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Experimental study on concrete beams reinforced with pseudoelastic Ni-Ti continuous rectangular spiral reinforcement failing in shear

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ABSTRACT

Shear failures in reinforced concrete beams are associated with brittle collapses, practically without reaction capacity by users, which may be associated with human and material losses. This behavior is related to low deformations at failure, which makes predicting failure difficult. Ni-Ti is the most commonly used shape memory alloy and is an exceptional material that has the ability to achieve high deformations and to return to a predefined shape after unloading or upon heating. An experimental campaign focused on assessing the possibility of obtaining more ductile shear failures using a Ni-Ti alloy reinforcement that shows pseudoelasticity at ambient temperature is presented. Seven small-scale reinforced concrete beams were tested to assess the feasibility of this idea. It is shown that the Ni-Ti spiral reinforcement makes it possible to obtain highly deformable concrete elements even for beams failing in shear.

1. Introduction

The shear failure of concrete is well recognized to be sudden and brittle in nature, with little or no warning, especially for concrete beams reinforced only with longitudinal tensile reinforcement [1]. This brittle behavior is the object of detailed analysis in the case of structures that may be affected by an earthquake [2]. Modern seismic codes impose a series of detailing provisions aimed to prevent failure in beam-column joints, such as the ones shown in Fig. 1, leading to failure due to beam ductile plastic hinges [3].

The main shear transfer mechanisms [4] are the shear transferred by the concrete compression chord, across the web cracks, by the longitudinal reinforcement (dowel action), by the stirrups if they exist and by arch effect close to the supports. In general, failure occurs when the shear critical crack propagates to the load application point, as predicted by different shear mechanical models [5–7]. For beams with stirrups, one or several stirrups may break just after the critical crack crosses the compression chord reaching the load application point. The use of rectangular continuous spiral steel reinforcement as shear reinforcement in elements with rectangular or T cross sections has been recently studied [8,9]. Continuous rectangular spiral transverse reinforcements have also been used to reinforce concrete columns and beam-columns connections to enhance constructability and to improve their seismic performance [10–12]. As Karayannis and Chalioris highlighted [8], the installation of steel spiral reinforcement reduces labor costs with respect to the installation of the single closed stirrups and reduces the amount of steel because common single closed stirrups require the formation of two end hooks for anchorage that are not needed in spiral reinforcement. However, common continuous spiral reinforcement includes two links with opposite inclination and, therefore, only one of these links has the right inclination to resist against the applied shear. To avoid this inconvenience, an advanced rectangular steel spiral reinforcement that consists of shear-favorably inclined vertical links was presented and tested as the shear reinforcement for shear-critical beams [8]. The authors reported an increase in the shear strength due to the use of the advanced rectangular continuous spiral reinforcement compared to single closed stirrups and a significantly improved post-peak behavior, with a significant middle span deflection ductility index.

The interesting properties of shape memory alloys (SMAs) have increased the development of investigations and studies for the possible applications of these alloys in the field of civil engineering [13–21]. In terms of structural engineering, these alloys have three key properties: shape memory effect, pseudoelasticity (or superelasticity) and damping capacity. The shape memory effect refers to the phenomenon whereby SMAs are capable of returning to a predefined shape upon heating. Pseudoelasticity means that SMAs may be able to undergo high inelastic deformations and, despite these, return to their original shape upon unloading. The third property, linked to the two previous properties, is due to the

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Fig. 1. Strong beam and weak column failures, from [3].

capacity to convert mechanical energy into thermal energy and, therefore, to the possibility of reducing the movements or vibrations of a structure. All of these properties are, in fact, the result of the reversible phase transformation SMAs undergo, the so-called martensitic transformation [22]. The fundamentals of the martensitic transformation will be presented in next section.

In this paper, pseudoelastic Ni-Ti continuous rectangular spiral reinforcement will be used to allow very high deformations in rectangular beams to ensure ductile shear failures, similar to ductile bending failures, preventing brittle structural collapses due to shear. To the authors' best knowledge, the beams presented in this paper are the first beams reported with spiral Ni-Ti shear reinforcement failing in shear. It must be taken into account that it is not possible to completely replace steel reinforcement with SMAs in a structure with the current technology and cost of SMAs, but to use SMAs only in specific critical zones to give to the structure the ability to respond exceptionally to blast, accidental or seismic loads. Aiming to minimize the amount of SMAs, continuous rectangular spirals were used in this research, as the use of conventional stirrups would have required anchorage hooks, increasing the amount of the required SMA. Although more research is needed, the test results definitely show that it is possible to achieve ductile shear failures.

