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DEFLECTION OF FLEXIBLE BEAMS USING SHAPE MEMORY ALLOY ACTUATORS

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Abstract: *In this paper, experimental tests concerning the deflection by eccentric buckling of a flexible beam using Ti-Ni shape memory alloy (SMA) wires are described and discussed illustrating the potentiality of these actuators generating forces and displacements. In order to determine these capacities, a simple structure composed of an aluminum beam (25x1x240mm) clamped at one end and free at the other was designed and implemented. The beam can be loaded by weights for different eccentricity values while its deflection is monitored at a specific point located at 75mm from the clamped end using a LVDT displacement sensor. Experimental results for the obtained deflection by applying weights between 0 and 2 kg have demonstrated a good agreement with theoretical previsions. After this characterization, the Ti-Ni-Cu SMA wires (0,29mm in diameter) were trained by a thermal cycling under constant load procedure before its insertion on the beam. The contraction of the SMA wire actuator under 150MPa was of the order of 4,5% while after the training procedure and in the absence of external loads this contraction was reduced for 2,5%. A single trained SMA wire actuator was introduced in different eccentricities of the flexible beam and electrically heated by an AC power source. The results show that forces as higher as 20N can appear in the free end of the beam when an electric power of 0,9W is applied on the extremities of the single trained SMA wire actuator.*

Keywords: *Shape memory alloys, actuators, beam deflection, eccentric buckling.*

1. Introduction

In the last years an increasing attention has been done to the application of induced strain actuators in smart structure technologies (Srinivasan and McFarland, 2001). A variety of these actuators are disposable today, but the more promising are the ones based on the shape memory effect (SME) of metallic alloys and piezoelectric effect (PZE) of some ceramic materials. An overview of the state of the art and engineering research in smart structures and materials was presented recently by Flatau and Chong (2002). Previously strained shape memory alloy (SMA) actuator recover its original shape when heated above a critical temperature. In the case of SMA wire actuators under uniaxial tensile mechanical load, this shape recovery corresponds to a contraction and the actuator provides a useful external mechanical work. However, the thermoelastic martensitic transformation at the origin of this SME phenomenon is characterized by four transformation temperatures (M_s, M_f, A_s e A_f, typically in raising order) describing a hysteresis loop between two crystalline structures (Otsuka and Wayman, 1998). Investigations into structural control applications utilizing induced strain actuation mechanisms have largely focused on vibration and noise suppression and to a lesser degree on altering structural shapes for improved performance (Loughlan *et al.*, 2002). For application of SMA linear actuators in active structures aiming improves active vibration suppression and /or shape control, SMA wires can be incorporated internal or externally to the structure. In the first case, the developed structure corresponds to smart composites (beams, plates or panels) and activation of SMA wire actuators allow to improve static deflection and modal characteristics of the composite (Flatau and Chong, 2002; Sun *et al.*, 2002; Lau *et al.*, 2002; Thompson and Loughlan, 2001; Sun *et al.*, 2000; Ostachowicz *et al.*, 2000). However, external actuators have better control authority since the actuator can be placed at different offset distances from the beam. The moment, caused by the actuation force from the externally line actuator, is much greater than that in a composite beam with an embedded line actuator along the beam and with the same magnitude of the actuation force (Shu *et al.*, 1997). Such a configuration also allows the introduction of fast convection cooling, which is very important in shape control applications that require a high-frequency response of SMA actuators. Rediniotis *et al.* (2002) have employed this configuration to develop an active hydrofoil actuated by SMA line actuators. There are some reported cases of using similar configurations of externally attached SMA wire actuators (Shu *et al.*, 1997; Baz *et al.*, 1995; Chaudry and Rogers, 1991), but it are not numerous comparing with embedded SMA actuator cases.

In this paper, a mainly experimental study concerning deflection of elastic beams by eccentric buckling using an externally placed single SMA actuator wire is performed. The SMA wire is previously trained by a thermal cycling under constant loading procedure before attachment along the beam. The magnitude of the forces appearing at the free end of the beam is estimated comparing deflection produced by electrical heating of the SMA wire with the one measured by applying growing dead weights on the beam.

