a parametric study to validate the proposed constitutive model of Ni-Ti bars, including instability in compression.

1. Introduction

Shape Memory Alloys (SMA) were discovered in 1932, but not until 30 years later did the first practical applications with SMA evolve. SMA is a material capable of undergoing considerable recoverable strains of 5–6% without displaying plastic strains. Its high durability, excellent dissipation capacity, high resistance to fatigue and its strain recovery capacity provide SMA material with numerous application possibilities in civil engineering [1–3], specifically in seismic design [4–7] and in prestressing and active confinement [8–14].

SMA has two different crystalline structures. The prevailing crystalline structure depends on temperature and the external stress applied. The high-temperature stable phase is known as

* Corresponding author.
E-mail addresses: japebar@upv.es (J. Pereiro-Barceló), jlbonet@cst.upv.es (J.L. Bonet).

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austenite, while the low-temperature stable phase is known as martensite [15,16]. The mechanical behavior that makes these alloys unique is closely related with transformation between both phases. The shape memory effect (SME) and the superelastic effect are two exclusive properties of these materials. The former is the capacity to recover its original shape by heating, whereas the latter is the capacity to recover major strains after withdrawing the applied load [17].

According to DesRoches et al. [18], SMA made of Ni-Ti displays the SME below the martensitic transformation finalization temperature M_f ($T < M_f$). Strains resulting from an applied external load are recovered by heating the material above austenitic transformation finalization temperature A_f. If Ni-Ti is in the austenite phase ($M_f < A_f < T$), martensite is generated when the material is submitted to a stress state, and the material reverts to austenite and recovers its original shape when the load is withdrawn. This effect is known as superelasticity. At an ever higher temperature (higher than M_d, which is the temperature at which the stress that causes martensite transformation is over the critical stress of permanent plastic strains), the material undergoes plastic strains under very high stress conditions.

Research literature includes models of the cyclic stress–strain behavior of SMA [19–24]. However, these models do not consider the instability due to compression in the SMA stress–strain relationship. This effect is particularly important for predicting the behavior of elements that undergo strong seismic action.

Modifications of a nonlinear cyclic stress–strain relationship, including instability due to compression, have been proposed in steel bars. It is worth highlighting the modifications of the Menegotto-Pinto cyclic stress–strain relationship [25,26] by Gomes and Appleton [27], and by Dhakal and Maekawa [28]. Gomes and Appleton [27] proposed a stress–strain path based on the equilibrium of a plastic mechanism that took place after instability. Dhakal and Maekawa [28] put forward a constitutive equation of steel bars including instability due to compression, based on a finite element model. Massone and Moroder [29] proposed a steel model based on the plasticity concentration on plastic hinges capable of adding initial imperfection. Massone and López [30] extended aforementioned model by considering the effect of stirrups and concrete core expansion for bars inserted into a concrete section.

Several authors have reported experimental tests carried out with isolated steel bars submitted to compression loads: Mander [31], Mander [32], Monti and Nuti [33], Rodriguez et al. [34], Bayrak and Sheikh [35], Bae et al. [36]. The research literature on the behavior of SMA bars subjected to compression is much shorter than that on steel. Rahman et al. [37] and Rahmanand Tani [38] carried out a series of experimental tests on Ni-Ti bars, for different slenderness ratios, to study the instability under compression. They found that, unlike what happens in conventional materials like steel, for low slenderness ratios, Ni-Ti was capable of maintaining significantly high loads beyond the instability point, and could even increase the load capacity in some cases after going beyond a first instability point to then find a second instability point from which the load decreases. Similarly, Rahman and Tani [38] performed finite element analyses based on the large strain theory to predict the average stress and the equivalent strain curves of short Ni-Ti bars. Movchan et al. [39] and Movchan et al. [40] theoretically analyzed the instability in compression of SMA bars using the fraction volume concept of the martensitic phase. They concluded that the transformation of typical SMA phases affected the solution to the problem. Finally, Richter et al. [41] numerically analyzed the phenomenon so-called anti-buckling effect reported by Urushiyama et al. [42] in their experimental tests of Ni-Ti-Cu bars. This phenomenon takes place in bars in the martensitic phase that undergo uniaxial compression and subsequent bending. These authors attributed it to the constitution of different martensitic phases during the loading process. The model proposed by these authors is capable of representing this particular phenomenon in a pseudoelastic SMA regime.

The properties of Ni-Ti (superelasticity and damping capacity) make it suitable to be used in concrete elements [2,43–45]. Therefore, a constitutive equation of SMA rebars that considers instability due to compression behavior, as it happens in steel reinforcements, enables the modelling of the reinforcement as a perfectly straight bar without having to consider a possible local imperfection of the bar in the model.

In view of the research literature, very few experimental studies have been conducted with isolated Ni-Ti bars that undergo compression loads [37,38]. Besides, the studied diameter (ϕ = 2mm) is shorter than that normally used as the compression reinforcement in concrete structures. Finally, there is no analytical or simplified model that can be used to calculate the constitutive equation in compression of the Ni-Ti including instability due to compression.

Therefore, this paper proposes an analytical model for the calculation of the behavior of the bar which takes into account the instability in compression, that is to say, a model to get the average stress – equivalent strain relationship that includes buckling effects. It is noteworthy to mention that this average stress – equivalent strain relationship takes into account structural aspects, and it is different from the fundamental stress–strain relationship of the material. In order to obtain the average stress – equivalent strain relationship, it is necessary to know beforehand the fundamental stress–strain behavior of the Ni-Ti as material, both in tension and in compression. To meet this objective, an experimental campaign was carried out with Ni-Ti bars. Then a finite element model was calibrated based on the experimental results to conduct and discuss a parametric study. Finally, an analytical model was proposed to modify the constitutive average stress – equivalent strain equation in compression of the Ni-Ti bars taking into account the instability. The results obtained with this model were then compared to those obtained with both the finite element model and experimental tests.

2. Experimental program

A series of six experimental tests were performed with Ni-Ti bars subjected to compression. The obtained data were used to calibrate a numerical finite element model. Thirty steel bars were tested beforehand, for two reasons. Firstly, to validate the test configuration. To do so, the variation in the experimental results was analyzed and compared with the instability curve known as the "Column Research Council" (CRC) design curve [46]. Secondly, to have data to calibrate the independent finite element model parameters of the material stress–strain properties, like stiffness of certain boundary conditions (Section 3.1). The steel and Ni-Ti bars employed in the tests were 12-mm in diameter.

2.1. Material characterization

In this section, the characteristics of Ni-Ti and steel are described. In the case of Ni-Ti, three types of tests were conducted: simple stress–strain tests, compression tests and a Differential Scanning Calorimetry (DSC) test. A short Ni-Ti column, with a free length of 10 mm, was tested in compression. This length is small enough so as to disregard the possible second order effects of the bar due to geometrical imperfections or to the application of the load. Finally, the steel bar was tested to obtain the stress–strain relationship according to standard UNE-EN ISO 6892-1 [47]. The