COB-2019-0481

EXPERIMENTAL ANALYSIS OF AN ORIGAMI CELL ACTUATED BY SHAPE MEMORY ALLOYS

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Abstract. Origami structures have an increasing importance on the manufacturing of self-expandable systems applicable in several fields, from medicine to robotics and aerospace structures. Shape memory alloys (SMAs) are smart materials, which can develop recover strain up to 10% and generate high forces for actuation through the coupling of thermal and mechanical domains ,that present an interesting actuation capability for these systems. This paper presents an experimental analysis of an origami structure built with a waterbomb folding pattern. The actuation is provided by Z-shape torsional SMAs actuators heated by joule effect through the application of an electric current. A quasi-static analysis of a unit cell submitted to cyclic thermal cycles is carried out and origami structure movement is analyzed with laser sensors.

Keywords: Origami, shape memory alloys, self-expandable structures.

1. INTRODUCTION

Origami is a word from Japanese meaning *ori* = fold and *kami* = paper. Origami has the objective to generate intricate tridimensional objects from 2D sheet of paper, usually without the use of glue or cuts. Origami design is related to mathematical studies that analyze several possibilities, being exploited to produce complex structures that enables different perspectives for self-expandable systems which can shift from a compact to an elongated shape (Miura, 1994; Tachi, 2010, Miyashita, 2014).

The combination of origami structures with smart materials, especially shape memory alloys (SMAs), have been presenting promising results due to its capacity to recover from large displacements and generate high forces maintaining a low profile and relatively simple construction (Fonseca, 2017; Fonseca, 2019; Kuribayashi, 2006; Lee et al., 2013; Godard, 2003; Felton, 2014).

This paper deals with an experimental analysis of an origami stent strucure, initially porposed by Koh (2014) and numerically investigated by Rodrigues et al. (2017). Waterbomb folding pattern is of concern, and a thermomechanical system of SMA Z-shape torsional springs are employed to provide the drive motion for the actuation.

2. ORIGAMI ANALYSIS

A waterbomb folding pattern, which can be used to build different kinds of origamis as stents and wheels, is considered in this paper. Geometrical relations are based on symmetry hypotesis, where the general behaviour of the structure can be represented by each square cell. Therefore, a single unit cell can be employed for the analysis of a structure composed by several unit cells. Also, all motions and foldings take place on the creases and the cell have rigid facets.

Figure 1a illustrate the unit cell of this pattern, composed of two valley folds (red lines) and one mountain fold (blue line), the angle α_0 determines if the cell is square or rectangular, the length AB equals to L, therefore, $L_2 = L/\tan(\alpha_0)$. Figures 1b and 1c presents different applications for the same fold.
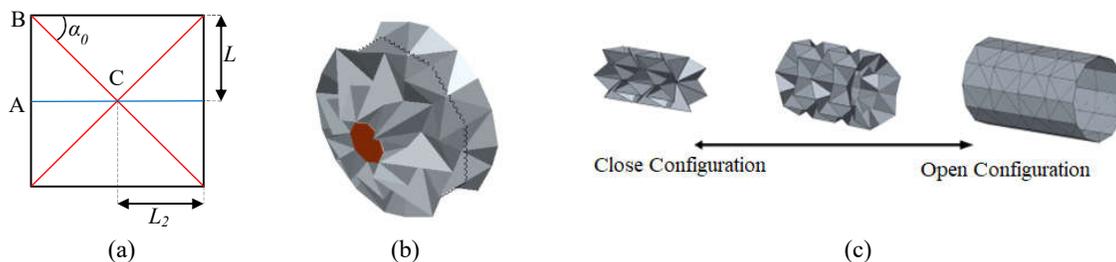
| (a) | (b) | (c) |

Figure 1. (a) Geometric representation of unitary cell. Different applications: (b) Origami wheel (Fonseca, 2019) and (c) Origami stent (Rodrigues, 2017)

