STATIC TESTS OF AN ACTIVE COMPOSITE BEAM: EPOXY REINFORCED BY TRAINED Ni-Ti SHAPE MEMORY WIRES

Rômulo Pierre Batista dos Reis, soromulo@hotmail.com
Luiz Fernando Alves Rodrigues, luizalvescg@yahoo.com.br
Marcio Diniz da Silva, marciodinizdasilva@gmail.com
Carlos José de Araújo, carlos@dem.ufcg.edu.br
Multidisciplinary Laboratory on Active Materials and Structures
Department of Mechanical Engineering
Universidade Federal de Campina Grande
Caixa Postal: 10069, Cep: 58109-970
Campina Grande – PB, Brazil

Abstract. *In this work, an epoxy beam reinforced by Ni-Ti shape memoy alloy (SMA) wires was developed and experimentally studied. This active composite contains five pre-trained Ni-Ti SMA wire actuators, evenly distributed along the neutral plane of the epoxy beam,which can be activated by resistive heating. The results of different ways for electrical activation of the active composite in a simply clamped mode are discussed. A thermal buckling effect was verified and the temperature – deflection behavior demonstrate how the shape recovery forces affect the active composite beam.*

***Keywords**: Shape memory alloys, smart composites, epoxy beam, Nitinol.*

1. INTRODUCTION

Shape memory alloy (SMA) thin wires are linear actuators that can be embedded in simple polymeric resins and in more complex systems, like prepregs resin matrix products, to develop active hybrid composites. These SMA hybrid composites (SMAHC) can provide structural vibration suppression and control of natural frequencies (Lau *et al*, 2002; Zhang *et al*, 2006), enhancement of mechanical strength (Shimamoto *et al*, 2004), damage suppression (Xu *et al*, 2003), thermal buckling and post-buckling response (Lee & Choi, 1999), structural acoustic control (Saunders *et al*, 1990), impact energy absorption (Kiesling *et al*, 1996), and many others important tasks. These smart effects are due to the large increase of the elastic modulus and/or internal stresses generated during a moderate heating of the SMA embedded wires. Although denominated in the literature as smart composites, the possible smartness of these special composites is still a controversy point (Michaud, 2004).

Design of these modern composites almost always incorporates, besides Ni-Ti SMA thin wires, others reinforcing fibers, like glass, carbon and Kevlar fibers (Wey *et al*, 1998). When SMAHC is manufactured from pure polymeric resins with embedded SMA wires, epoxy and polyurethanes have been reported (Bruck *et al*, 2002; Umezaki, 2006). Although considering your relative fabrication simplicity, composites done with pure resins were little studied when compared those obtained from commercial prepregs.

In this work, an experimental study concerning the electrical actuation of a SMAHC cantilevered beam is presented. The designed active composite beam consists of a pure epoxy resin with five pre-trained Ni-Ti wires along the neutral plane of the beam. The tip deflection of the beam by thermal buckling effect was verified for different electrical activation modes of the Ni-Ti SMA wires.

2. EXPERIMENTAL PROCEDURE

The active hybrid composite developed in this study consists of a simple epoxy resin matrix reinforced by unidirectional pre-trained Ni-Ti wires. It was used a SQ 2001 epoxy resin mixed with the SQ 3131 hardener, both supplied by Silaex Inc. (Brazil), in the proportion of 4:1 in mass. A Ni-Ti binary SMA wire of 0.29 mm in diameter, named alloy M, was obtained from Memory-Metalle Inc. (Germany).

2.1. Training and characterization of the Ni-Ti SMA wire

Before fabrication of the active composite beam, the Ni-Ti SMA wires were stabilized by training using a thermal cycling under constant load procedure. Firstly, the as-received Ni-Ti wire was annealed at 400 ^{o}C for 900 s. Two meters of the heat-treated Ni-Ti wire under a dead weight corresponding to a tensile stress of 200 MPa was submitted to 1000 heating and cooling cycles (contraction and expansion) using electrical resistive heating, as indicated in Fig. 1. At the end of this training process it was verified a plastic strain of the order of 5.7 %.

