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Design and Optimization of Compliant Cellular Structures for Morphing Aircraft Skins

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ABSTRACT

Design of transformable skins is currently a focus of considerable research for morphing aircraft structures. This work aims to develop a structural concept of flexible skins, which should be flexible to achieve large-scale continuous deformations, yet having sufficient stiffness to withstand large aerodynamic forces, and be light. The basic concept is compliant cellular structures made up of the re-entrant cells with negative Poisson's ratio (NPR) and shape memory alloy (SMA) tendon actuators. By controlling the temperatures of the SMA actuators, the shape and plane area of compliant cellular structure can be changed continuously. The mechanical characteristics of compliant cellular structures are here investigated through a numerical model and experimental investigations. Some numerical formulations accurately describe the behavior of the compliant structures and SMA actuators. And optimization of the design parameters is considered to make the compliant cellular structures tradeoff between the skin flexibility and structural stiffness. Experimental tests are also performed to demonstrate the accuracy of the model and to illustrate the properties of the adaptive flexible skin prototype.

Keywords: Morphing aircraft, Flexible skins, Compliant cellular structures, Optimal design, Shape memory alloy.

1. INTRODUCTION

The “morphing aircraft” which can operate efficiently over a wide range of different flight conditions and environments via geometry changing has been increased interest. However, a number of problems have thus far restricted its use by engineers. One of the major problems is difficulties in designing transformable skins which should be flexible yet having sufficient stiffness to withstand large aerodynamic forces[1]. Currently, there are two common solutions for achieving smoothly transformable skins. One is using smart materials and structures, and the other is using compliant mechanisms.

The smart materials commonly include shape memory alloys (SMA), piezoquartz, and shape memory polyurethane (SMP) etc[2]. In one study, SMA and SMP were incorporated into the skin design to minimize the energy required to morph by enabling transition between rigid and elastomer states during shape change[3].

Unlike conventional rigid-link mechanisms, compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only, which exploit the inherent mechanical deformation of materials[4]. Compliant mechanisms take advantage of flexure to achieve transmission of motion and force, rather than the rigid-body mechanisms used in traditional engineering design. Furthermore, the smooth and continuous deformations of compliant mechanisms are particularly suitable for the fluid dynamics. As opposed to smart material actuators, compliant mechanisms offer significant advantages in that they are scalable, ranging from micro-scale to large scale.

But morphing aircraft usually requites the acreage of some parts enlarged or shrunk in different flight conditions. This application actually demands a property that skins expand (shrink) along one axis when stretched (compressed) along an orthogonal axis. It is just the negative Poisson's ratio (NPR) materials' property not defying the laws of elasticity theory[5]. But the NPR material can not be used to make aircraft recently because of its low stiffness and spongy texture. This study was aimed at achieving this special flexible skin by designing compliant mechanisms with NPR effect.

2. Geometrically Transformable Wings

Geometrically transformable wings are particularly important in morphing aircraft applications. One of the typical applications is shown in Figure1, which enables large changing of aspect ratio and area.

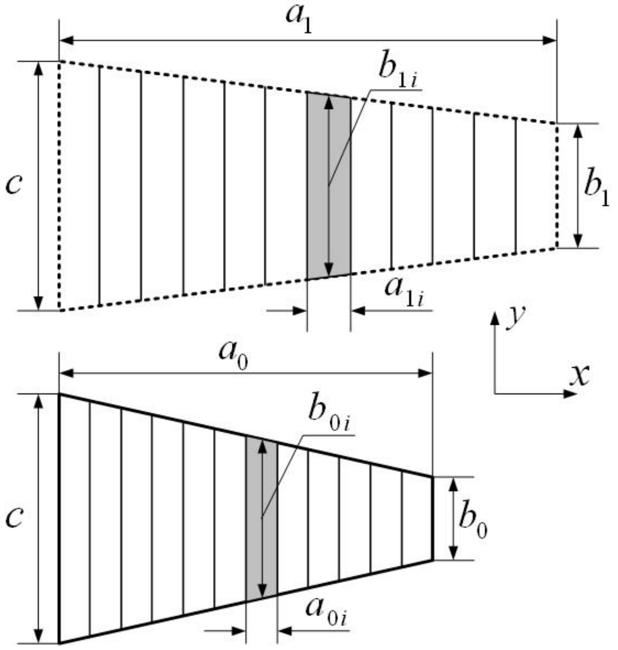


Figure 1: The wing which can change aspect ratio and area

If the wingspan is divided into N equal sections along the horizontal axis, the Poisson's ratio of each section can be defined by the equation