The self expandable origami structure analysed has basically three basic configurations: 1- opened; 2- relaxed; and 3-closed. Figure 2 presents the different geometric configurations, where for the opened configuration points A, A_2 and C become colinears. Origami geometrical analysis is monitored through three angles: θ, β and φ. These angles are coupled and, therefore, the whole system can be described as a function of a single angle. Equation (1) presents geometrical relationships expressing φ and β as a function of θ.
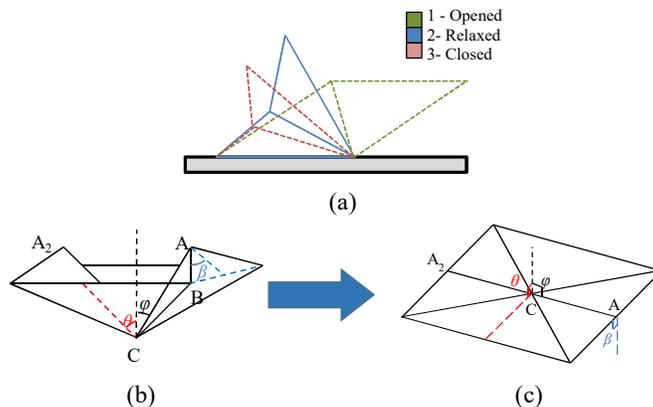

Figure 2. (a) Origami unit cell in three different geometric configurations; (b) Closed origami; (c) Opened origami.

$$\varphi = \arcsin\left(\frac{1-\tan^2(\alpha_0)\cos^2(\theta)}{1+\tan^2(\alpha_0)\cos^2(\theta)}\right) \quad \text{and} \quad \beta = \theta \tag{1}$$

The actuation of the structure is achieved through SMA torsional Z-shape torsional spring actuators. SMAs have the capability to recover a previous known form after a thermo-mechanical loading process. Basically, SMAs present solid phase transformations that can be induced either by mechanical or thermal loadings.

The origami actuation system employs Z-shape torsional actuators, Fig. 3a, composed by a central body with length $L_s=15\ mm$ and diameter $d_s = 0.508$ mm, which generates a torque, based on the pre-load, due to thermal actuation (Koh, 2014). The springs are made of FLEXINOL® Actuator Wire 0.02". The Z-shape torsional spring fabrication process involves the following stages: 1) the wire is fixed to a metal jig (Fig.3b); 2) heat treated at 738.15 K (465°C) for 30 minutes; 3) water-cooled; 4) cut the wire; and 5) deform the central body by a 360° twist. After the process, the wire retains the Z-shape. The jig shown in Fig.3b allows that fourteen springs be prepared at the same time, where black dots represent the position of the bolts, and the red dots mark where each spring is individually cut to the final shape.
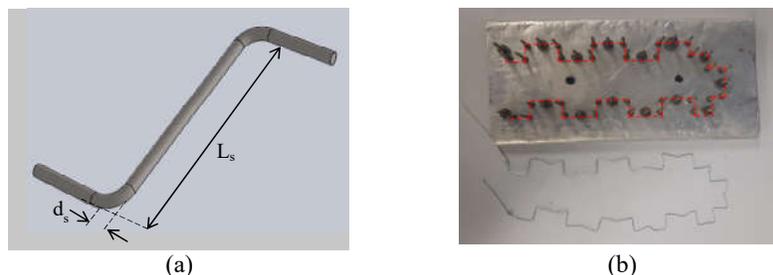

| (a) | (b) |

Figure 3. (a) Torsional SMA Z-shape torsional spring; (b) Pattern of the wire and metal jig