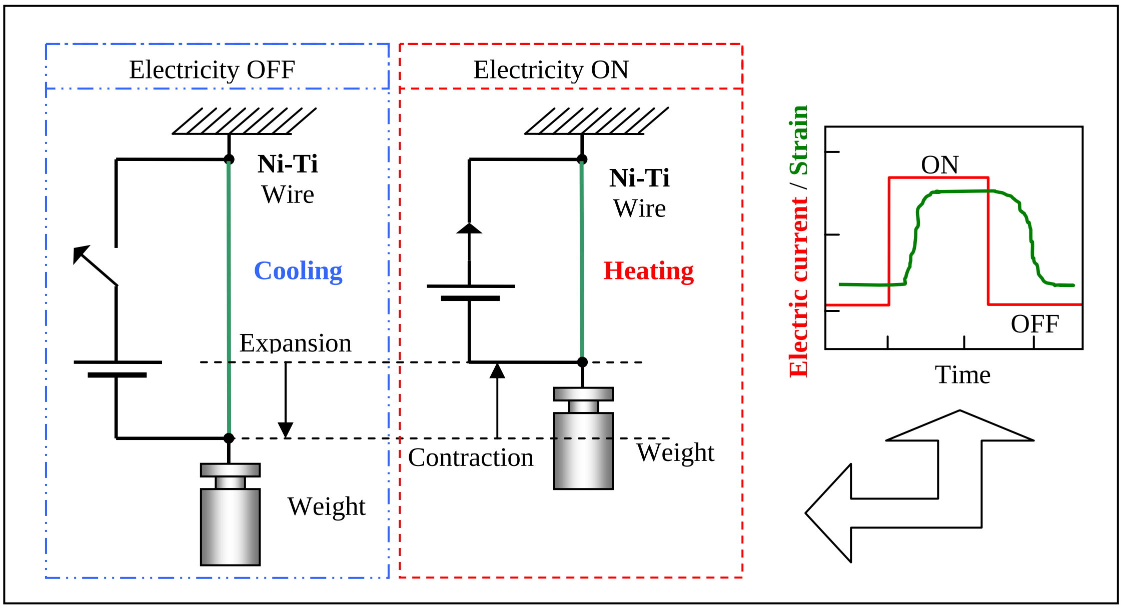

Figure 1. Training schema applied to the Ni-Ti SMA wire before insertion in epoxy resin.

After training, the martensitic transformation at the origin of the shape memory effect (SME) was verified by electrical resistance (R) as a function of temperature (T) in a specific apparatus previously designed for this task (Reis *et al*, 2006). Figure 2 show the $R - T$ curve of the trained Ni-Ti wire indicating the transformation temperatures obtained by the tangent method. It was observed that the wire actuator transforms in two-step during cooling, from austenite to the R-phase (R_s = 49.3 ^oC) and then to martensite (M_s = 28.4 ^oC and M_f = 4.1 ^oC), as is well known from literature (Otsuka & Wayman, 1998; Otsuka & Ren, 2005). Activation by heating occurs in a single step, starting at A_s = 54.0 ^oC and is completed at about A_s = 67.3 ^oC. Then, complete activation of the trained Ni-Ti wire by resistive heating must use an electrical current corresponding to about 70 ^oC.

