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Shape memory alloy CuAlBe strands subjected to cyclic axial loads

J.F. Beltran, C. Cruz, R. Herrera, O. Moroni *

Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas, Beaucheff 850, Santiago, Chile

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ABSTRACT

Structural cables are composed of wires helically wound into strands, which, in turn, are wound around a core. They have high redundancy and can be used to carry large tensile forces in many civil engineering structures. Better dissipation and/or recentering capacity can be expected if the cable is composed of shape memory alloy (SMA) wires in the austenite phase. Tensile tests were performed on strands made of CuAlBe SMA wires to characterize their behavior and demonstrate their potential utility as adaptive or resilient tension elements. In particular, equivalent viscous damping and forward-transformation and maximum stresses were determined for different strain amplitudes. Nearly ideal superelastic properties were obtained up to 3% axial strain. The equivalent damping increased with strain, reaching a value of 4% for a strain amplitude of 5%. Strand experimental results were used to validate a two-dimensional numerical model developed to estimate the strand response to axisymmetric loads within the superelastic deformation range. The model relies on the linearization of the wire geometry and on a multilinear CuAlBe wire stress–strain relationship. The proposed model adequately predicts the maximum strand stress and the residual strains for different strain amplitudes.

1. Introduction

Shape memory alloys (SMAs) are metallic alloys that are able to recover their original shape through a phase transformation in the material caused by the imposition of a temperature (shape memory effect) and/or stress field (pseudoelasticity or superelasticity). These unique thermomechanical properties have made SMAs a promising material for orthodontics, medical, and engineering applications. Basically, there are two phases associated with SMAs, namely the austenite phase and the martensite phase. Austenite is stable at high temperatures and low stresses whereas martensite is stable at low temperatures and high stresses. Four temperatures define the phase transformation limits: martensite start (M_S), martensite finish (M_f), austenite start (A_s), and austenite finish (A_f). Copper-based SMAs possess thermomechanical properties that make them ideal for energy dissipation and recentering devices for structural applications. However, adequate dissipation and recentering characteristics have only been achieved for small-diameter SMA wires and rods tested as single elements in tension, or in small-scale models tested in shaking tables [1–5]. Attempts to achieve the same characteristics for larger sizes required in real structures have been unsuccessful, due in part to the large variability in mechanical properties, depending on the manufacturer and thermal treatment used [6,7]. This variability makes it difficult to define representative material properties, needed for the design of a real structure.

The use of structural cables made of small-diameter SMA wires seems to be an alternative application of this material to civil structures. Cables have high redundancy and can be used to carry large tensile forces. Improved dissipation and/or recentering capabilities can be expected, if the cable is formed by SMA wires in the austenite phase.

Few tests results have been reported in the literature on SMA cables subjected to axisymmetric loads. Reedlunn and Shaw [8] conducted experiments on two commercially available Nitinol cables. The specimens were uniaxially loaded in tension, and infrared imaging was used to monitor transformation activity. The elongation rate was rather low. The response qualitatively matches the typical behavior of NiTi wires when the helix angle is low, but it differs substantially for a larger helix angle. In the latter, the hysteresis boucles are rather small and so is the energy loss per cycle. Additionally, in both cases, residual deformations are apparent.

This paper presents results from experimental and numerical studies conducted on strands made of CuAlBe SMA wires. The objectives of these studies were to characterize the behavior of SMA strands and explore their potential utility as adaptive or resilient tension elements. Parallel and twisted strands were uniaxially loaded considering constant and variable strain amplitudes. Then, the equivalent viscous damping (ξ), and forward-transformation (σ_t) and ultimate (σ_u) stresses were determined from the stress–strain curves, for each maximum strain. In addition, strand experimental results were used to validate a two-dimensional (2D) analytical discrete model to estimate the cable

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* Corresponding author.
E-mail address: mmoroni@ing.uchile.cl (O. Moroni).

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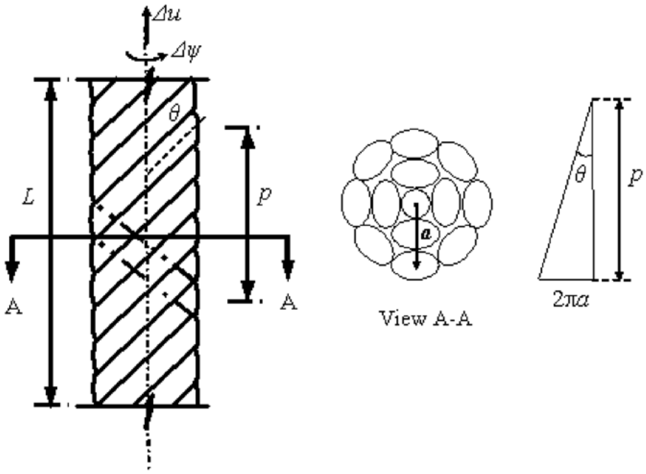

Fig. 1. Cable geometry.

response under axisymmetric loads. In this model, the wire geometry is linearized and, based on the work by Motahari and Ghassemieh [9], a multilinear CuAlBe SMA wire stress–strain curve was used for computational purposes. The original work by Motahari and Ghassemieh [9] was extended to include the residual deformation experienced by each CuAlBe SMA wire after each strain cycle. Comparisons were made between the responses of strands with parallel and twisted configurations, and between the responses of the strands and individual wire.