3. EXPERIMENTAL PROCEDURE

Experimental tests are developed considering a unit cell prototype built from paper covered by polyamide, which promotes a thermal insulation from the high temperature present in the actuated SMA Z-shape torsional springs. The creases are made with polyamide in order to reduce the mechanical resistance when folding. Actuation is provided by two pairs of antagonist SMA Z-shape torsional springs. The actuators are fixed as shown in Fig. 4a and 4b. Note that the closing pair is attached to the inner side and the opening pair is attached to the outer, in a way that they never touch each other. L_s section of each SMA actuator is positioned on the median fold and the two arms are attached to the paper, delivering the torque to the link sheets. Actuation is provided by electric current and each actuator pair is connected in series to assure the same current passing by the circuit. The terminals are plugged to a DC Power Supply where the current and voltage on the system are remotely controlled through an Arduino device programed to subject the actuators to cyclic loadings.
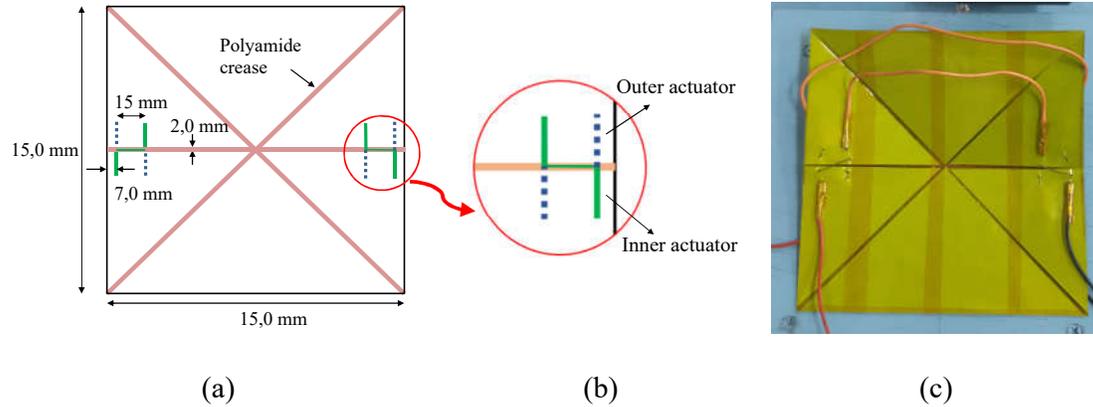

Figure 3. Origami unit cell: (a) Origami unit cell schematic representation; (b) Actuators positioning; (c) Origami prototype.

The actuation of the SMA Z-shape springs is obtained through the application of synchronized on-off cyclic electric current, promoting the origami transition between the three configurations shown in Fig. 2: 1, 2 and 3. Two laser sensors, a MICRO-EPSILON® optoNCDT model and a Baumer OADM 20I4460/S14C model, both with a measuring distance of 100 mm, positioned side-by-side with a 37 mm distance between beams, are used to follow the geometric configuration chances of the origami unit cell by measure the displacement of 2 points in the origami surface, as shown in Fig. 5a. The use of two sensors permit to analyze geometric characteristics of the movement as asymmetries developed in the structure.

The origami is fixed to a wood base and the lasers are positioned at different distances due to each focal point, but at the same height $h = 8$ mm from the base. By measure a distance d, which varies with the actuating of the system, Fig 5b, it is possible to obtain the internal angle δ used to describe the origami unit cell movement:

$$\delta = \arctan\left(\frac{h}{d}\right) \tag{2}$$

Equation (2) is used to represent the internal angle of each side of the origami measured by laser sensors 1 and 2, respectively, δ_1 and δ_2.
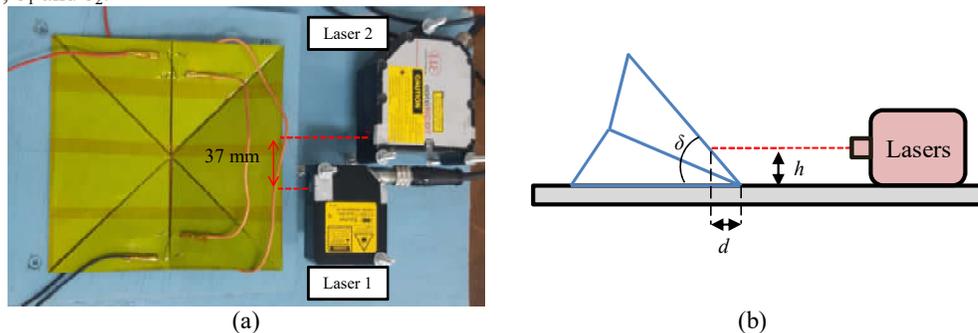

Figure 4. Experimental configuration: (a) Positioning of the laser sensors; (b) Side-view illustration of configuration.