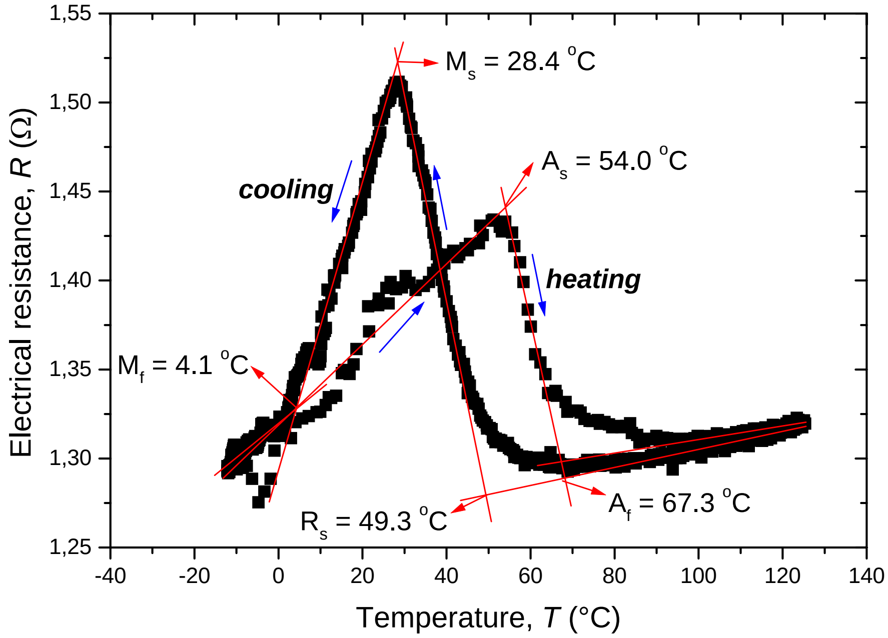

Figure 2. Transformation temperatures of the trained Ni-Ti SMA wire measured by electrical resistance change.

The electrical activation of the trained Ni-Ti wire under constant tensile load was characterized using a simple machine described in a previous paper (De Araújo & Lima, 2005). Figure 3 show the contraction by SME of a Ni-Ti wire sample with 100 mm in length.

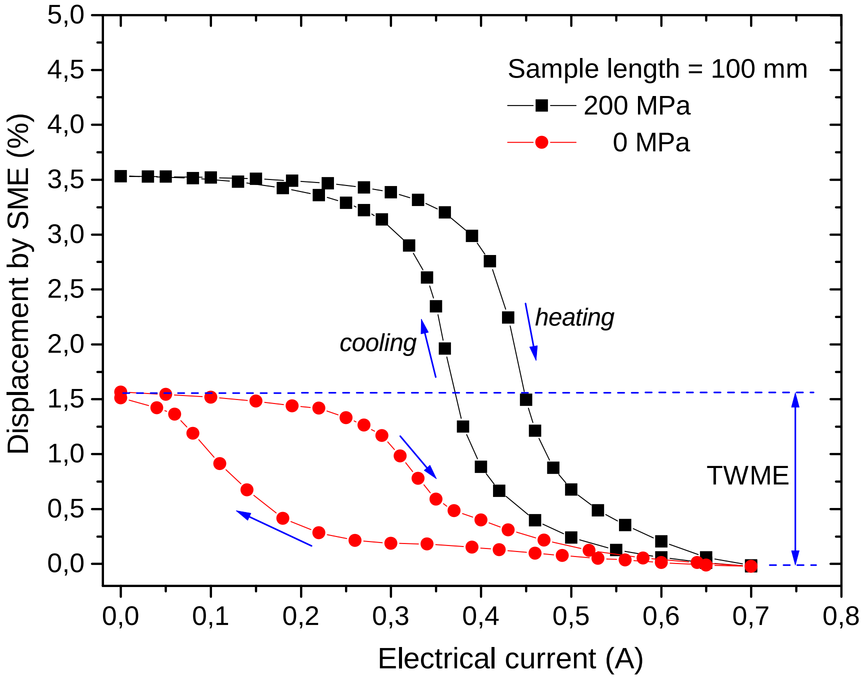

Figure 3. Contraction and expansion of the trained Ni-Ti SMA wire.

It can be verified from Fig. 3 that increasing applied load until 200 MPa improves the Two-Way Memory Effect (TWME) from 1.5 % to 3.5 %. This increase in the TWME is accompanied by a reduction in the electrical current hysteresis. Activation of the trained Ni-Ti SMA wire starts at about 300 mA and finishes at 700 mA.

2.2. Specimen fabrication

The designed active composite beam has 300 x 25 x 4 mm^3 and was manufactured at ambient temperature and pressure by stretching out each trained Ni-Ti SMA individually in an aluminum mold and spilling the epoxy resin on them, as indicated in Fig. 4. This active composite contains five pre-trained Ni-Ti SMA wire actuators, evenly distributed along the neutral plane of the epoxy beam, which can be activated by resistive heating.

