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Superelastic shape memory alloy cables for reinforced concrete applications

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HIGHLIGHTS

- Relatively large-diameter Ni-Ti cables characterized for their use in RC members.
- Uniaxial tensile tests at different temperatures and loading rates performed.
- Bonding tests between the cable and conventional concrete carried out.
- The cables have been used to reinforce two small scale concrete beams.
- Modulus of elasticity should be increased by adjusting the alloy or heat treatment process.

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ABSTRACT

The research on shape memory alloys (SMAs) has attracted a lot of attention in recent years for different structural engineering applications. In this paper the performance of relatively large-diameter Ni-Ti SMA cables is depicted for their use in reinforced concrete applications. The cable was characterized through a complete experimental program, including electrical resistance tests to determine the phase transformation temperatures, monotonic uniaxial tensile tests at different temperatures and loading rates, and cyclic tests to quantify the amount of strain ratcheting. Moreover, bonding tests between the cable and conventional concrete were performed. Lastly, the cable was placed inside real beam specimens to work as longitudinal reinforcement. The low modulus of elasticity of the SMA cables used here was a limiting factor that needs improvement, but the good strain recovery of superelastic SMA cable presents novel and untapped opportunities for its use as reinforcement in concrete.

1. Introduction

Shape memory alloys (SMAs) are singular materials that have the ability to achieve high deformations and to return to a predefined shape after either mechanical unloading or upon heating above an activation temperature. SMAs are considered smart materials because of this distinctive characteristic and are regularly used in different fields and industries such as aviation, surgical medical equipment, and implants [1]. In terms of structural engineering, there are three key properties of SMAs: superelasticity (or pseudo-elasticity), shape memory effect (SME) and damping capacity. Superelasticity is the phenomenon whereby SMAs may be able to undergo large non-linear deformations and, despite these, return to their original shape upon unloading. Shape memory effect refer to the phenomenon whereby SMAs are capable of returning to a predefined shape upon heating. The damping capacity is the ability of these alloys to convert mechanical energy into thermal energy and, thereby, possibly reduce movements or vibrations of a structure. All these properties are the result of thermoelastic martensitic transformations.

The interesting properties of SMAs have inspired the research of possible applications of these alloys in the field of civil engineering [2–9]. For some alloys, such as Ni-Ti, the manufacturing of SMA cables is a promising way to resolve longstanding impediments to economically realizing large scale SMA elements [10,11], although some researchers have already successfully used 12–32 mm diameter SMA bars [12–15]. By leveraging the highly optimized manufacturing processes currently available for wire, the cable form results in a large-force SMA element with superior properties for substantially less cost than a monolithic bar of

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comparable size [10]. Moreover, conventional steel cables are a very common construction product.

The study of the mechanical properties of SMA cables is still in an incipient stage. Reedlunn et. al. [10,11] studied the superelastic behavior of two Ni-Ti cable constructions, a 7 × 7 right regular lay and a 1 × 27 alternating lay. The external diameter of the cables studied were 2.475 mm and 1.582 mm. Ozbulut et al. [16] explored the performance of a 8 mm diameter Ni-Ti cable for its potential use in civil engineering, focusing in cyclic uniaxial tests. Carboni et al. [17] studied the hysteresis of multi-configuration assemblies of Ni-Ti and steel strands.

In this paper, an 8 mm Ni-Ti cable specifically manufactured for this study was characterized through a complete experimental program, including electrical resistance tests to determine the phase transformation temperatures, uniaxial tensile tests at different loading rates and temperatures, a cyclic test to quantify the shakedown behavior, and a test to ultimate failure. Moreover, bonding tests between the cable and conventional concrete were performed to measure the bonding properties. Lastly, the cable was placed inside real beam specimens and shown to work as longitudinal reinforcement.