Different cyclic thermal loads are considered in order to verify the open-close process. Thermal actuation is provided through Joule effect using a DC power supply controlled by an Arduino to submit the SMA Z-shape spring actuators to a synchronized on-off cyclic cycles. A initial training process of 50 open-close cycles was applied to the origami unit cell before the experimental test used to analyze the system behavior. An on-off current of 2.5 A is applied, where each pair actuated alternately for 2 min, with a 2 min gap to allow the complete cooling and relaxation of the SMAs before the actuation of the antagonistic pair.

4. RESULTS AND DISCUSSION

The tests were conducted using four different magnitudes of electrical currents: 1.0 A, 1.5 A, 2.0 A, and 2.5 A. For all the test developed, the first cycle of actuation is set to 2.5 A, to establish an equal initial condition configuration. Figure 5 shows the response of the system for each magnitude of current.

Note that, when the opening pair is activated, it increases the angle of the origami and, when the electric current is turned off, it starts to cool and return to a relax configuration. Similarly, when activating the closing pair, there is a decrease on the angle and, when the electric current is again turned off, the origami open and returns to a middle point. An asymmetry is noticeable in all of the tests with one side constantly maintaining a wider angle; a grey dashed line is plotted to reference the mean angle of the structure.

For the lower electric current, the temperature is not high enough to transform the SMA, resulting in an indistinguishable actuation, Fig 5a. For every larger current, the actuation power increases, generating a larger range for the internal angle. Figure 6 shows a comparison among the four cases analyzed.
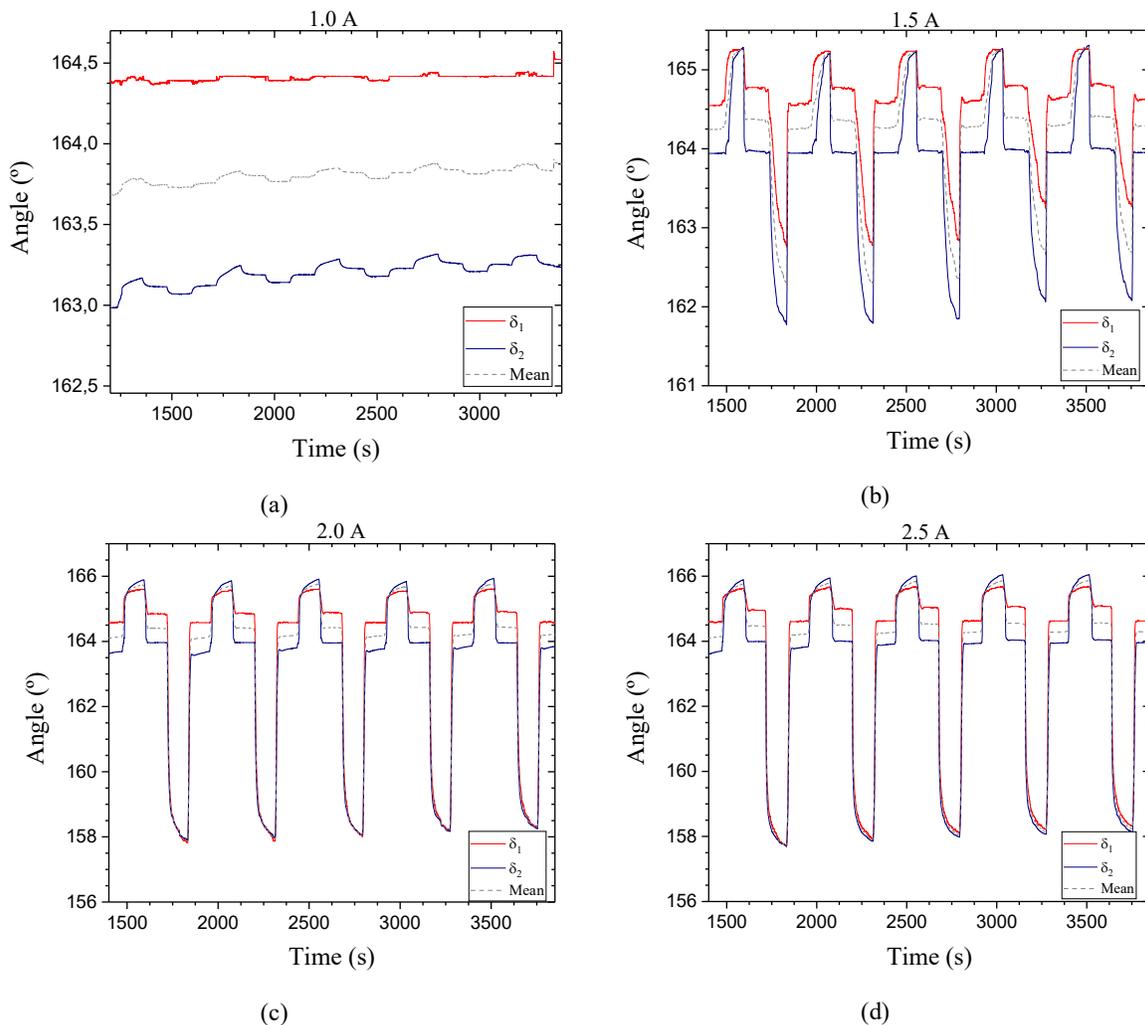