2. Experimental procedure

2.1. Mechanical structure of the test bench

Figure 1 shows the design and a picture of the mechanical structure developed to test flexible beams actuated by SMA wire actuators. This test platform is essentially composed by a rigid frame *(1)* with a system to adjust eccentricity *(2)* and a special rail *(3)* for positioning the LVDT displacement sensor accommodated in a mobile support *(4)*. The flexible aluminum beam *(5)* having dimensions 25x1x240mm is rigidly clamped on the frame *(1)*. For the displacement versus load characterization, eccentric load is applied using a dead weight connected by a thin nylon wire passing through the eccentricity adjustment system *(2)* until the free end of the beam *(5)*. To activate the beam electrically, without external loads (dead weights), the nylon wire is replaced by the SMA wire actuator attached between the free end and the clamped one.

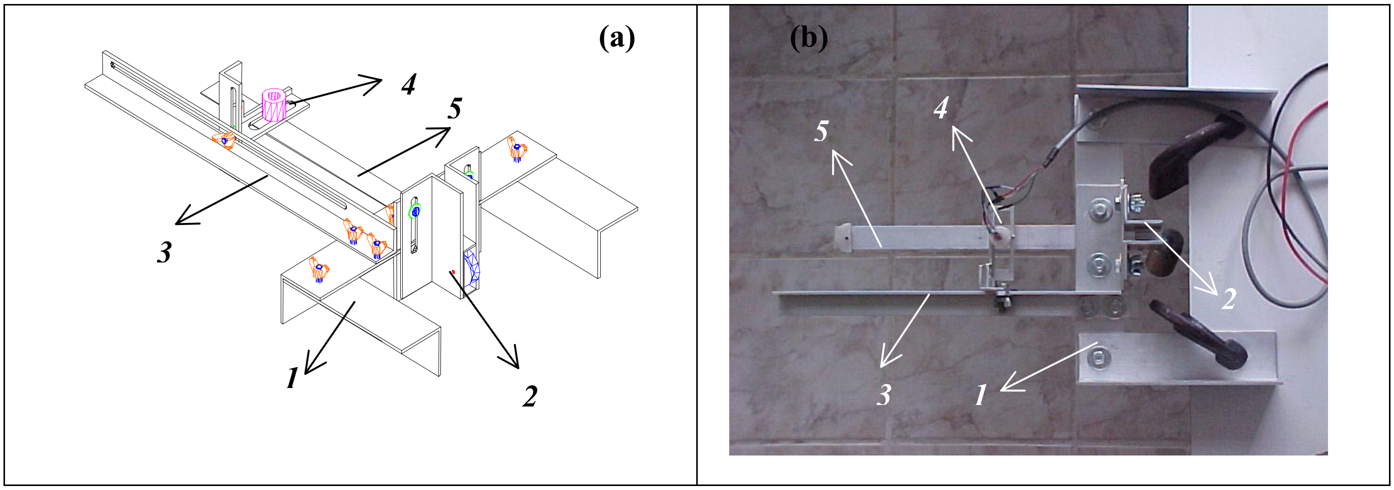

Figure 1 – Mechanical structure of the test platform. (a) AUTOCAD design. (b) Laboratory construction. *(1)* Frame; *(2)* system for eccentricity adjustment; *(3)* rail; *(4)* mobile LVDT support; *(5)* aluminum beam.

2.2. SMA actuators and training procedure

The actuators used in this study are Ti-Ni-Cu SMA wires (0,29mm in diameter), supplied by Advanced Materials Technologies Inc. (De Araújo, 1999). The transformation temperatures measured with a DSC Mettler TA3000 calorimeter are: M_f = 28,0 ^{o}C, M_s = 39,4 ^{o}C, A_s = 46,5 ^{o}C and A_f = 58,0 ^{o}C. The SMA wire to be inserted eccentrically in the elastic beam was previously trained to stabilize its displacement response by electrical heating (contraction). This training procedure consists in 100 heating/cooling cycles with the SMA wire actuator under a dead weight of the order of 10N. In this case, heating is carried out using an AC power source and cooling is due to natural convection in surrounding air. During training, the measured contraction was 4,5% and after that, contraction by electrical heating was reduced to 2,5% in absence of external loads.