2. Thermo-mechanical characterization of the Ni-Ti cables

2.1. Materials

Relatively large superelastic Ni-Ti cables were provided by Fort Wayne Metals Research for thermo-mechanical characterization. The cable specimens were provided in 305 mm (12 inch) lengths, each consisting of 49 wires (each of 0.885 mm nominal diameter) in a conventional 7 × 7 cable construction with about an 8 mm outer diameter. This is a hierarchical structure consisting of seven wires (six wires wrapped helically around a central wire) within each strand, and seven strands (six strands wound around a central straight strand) in the entire cable. The Ni-Ti wires were superelastic at room temperature, indicating a slightly Ni rich chemical composition (50.95 at.% Ni, certified by the manufacturer). The precise heat treatment was not released by the manufacturer, but after being wound into the 7 × 7 structure, the wires were shape set at an aging temperature (typically near 500 °C) to maintain their helical forms and avoid unwinding at room temperature.

Electrical resistance tests were performed to determine the phase transformation temperatures of Ni-Ti material. The experimental technique used was four wire alternating current (a.c.) impedance measurements at a frequency of 686 Hz [18]. The real part of the impedance R was measured by means of a lock-in amplifier, which provided high resolution measurements. The temperature range analyzed was from −190 °C to 80 °C. More information about the test setup and the interpretation of the results may be found in [18]. Fig. 1 provides the results, showing an austenite finish temperature of $A_f = 43$ °C and a martensite finish temperature of $M_f = -148$ °C. Note that the A_f temperature is slightly high according to the Ni content of the alloy declared by the manufacturer. A third martensitic phase, called the R-phase (rhombohedral), was detected in the test during cooling between 43 °C and 0 °C, the presence of which is common in commercial Ni-Ti alloys, arising from residual stress fields and dislocations in cold worked/heat treated alloys [19].

The cables used here were quite similar to one of the cables used in the study by Reedlunn et al. [10,11] provided by the same manufacturer, although those used smaller wires (0.27 mm wire diameter). Despite using, in this study, a different technique to establish the transformation temperatures, it is expected that the differential scanning calorimetry (DSC) thermogram of Fig. 3a in Reedlunn et al. [10] could be also representative, after about a 20 °C shift (increase), of the transformation temperatures of the cables used in this study. The DSC thermogram from Reedlun et al. [10] also shows the presence of the R-phase. After heat treatment by the manufacturer and allowed to cool, the material began to transform from austenite to R-phase at 43 °C, thereby leaving a mixture of austenite and R-phase at room temperature. The as-received condition, therefore, was not fully austenite, which although it is often ignored in other applications (and models), it actually does affect the initial mechanical response of the cables shown later.

2.2. Thermo-mechanical experiments

The experiments performed for the thermo-mechanical characterization of the SMA cables explored various aspects of their mechanical behavior, including their strain rate sensitivity, temperature dependence, core wire behavior, cyclic shakedown, and

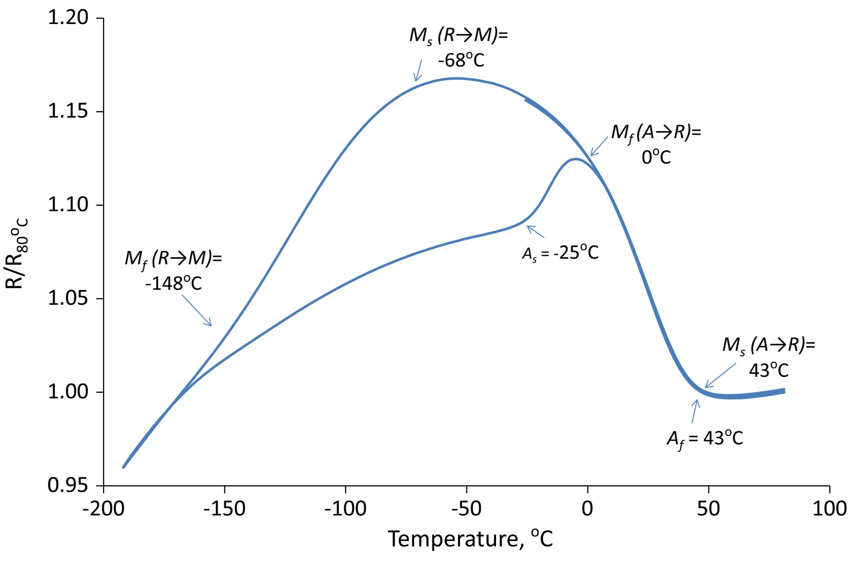

Fig. 1. Temperature dependence of resistance for a sample of the cable. Data are normalized to the value of resistance at 80 °C.