$$\mu_{xyi} = -\frac{\varepsilon_{yi}}{\varepsilon_{xi}} = -\frac{(b_{1i} - b_{0i})/b_{0i}}{(a_{1i} - a_{0i})/a_{0i}} \qquad (1 \le i \le N) \tag{1}$$

where a_{0i} and b_{0i} are the initial width and initial length of the plane section i, while a_{1i} and b_{1i} are their final width and final length. The relationship between the section i and the whole wingspan is given by

$$a_{0i} = \frac{a_0}{N} \tag{2}$$

$$b_{0i} = b_0 + (c - b_0)\left(1 - \frac{2i-1}{2N}\right) \tag{3}$$

$$a_{1i} = \frac{a_1}{N} \tag{4}$$

$$b_{1i} = b_1 + (c - b_1)\left(1 - \frac{2i-1}{2N}\right) \tag{5}$$

Hence, μ_{xyi} is given by Equation 6.

$$\mu_{xyi} = -\frac{a_0}{a_1 - a_0} \cdot \frac{b_1 - b_0}{c\left(\frac{2N}{2i-1} - 1\right) + b_0} \qquad (1 \le i \le N) \tag{6}$$

Apparently, the Poisson's ratio μ_{xyi} is negative when

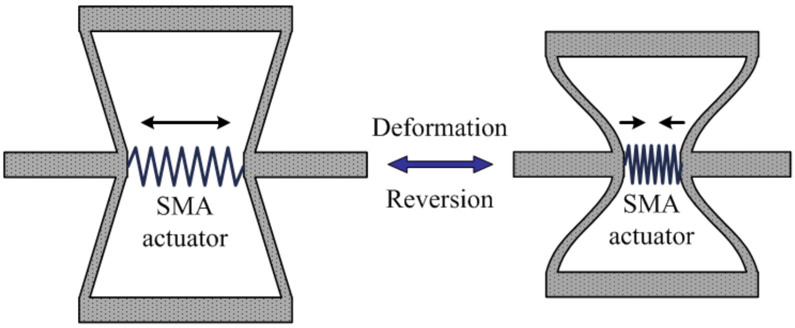
$$(a_1 - a_0)(b_1 - b_0) > 0 \tag{7}$$

3. Compliant Cellular Structures with Negative Poisson's Ratio

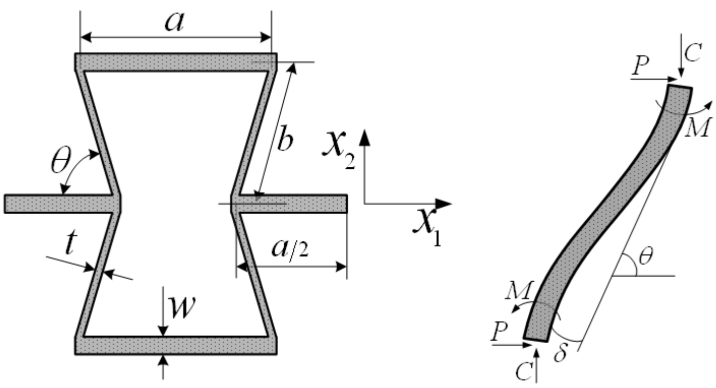
3-1 Compliant Cell and Its Mechanical Characters

The design of compliant structures is based on the re-entrant cell shown in Figure 2(a). The re-entrant cells can only deform when compressed or constringed. SMA actuators are embedded to make the structures change shape automatically.

Rivet the SMA actuator inside the re-entrant cell, as Figure 5 shows. When heated, SMA actuator will shrink, which makes the ribs of cell structures bended. When cooled, the stiffness of SMA actuator will decline. And the elastic restoring force can stretch the SMA actuator to make the cell structures resile.