Figure 5. Response curves of the internal angles δ_1 and δ_2 for different magnitudes of electric current.
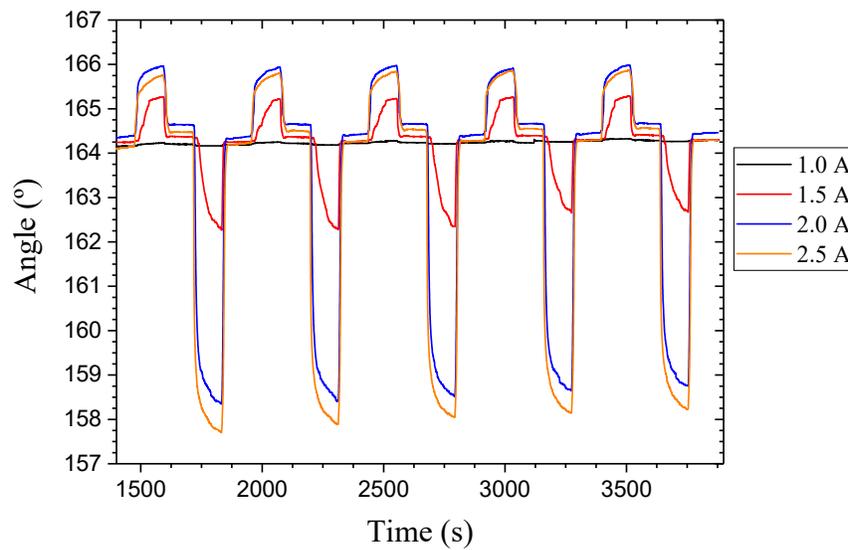(a) 1.0 A; (b) 1.5 A; (c) 2.0 A; (d) 2.5 A.

Figure 6. Comparison of origami experimental test for different current loads.

5. CONCLUSIONS

This paper presents an experimental analysis of an origami unit cell built from a waterbomb folding pattern actuated by pairs of SMA Z-shape torsional springs. Due to geometrical relations based on symmetry hypotesis, the analysis of a single unit cell can be employed to study the behavior of a structure composed by several unit cells as self-expandable systems. A DC power supply controlled by an Arduino device is employed to promote thermal cyclic loadings through Joule effect resultant from the application of on-off cyclic electric current. Laser measurements monitor the geometric configuration of the unit cell through the displacement of two points showing the open-close process. Results show that higher electric currents applied increase the actuation range of the origami, allowing adjustable top and bottom position angles. An intrinsic asymmetry of the structure is noticeable, especially when the structure is not actuated, on the relaxed configuration.

6. ACKNOWLODGEMNETS

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