2. Cable characterization and modeling

A cable is a hierarchical structure constructed by wrapping in a helical fashion a group of thin wires around a single straight wire to form a strand. A group of strands is then laid helically around a straight core to form a cable (twisted wire cable). Strands can be wrapped around the core in concentric circles to form what it is called the layers of the cable. For a cable subjected to axisymmetric loads, it is assumed that the initial and deformed configurations of the wires can be described by a circular helix. Hence, three geometric parameters are needed to describe a wire configuration: the helix radius (a); the projected length of the rope component on the core axis (L); and the pitch distance (p), as shown in Fig. 1. The helix radius is the distance measured from the core axis to the centerline of the wire and the pitch distance of a wire is the distance along the core component, measured for a variation of a swept angle from 0 to 2π.

A cable can be a critical component in many engineering applications, including cranes, lifts, mine hoisting, bridges, electrical conductors, offshore mooring, and so on. Different classes of cables, suited for different purposes, have a different number and arrangement of rope elements within the cable cross-section, and the cable elements can be made of different materials. Each field of cable application has developed a specific body of knowledge, based on extensive testing and field experience, leading to empirical rules for each particular application. Unifying these empirical rules under some general mathematical and mechanics-based theory would allow a better understanding, and in the long term, a better prediction of the mechanical behavior of cables than current methods permit. In addition, a unified modeling approach can help reduce the need for expensive tests under a variety of operating conditions. Thus, due to their extensive use and the need to predict their behavior, several researchers have developed analytical models to estimate the cable response based on the material properties and the geometrical arrangement of the wires [10,11].

Several 2D mathematical models are currently available to predict the response of metallic and synthetic-fiber cables subjected to axisymmetric loads. These models can be divided into two categories according to their formulation: discrete models, in which equations are established for each individual wire and then assembled to obtain the response of the cable; and semi-continuum models, in which each wire layer is replaced by a transversely isotropic layer. In this study, emphasis is placed on discrete models, which are the most commonly employed in numerical studies. According to Jolicoeur and Cardou [12] and Cardou and Jolicoeur [10], current discrete mathematical models for predicting metallic cable response can essentially be divided into two categories, depending on the types of hypotheses employed: (a) fiber models, in which the wires can develop only tensile forces [13–18]; and (b) rod models, which are an extension of the fiber model, in which the wires can develop tensile and shear forces, as well as bending and twisting moments [19–25].

A major contribution to discrete fiber models has been made by Leech [26,27], for the case of synthetic-fiber cables. This discrete fiber model considers the hierarchical structure of a cable's geometry, and it addresses the effects of frictional forces, transverse deformation of the cable cross-section, heat generation due to fiber hysteresis, and fatigue on the cable behavior [28]. Beltran and Williamson [29,30] have presented a discrete rod model to simulate synthetic-fiber cable responses under axial loads. This model relies on previous models by Costello [22] and Leech [27], but focuses on taking into account the degradation of mechanical cable properties as a function of loading history and estimating the effect of broken cable elements on the overall cable response.

3. SMA constitutive models

During the last two decades, a lot of research has been conducted to develop SMA constitutive models. Most of these models can be classified in the following two categories: micromechanics-based models and phenomenological models. Micromechanics-based models give a constitutive relation for a single grain and then, through the use of averaging techniques, the constitutive relations for a representative volume element (RVE) are obtained. Although these models provide valuable information about the phase transformation process, they require a large amount of numerical computation to be performed and they are not easily applicable at the structure level. Thus, the use of such models to estimate the overall response of SMA structures is limited (see, among others, [31–33]). Phenomenological models are built on the principles of thermodynamics with internal variables to describe the material behavior and/or direct curve fitting of experimental data. These models are quite accurate in predicting the uniaxial response of SMAs and can be easily integrated into numerical algorithms developed to analyze structural systems (e.g. the finite element method) (see, among others, [34–37]).

4. Experimental procedure and results

Four 15 cm long strand specimens were constructed from 0.5 mm diameter CuAlBe wires, furnished by Trefimétaux, France. The nominal composition of the wires was Cu–11.8 wt%Al–0.5 wt%Be. The phase transformation temperatures reported by the manufacturer were $M_f = -47$ °C, $M_s = -18$ °C, $A_s = -20$ °C, and $A_f = 2$ °C. Since ambient temperatures for civil engineering structures are usually greater than the A_f transition temperature of 2 °C, the material was expected to operate within its superelastic range.

Based on previous research [1], it was decided to heat the wires at 700 °C for 20 s, which resulted in a nominal grain size of 60 μm, as shown in Fig. 2. Two specimens were formed by 6 wires wrapped around a single straight wire, followed by 12 wires