(a)



(b) (c)

Figure2: Re-entrant cell deformed by SMA actuator

The re-entrant cell structure has orthotropic elastic symmetry and its mechanical characters can be described by Equations 8 to 15. The width of rib is smaller than the width of girder, that is usually defined as $w \geq 2t$. According to the principle of elasticity, the flexibility of rib is much more than girder. So in the following analysis, the distortion of girder is ignored.

$$\frac{\rho^*}{\rho_s} = \frac{t}{b}\left(\frac{wa}{tb}+2\right) \Big/ \left[2\sin\theta\left(\frac{a}{b}-\cos\theta\right)\right] \tag{8}$$

$$\frac{E_1^*}{E_s} = \frac{\sigma_1/\varepsilon_1}{E_s} = \left(\frac{t}{b}\right)^3 \frac{\left(a/b-\cos\theta\right)}{\sin^3\theta} \tag{9}$$

$$\frac{E_2^*}{E_s} = \frac{\sigma_2/\varepsilon_2}{E_s} = \left(\frac{t}{b}\right)^3 \frac{\sin\theta}{\left(a/b-\cos\theta\right)\cos^2\theta} \tag{10}$$

$$v_{12}^* = -\frac{\varepsilon_2}{\varepsilon_1} = -\frac{\cos\theta\left(a/b-\cos\theta\right)}{\sin^2\theta} \tag{11}$$

$$E_1^* v_{21}^* = E_2^* v_{12}^* = -E_s\left(\frac{t}{b}\right)^3 \frac{1}{\sin\theta\cos\theta} \tag{12}$$

$$\frac{G_{12}^*}{E_s} = \frac{\tau}{\gamma E_s} = \left(\frac{t}{b}\right)^3 \frac{1}{2\left(a/b-\cos\theta\right)} \tag{13}$$

$$\frac{E_3^*}{E_s} = \frac{\sigma_3/\varepsilon_3}{E_s} = \frac{\rho^*}{\rho_s} \approx \frac{t}{b} \tag{14}$$

$$\frac{G_{13}^*}{E_s},\ \frac{G_{23}^*}{E_s} \sim \frac{\rho^*}{\rho_s} \approx \frac{t}{b} \tag{15}$$

3-2 Compliant Cellular Structures

The compliant cellular structures can be manufactured from planar sheets of aluminium or reinforced plastics, and made of re-entrant cells, which is shown in Figure 3.

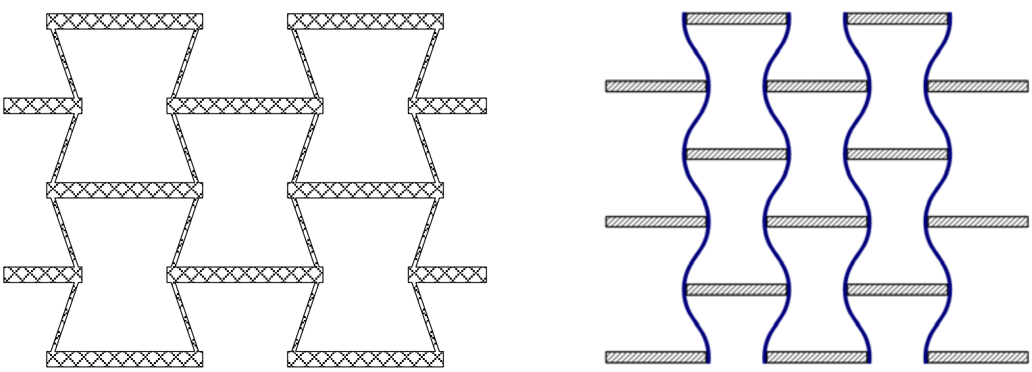


Figure 3: Rectangular compliant cellular structures

Unlike conventional honeycomb structures, compliant cellular structures will get fatter when stretched, and will get shiner when compressed. The rectangular compliant cellular structures possess the same Poisson's ratio with re-entrant cells, described by equation 11.

4. Optimum Design of Compliant Cellular Structures

In order to design compliant cellular structures which are flexible to change plane area yet having sufficient stiffness to resist large aerodynamic force, we used optimum design model as equation 16. And the optimum results interval is shown in Figure 4.

$$\min_{X} \ \frac{1}{E_s^2}\left[E_1^{*2}(X)+E_2^{*2}(X)\right]=\left(\frac{t}{b}\right)^6 \frac{(a/b-\cos\theta)^4\cos^4\theta+\sin^8\theta}{(a/b-\cos\theta)^2\cos^4\theta\sin^6\theta}$$

$$X=[a,b,t,h,\theta]^T \tag{16}$$

$$s.t \quad G_{12}^* \geq [G_{12}], \quad E_3^* \geq [E_3], \quad G_{13}^* \geq [G_{13}], \quad G_{23}^* \geq [G_{23}]$$