3. Results and discussions

3.1. Characterization of the elastic beam and theoretical analysis

Figure 2 illustrates the method used to measure the load versus deflection behavior by eccentric buckling of the beam and the experimental obtained results. In figure 2(a), it can be observed that the dead weight *P* is applied on the beam using a thin nylon wire, which passes trough two fixed acrylic plates. For all cases, the beam deflection *y(x)* is measured at the specific position *x* = 75mm as a function of eccentricity *e*. The response of the beam is shown in figure 2(b). For the theoretical analysis of figure 2(a), the general equation for beam-column-type situations without lateral loading (Benham *et al.*, 1996) was employed:

$$EI\frac{d^4y}{dx^4}+P\frac{d^2y}{dx^2}=0 \tag{1}$$

where *E* is the elasticity modulus, *I* is the *least* second moment of area of the cross-section and *P* is the applied load. The standard solution for equation (1) is

$$y(x) = Asin(kx) + B\cos(kx) + C \qquad (2)$$

where $k = \sqrt{\frac{P}{EI}}$ and *A*, *B* and *C* are constants related to the boundary conditions.

The equation (1) was solved by Chaudry and Rogers (1991) for a case identical to the one described in figure 2(a). The analytical solution found was

$$y(x) = e\left\{\frac{\cos kL - 1}{sinkL}(sinkx - kx) - \cos kx + 1\right\} \qquad (3)$$

Theoretical results obtained by applying equation (3) are plotted in figure 2(b) together with experimental ones and a relative good agreement can be observed. As expected, an identical load causes larger deflection by increasing eccentricity.

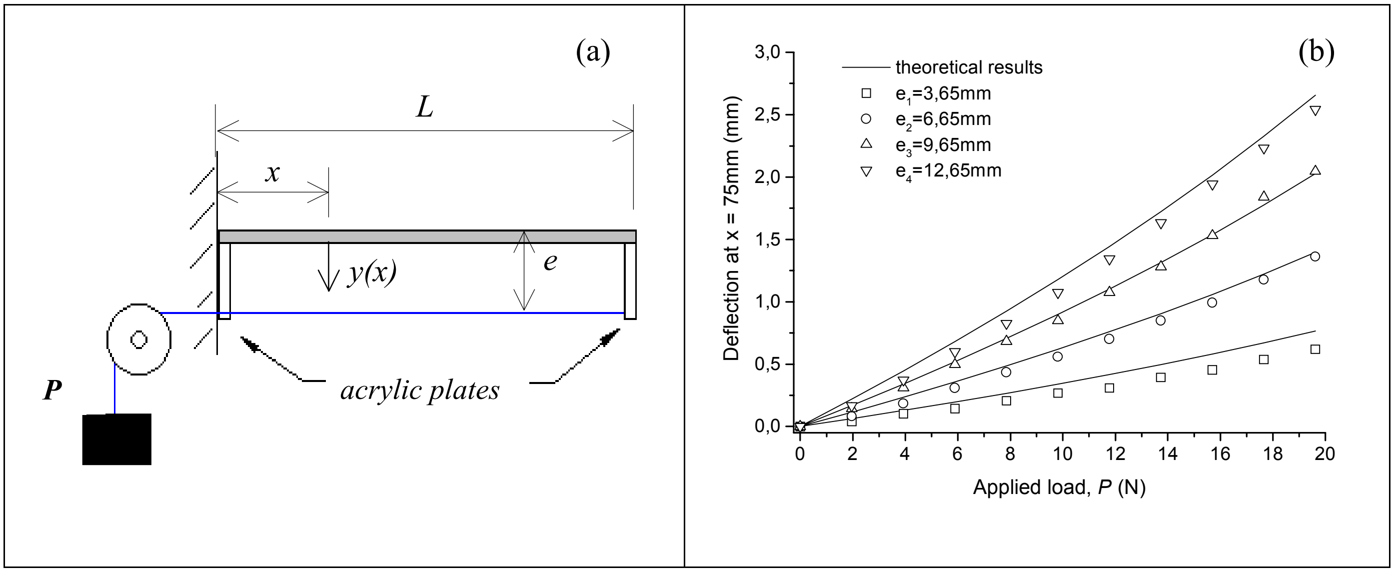

Figure 2 – Load versus deflection in elastic beams. (a) Method for application of the constant load on the beam. (b) Theoretical and experimental deflection response of the beam as a function of the load and eccentricity.