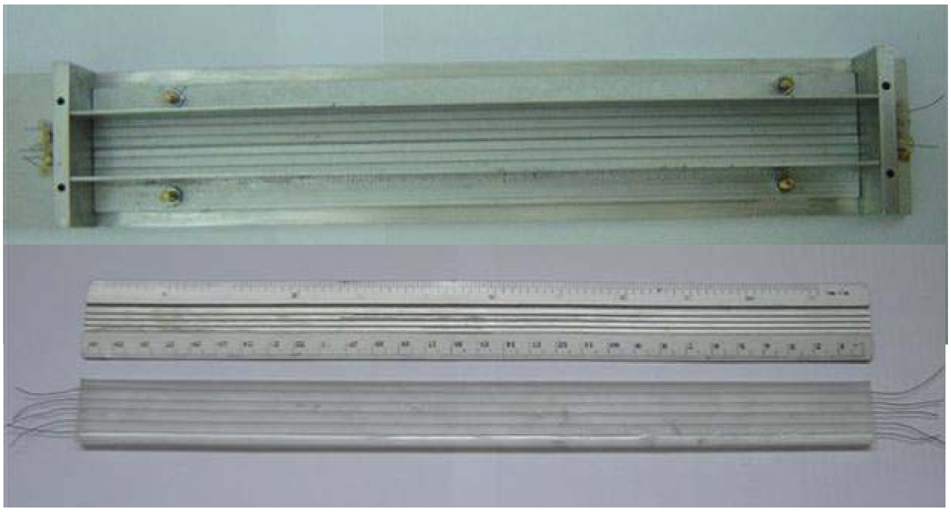

Figure 4. Metallic mold with the manufactured active epoxy-NiTi SMA composite beam.

2.3. Assembly for the static tests

The composite produced as indicated in Fig. 4 was tested in a simply clamped beam mode to verify the thermal buckling effect by electrical resistive heating of the pre-trained Ni-Ti SMA wires. Figure 5 show the test bench developed to drive electrical activation and monitoring of displacement and temperature of the composite beam. The active beam (1) is simply clamped on a rigid magnetic plate and a LVDT displacement sensor (Solartron, DF 5.0 model) (2) is installed to measure the tip deflection of the beam. An electrical plug (3) allows different ways for electrical activation of the Ni-Ti SMA wires while temperature is measured in three different points along the neutral plane of the beam using micro-thermocouples (80 μm in diameter, K type) (4) installed close to the Ni-Ti wires. Resistive heating is done by a programmable DC power supply (Agilent, E3633A model) (5) while displacement and temperatures of the beam and electrical resistance of the Ni-Ti SMA wires are stored in a data acquisition system (Agilent, 34970A model) (6).

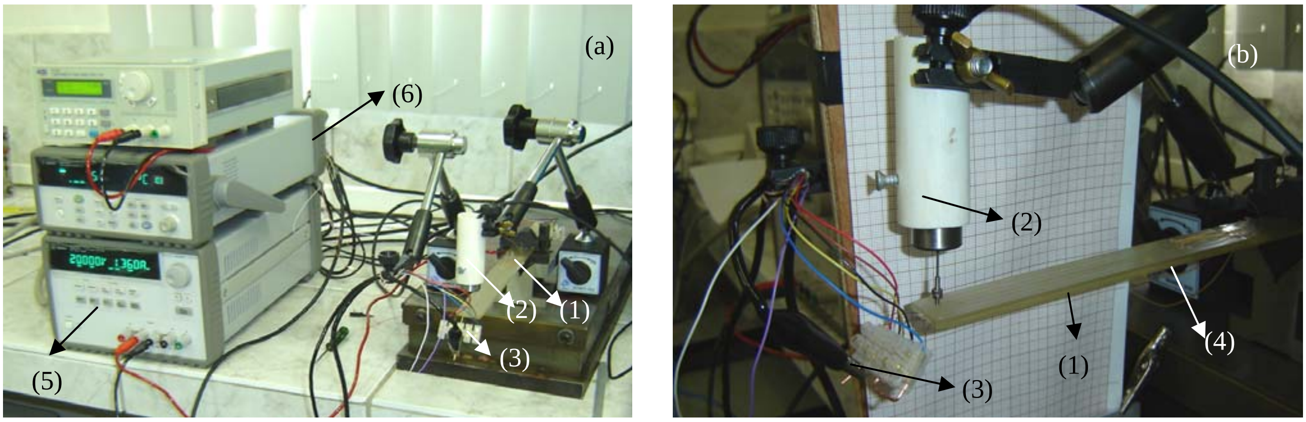

Figure 5. Assembly for static tests of the active composite beam. (a) General view. (b) Zoom view.

Figure 6 show the electrical activation schema for the cantilevered composite beam mounted as in Fig. 5. It is possible to activate one (01), two (02 and 03), three (04 and 05), four (06) or five (07) Ni-Ti SMA wires.