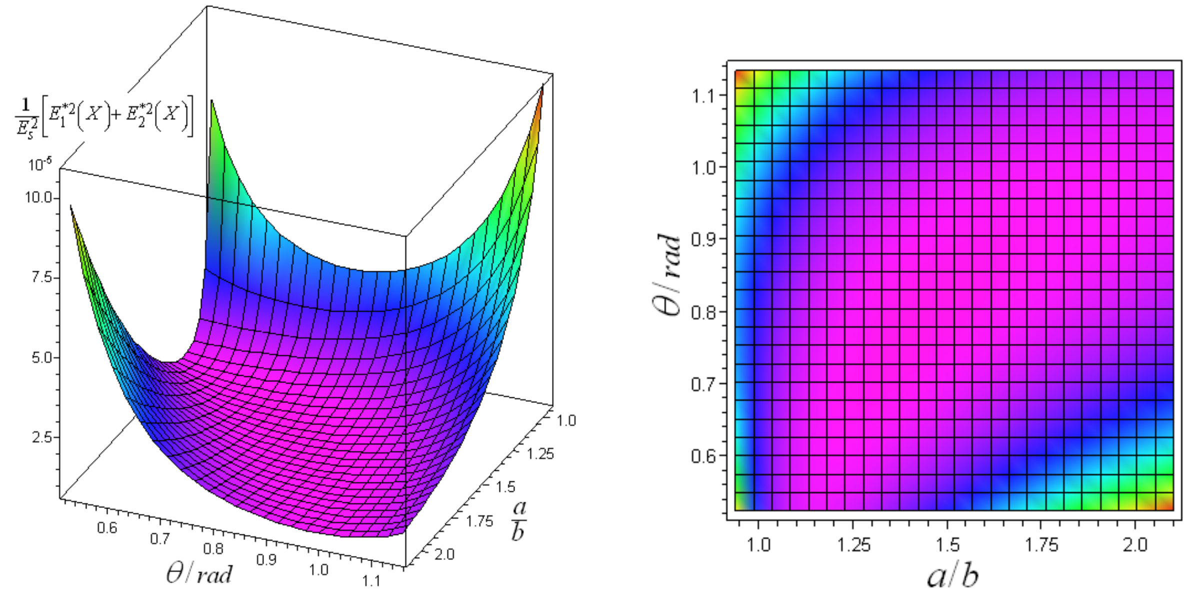
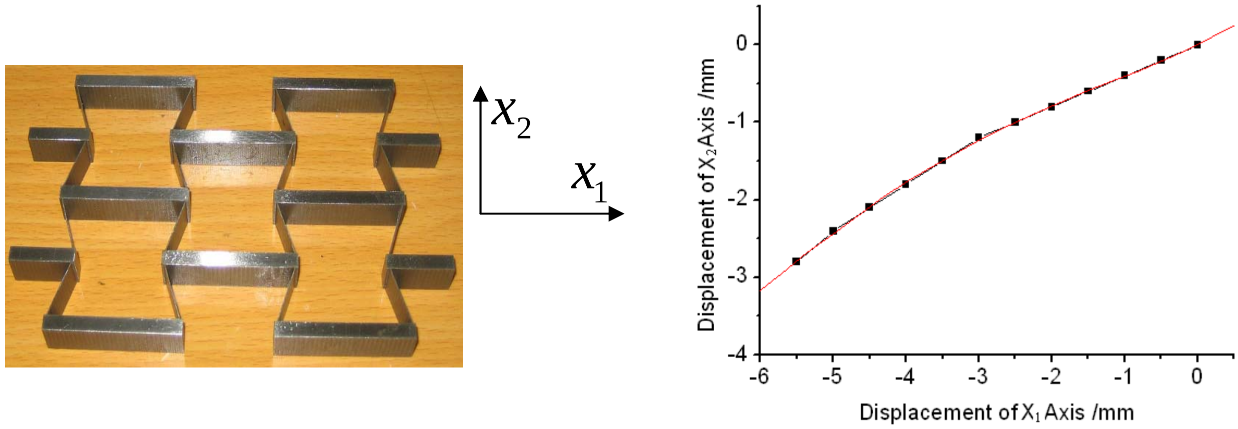


Figure 4: Optimization model and its optimum results interval

5. Experimental Results

A compliant cellular structure made up of four re-entrant cells with Negative Poisson's Ratio was tested under compressive loading at room temperature. The position of compliant honeycomb during compression test along the x_1-direction is shown as in Figure 5(a). And Figures 5(b) show that Poisson's Ratio of the compliant honeycomb is negative and has a nonlinear relationship with the displacement of x_1 axis.