2. Fundamentals of the martenistic tranformation

The martensitic transformation is a diffusionless, solid state displacive transformation in which the atoms move cooperatively and is normally accompanied by shear stresses that deform the structure homogeneously and that give rise to a change in the crystal structure as well as the associated volume [22]. Because it is a diffusionless displacive transformation, the new phase is constituted through small coordinated displacements of the atoms, where the displacements of neighboring atoms are smaller than the original interatomic distance. That is, two adjacent atoms will continue to be neighbors after the transformation and will conserve the atomic composition and the order of the initial phase. Although the variation in the relative position of the atoms is very small, the coordinated movement of all of the atoms leads to changes in volume and may bring about significant macroscopic deformations. Moreover, the diffusionless property of the martensitic transformation means that this can be obtained almost instantaneously at low temperatures where the diffusive movements of the atoms are negligible.

In the alloy used in this research, the martensitic transformation can be produced by changes in temperature or by the action of stresses (mechanical induction). In the former case, the martensitic transformation takes place within a finite interval of temperatures, during which there is a coexistence of the two phases: austenite and martensite. The martensitic transformation, or forward transformation, is induced upon cooling the austenite phase (high symmetry and stable at high temperatures) and consists of the appearance of the martensite phase (low symmetry and stable at low temperatures). In the absence of applied stresses, the temperature at which the process begins is known as M_s (martensite start), whereas M_f (martensite finish) is the temperature at which the transformation finishes. If the temperature is appropriate for the material to be in martensite ($T < M_f$), the reverse transformation can be induced by heating the material. Analogously to the above, the formation of austenite will start at temperature A_s (austenite start) and will finish at temperature A_f (austenite finish). The transformation shows thermal hysteresis; that is, the forward and reverse transformations do not take place at the same temperatures. These thermal properties of the transformation are shown in Fig. 2 in which, for a cooling and heating cycle, the percentage of martensite with respect to the total transformable material is represented as a function of temperature. Although not shown in Fig. 2, some SMA may show an intermediate phase, called the R-phase [23].

If the initial temperature is greater than A_f, the alloy will be in austenite phase and the stress-strain diagram may show pseudoelasticity (or superelasticity). In this case, the typical stress-strain diagram is made up of an initial elastic phase until σ^{Ms}, as shown in Fig. 3, with the initial elastic modulus of the austenite, followed by an approximately horizontal pseudo-plastic phase between σ^{Ms} and σ^{Mf} (Fig. 3), in which the phase transformation from austenite to martensite is produced by mechanical induction. After reaching σ^{Mf}, the alloy starts another elastic phase with the initial modulus of the martensite. At any point on the stress-strain diagram represented in Fig. 3, upon unloading, the material will return to the origin of the diagram without permanent strain through a hysteresis loop that dissipates energy, producing a damping effect. If, in this latter case, the stress were to continue increasing after the elastic phase of the martensite, a plastic branch of martensite would be produced that is irrecoverable upon unloading, a phenomenon not represented in Fig. 3. In the case in which the SMA is in austenite phase under the operating temperatures pseudoelasticity takes

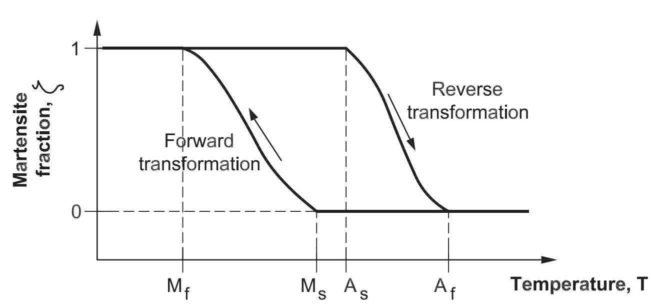

Fig. 2. Schematic phase transformation in SMAs according to temperature.