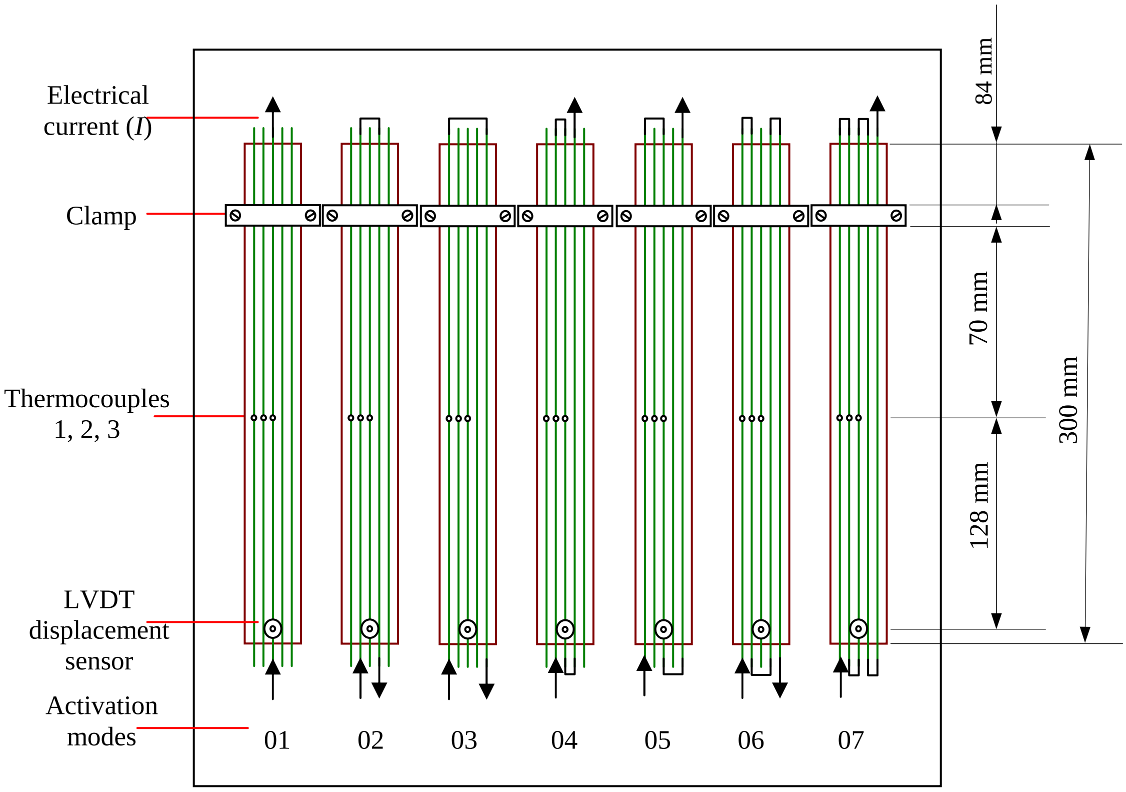

Figure 6. Different modes for electrical activation of the active composite beam.

3. RESULTS AND DISCUSSIONS

Figure 7 show some results of the static characterization of the active composite beam assembled as indicated in Fig. 4.