3.2. Activation by SMA actuator wires

After the experimental characterization of the flexible beam described in figure 2, a single trained SMA actuator wire was assembled between the acrylic plates to obtain deflection of the beam by electrical activation. Figure 3 shows a typical deflected aspect of the flexible aluminum beam during electrical heating of the SMA wire. The heat transfer between SMA wire and surrounding air is done by

$$\rho C_p V \frac{dT}{dt} = Ri(t)^2 - hA(T - T_\infty) \qquad (4)$$

where *V*, *A* and *R* are the volume, the surface area and the electrical resistance of the SMA wire, respectively. The specific mass ρ and the specific heat c_p are intrinsic properties of the material and *h* is the convective heat transfer coefficient between the wire and its surroundings at temperature T_∞. The steady-state value of the wire temperature, for a step current *I* when $dT/dt = 0$ is

$$T_{SS} = \frac{RI^2}{hA} + T_\infty \qquad (5)$$

The electrical current (*I*) and voltage (*U*) through the SMA wire was measured for the steady-state and the electrical power (*Pot*) was obtained by

$$Pot = UI = RI^2 \tag{6}$$

thus, equation (5) becomes

$$T_{SS} = \frac{Pot}{hA} + T_\infty \tag{7}$$

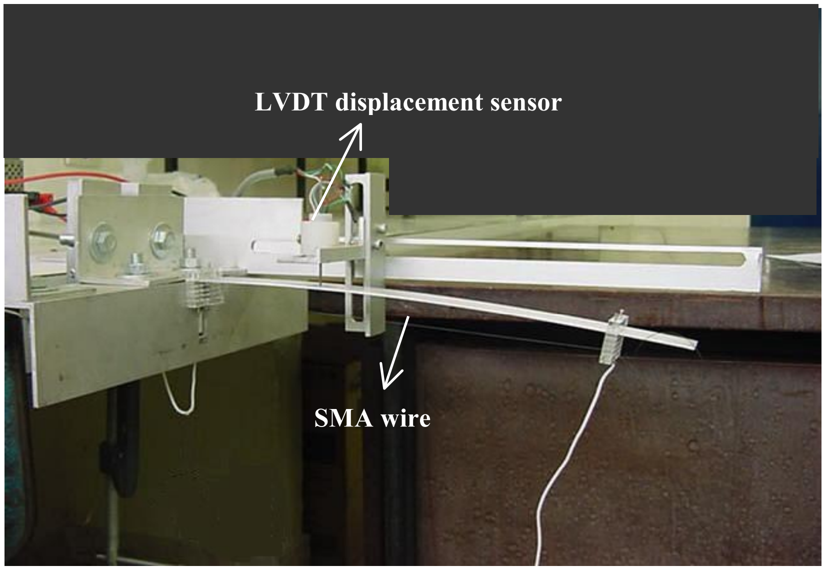

Figure 3 – Deflection of the elastic beam by activation of the SMA wire.

To estimate the SMA wire temperature T_{SS}, the convective heat transfer coefficient h was determined experimentally. Then, the electrical current and voltage were slowly raised until cause a small change in the LVDT signal, indicating that the SMA wire reached the A_s temperature. Therefore, for this minimum electrical power (Pot_{min}), equation (7) can be modified to estimate the h coefficient as follow:

$$h = \frac{Pot_{\min}}{A.(A_s - T_\infty)} \tag{8}$$

From equation (8) for Pot_{min} = 0,125 W, A = 2,186x10^{-4} m^2, A_s = 46,5 ^{o}C and T_∞ = 28 ^{o}C, the estimated h is 30,9 W/m^2.^{o}C. With this h value, the wire temperature for the steady-state T_{SS} can be obtained by equation (7).

Figure 4 shows the deflection of the elastic beam as a function of the external load together with the one obtained by electrical heating of the SMA wire for two values of eccentricity. During these tests, SMA wire temperature estimated from equation (7) reach values between 50 and 150^{o}C. From figures 4(a) and 4(b) it is possible to establish a relationship between applied load and electrical power, as shown in figure 5. As expected from figure 4, a linear relationship is confirmed in figure 5, with slopes practically independent of eccentricity. For the same supplied electrical power, the load appearing at the free end of the beam is higher for smaller eccentricities. However, in this case deflection is always larger for higher eccentricity levels, as can be observed comparing figures 4 and 5. Figure 5 also reveal that forces as high as 20N can be generated at the free end of the beam for a supplied power of about 0,8 and 0,9W. For comparison, Loughlan *et al.* (2002) recorded SMA tensile recovery force curves showing stable recovery forces of the order of 40N for a Ti-Ni wire with 0,3mm in diameter, initially pre-strained 6% and heated up to 100 ^{o}C. Considering that the contraction of the trained SMA wire in absence of applied loads was 2,5%, our results are compatible with the ones presented by Loughlan *et al.* (2002).