(a) (b)

Figure 5: Compression test on the compliant cellular structure

The SMA actuators produced by $TiNi_{50.2\%}$ wires were used to deform the compliant cellular structures. Unlike other actuators, the activity force in an SMA actuator comes from a dimensional change due to the solid state transformation, a process also known as SME. The transformation temperatures (martensite start temperature Ms, martensite finish temperature Mf, reverse transformation start temperature As and reverse transformation finish temperature Af) were tested by the Differential Scanning Calorimetry Thermo-analyzer.

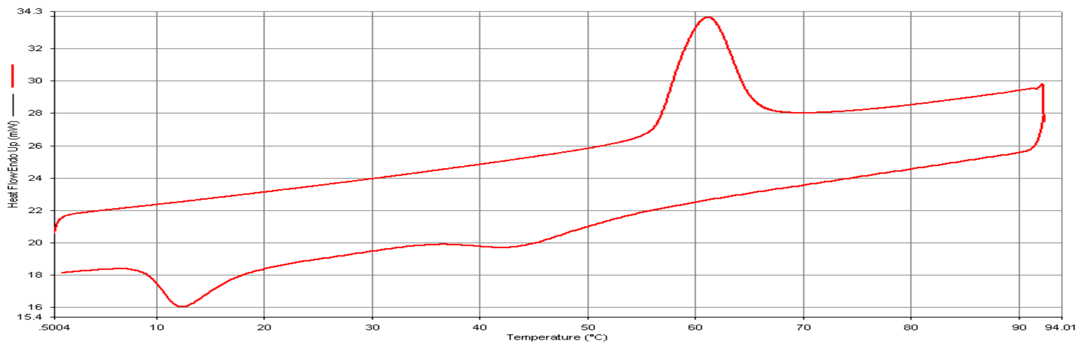


Figure 6: Transformation temperatures tested by the Differential Scanning Calorimetry Thermo-analyzer

The transformation temperatures of $TiNi_{50.2\%}$ are shown in Table 1 obtained from Figure 6.

Table 1: Transformation temperatures for SMA actuators

Mf	Ms	As	Af
35℃	54℃	56℃	65℃

Figure 7 shows the temperature deformation characteristics of the SMA actuators under different loads of 10kg, 20kg and 30kg. With the temperature increasing, SMA actuators shrink, and force the ribs of the honeycomb to bend. It is indicated that the compliant honeycomb mechanism can be deformed smoothly via controlling the temperature of SMA actuators.

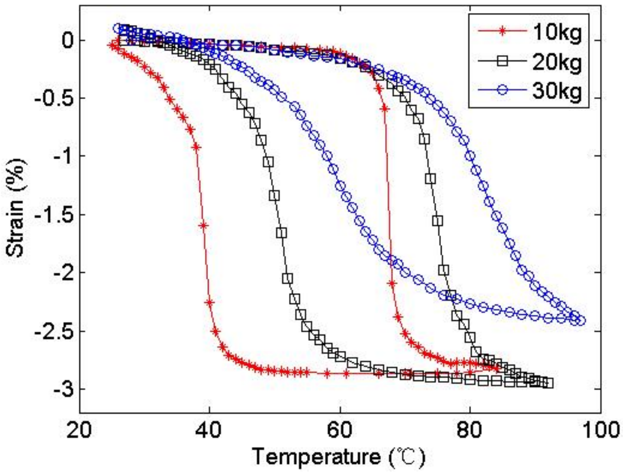


Figure 7: Deformation-temperature curves of SMA actuators under different loads

6. Conclusion

This work focuses on exploring the design and manufacturing of compliant cellular structures with negative Poisson's ratio using SMA actuators. The experimental values obtained in the compliant cellular structures and SMA actuators samples show that the plane area of compliant cellular structures can be changed by controlling the temperature of SMA actuators. And this character indicates that the SMA compliant cellular structures with negative Poisson's ratio could be used to design the flexible skins for morphing aircraft.

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