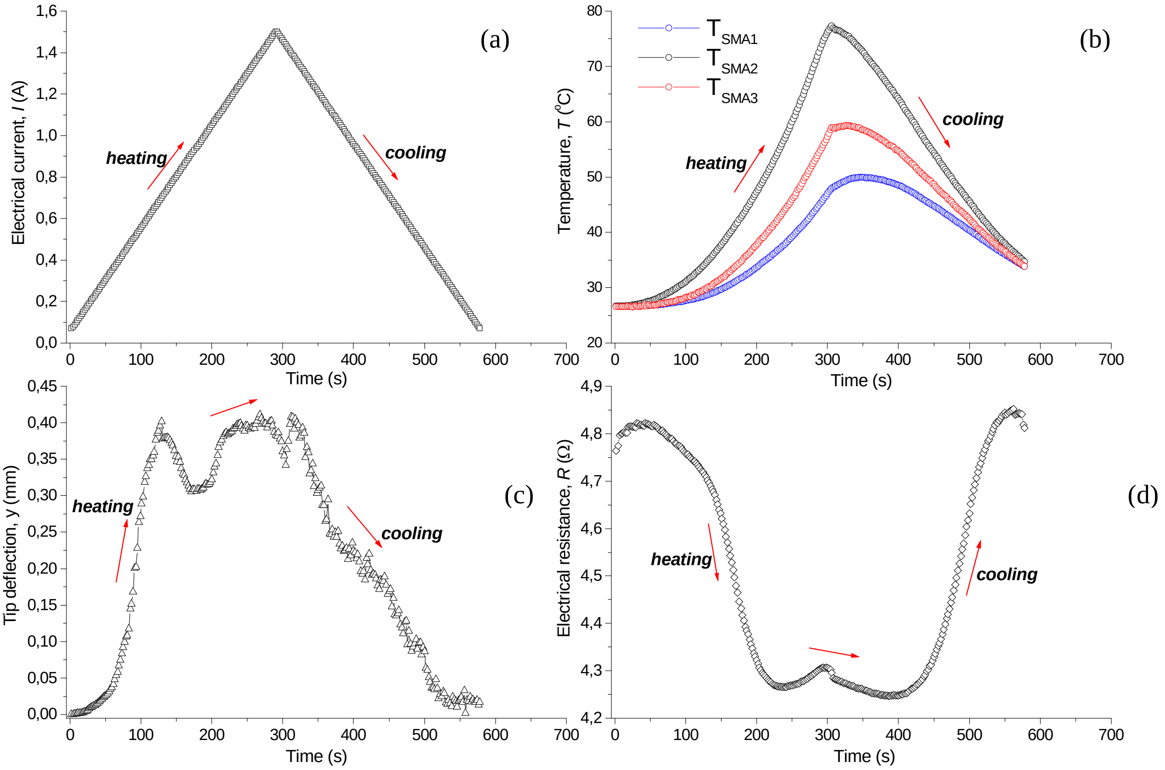

Figure 7. Time response of the active composite beam in the mode 02 (Fig. 5). (a) Electrical current activation wave. (b) Distribution of temperatures in the neutral plane of the beam. (c) Tip deflection of the beam. (d) Electrical resistance change of the Ni-Ti SMA wires during activation.

To drive the composite beam using each activation mode defined in Fig. 6, triangular electrical current waves were produced using the programmable DC power supply. As indicated in Fig. 7(a), to operate in mode 02 it was necessary a maximum current of the order of 1.5 A increasing from zero at a constant rate of 5 mA/s. Figure 7(b) show that using this electrical current wave, temperature of the beam reach about 80 ^{o}C near to the second and fourth activated Ni-Ti SMA wires. However, this activation mode leads to a temperature gradient between the lateral (~50 ^{o}C) and the center (~60 ^{o}C) of the beam, that is, its central strip becomes hotter than the lateral ones. The recovery stresses generated by the embedded Ni-Ti SMA wires cause a reversible buckling effect in the beam, as indicated by the tip deflection plotted in Fig. 7(c).This beam instability has the same sense of the gravity (weight). Figure 7(d) show that transformation of the activated Ni-Ti SMA wires is successfully accompanied by monitoring the ER change.

Figure 8 show the R – I hysteretic behavior of the activated Ni-Ti SMA wires with the corresponding y – I tip deflection response of the active beam. It can be verified that tip deflection of the beam starts quickly at about 400 mA at the same time that the transformation of the Ni-Ti wires, which is characterized by a continuous drops of its electrical resistance. The deflection tends to stabilize at about 0.4 mm between 700 and 1500 mA, when transformation of the Ni-Ti wires is completed. It was also observed that cooling of the active beam by turning off the electrical current passing through the actuator wires induce an almost linear recovery of the tip deflection.