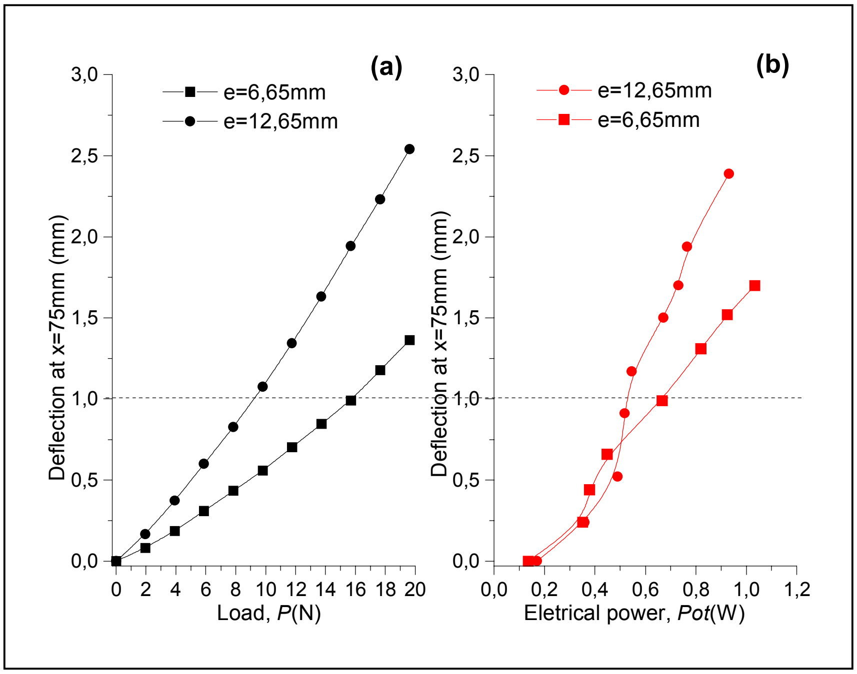

Figure 4 – Deflection of the elastic beam by eccentric buckling. (a) Deflection by application of a dead weight as illustrated in figure 2(a). (b) Deflection by electrical heating of the SMA wire as shown in figure 3.

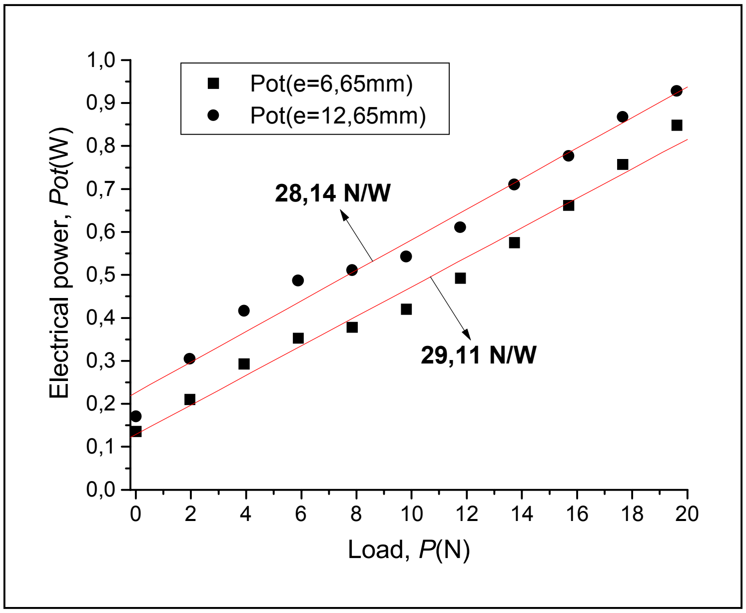

Figure 5 – Conjunction of figures 4(a) and 4(b).

4. Conclusions

An experimental test bench was especially designed to investigate deflection by eccentric buckling of elastic beams electrically activated using SMA wire actuators. In this platform, the actuator is placed externally to the beam and eccentricity can vary between 3,65 and 12,65mm in steps of 3mm. The load versus deflection characterization of the beam has demonstrated a good agreement with theoretical previsions. The conjunction of deflection results obtained by applying constant weights at the free end of the beam with the ones verified by electrical heating of the SMA wire has demonstrated a linear relationship between electrical power and force acting on the beam. Finally, the results show that forces as higher as 20N can appear in the free end of the beam when electric power in the range 0,8 - 0,9 W is applied on the extremities of the single trained SMA wire actuator.

5. Acknowledgments

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