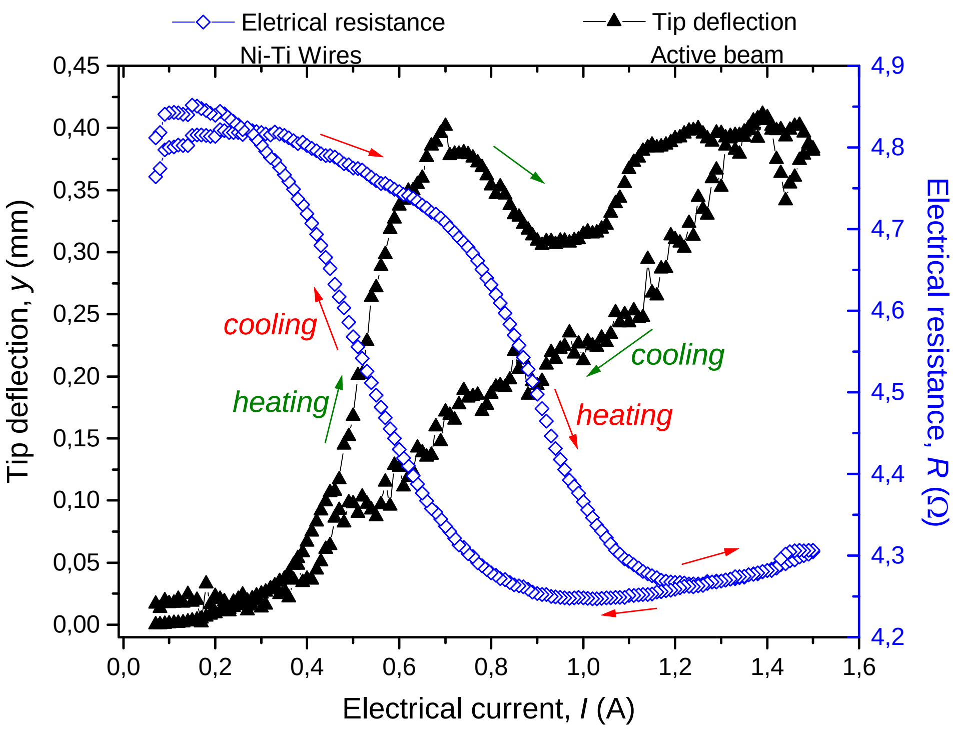

Figure 8. Tip deflection of the active beam and electrical resistance of the Ni-Ti wires as a function of electrical current. Mode 02.

The tip deflection behaviors for the others actuation modes defined in Fig. 6 are qualitatively similar to the ones verified in Fig. 7. Figure 9 show the maximum tip deflection (y_{max}) of the composite beam plotted as a function of the number of activated Ni-Ti SMA wires for each activation mode.

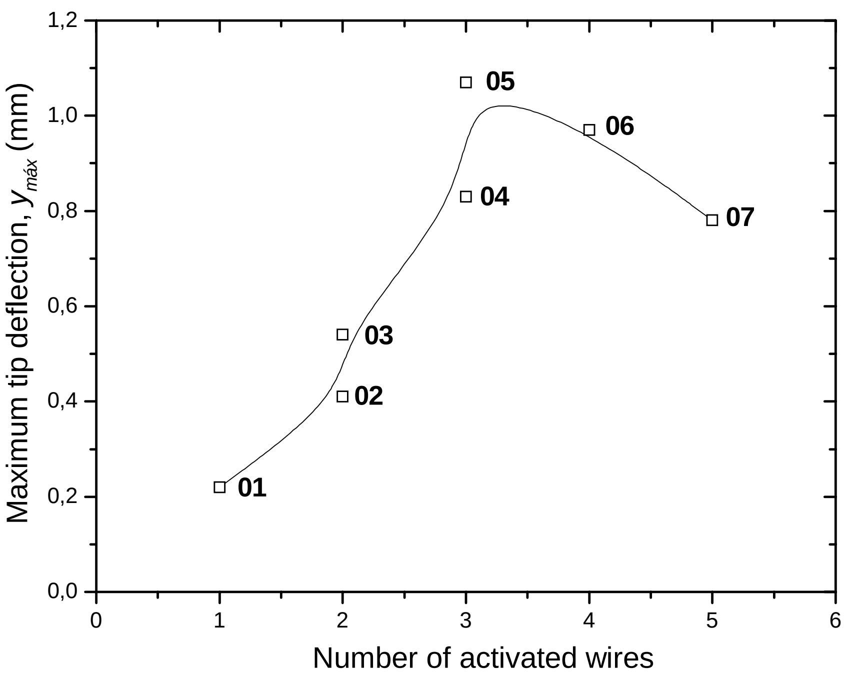

Figure 9. Maximum tip deflection for all actuation modes.

The designed active composite beam present maximum tip deflections between 0.2 and 1.1 mm. However, the tip deflection depends not only of the number of activated wires, but mainly of its distribution in the neutral plane of the beam. Actuation in mode 05 promotes a maximum tip deflection of the active beam. In this mode, three Ni-Ti wires are activated by passing electrical current, similarly to mode 04. However, mode 05 is most favorable because wire activation is done with central (T_{SMA3}) and extremity lateral (T_{SMA1}) wires while in mode 04 the three central (T_{SMA2} and T_{SMA3}) wires are activated, as can be verified in Fig. 10. Then, in mode 05 the two Ni-Ti wires between the central and lateral ones (T_{SMA2}) are also activated (80 ^{o}C) by heat conduction in the transverse sense of the beam (Fig. 10b), contrarily to mode 04 where extremity lateral wires are not fully activated (55 ^{o}C, Fig. 10a).

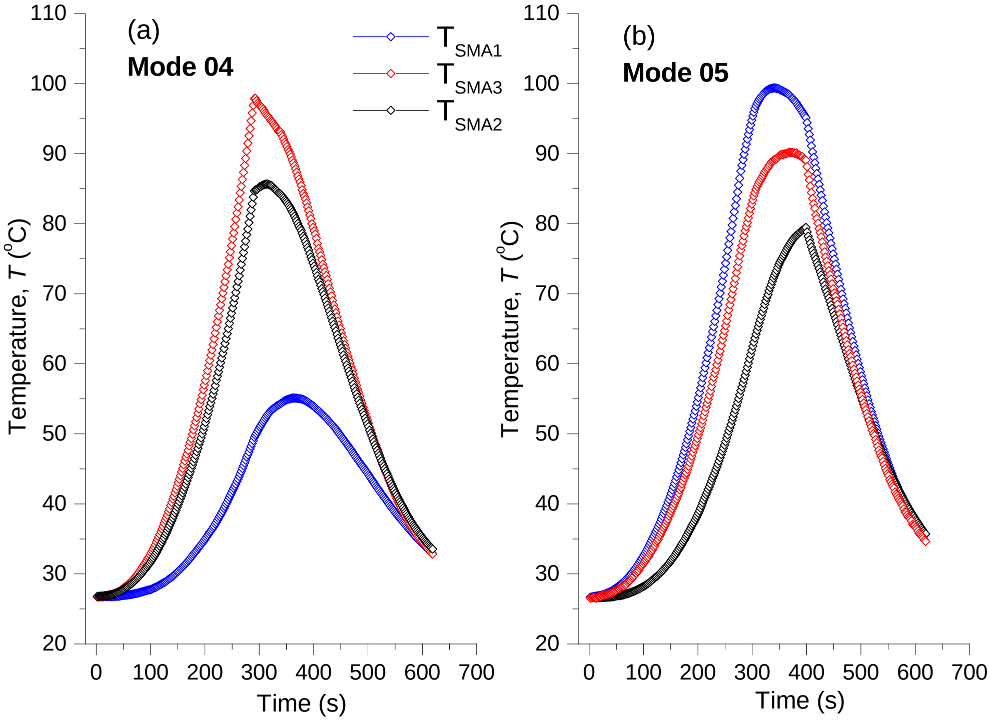

Figure 10. Temperature distributions during activation of the active composite beam. (a) Mode 04. (b) Mode 05.

Figure 9 also show that electrical activation using four and five Ni-Ti wires (modes 06 and 07) lead to a small drop in y_{max} in comparison with mode 05. This behavior was attributed to the fact that a more homogeneous heating of the epoxy resin, as obtained by modes 06 and 07, increase its thermal expansion in the opposite sense of the recover forces originated by the Ni-Ti wires.

4. CONCLUSIONS

The thermal buckling behavior of an active composite beam made of pure epoxy resin with embedded pre-trained Ni-Ti SMA wires was experimentally investigated. The designed beam has five actuator wires evenly distributed along its neutral plane. Seven actuation modes were established and tested in a cantilevered beam way. It was demonstrated that electrical activation of three actuator wires (central and extremity lateral) are sufficient to achieve a maximum tip deflection of approximately 1.1 mm by thermal buckling. It appears that activation using more than three Ni-Ti wires cause an excessive thermal expansion of the epoxy resin decreasing the resulting force on the beam and the corresponding tip deflection.

5. ACKNOWLEDGEMENTS

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