Materials Letters 181 (2016) 285–288

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

A bi-material structure with Poisson's ratio tunable from positive to negative via temperature control

Dong Li [a,*], Jie Ma [a], Liang Dong [b], Roderic S. Lakes [c]

[a] *College of Sciences, Northeastern University, Shenyang 110819, PR China*
[b] *Materials Science and Engineering University of Virginia, Charlottesville, VA 22904, USA*
[c] *Department of Engineering Physics, University of Wisconsin, Madison, WI 53706-1687, USA*

ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form
1 June 2016
Accepted 11 June 2016
Available online 12 June 2016

Keywords:
Thermal properties
Negative poisson's ratio
Simulation and modelling
Elastic properties

ABSTRACT

In this paper, a two-dimensional quadrilateral cellular structure made from bi-material strips was designed and its thermal deformation behaviors were studied via experimental, analytical and numerical approaches. It has been shown that the cell shape of the structure can be tuned from convex to concave (or vice versa) and hence the Poisson's ratio from positive to negative (or vice versa) with a change in temperature. At any specific temperature with a non-zero ΔT, the absolute value of the structure's Poisson's ratio decreased rapidly at first with an increasing compression strain ε_y and then more slowly as it approached a constant of approximately 1 when $\varepsilon_y > 0.1$. A maximum absolute value of the Poisson's ratio of approximately 12 was found at $\varepsilon_y = 0.001$ at a 10 °C temperature change.

1. Introduction

Poisson's ratio is defined as the ratio of the transverse contraction strain to the longitudinal extension strain in tension. Most natural solids have a positive Poisson's ratio near 0.3. Negative Poisson's ratio has been observed in designed cellular materials with re-entrant structures in both 2-D and 3-D structures[1–5]. Negative Poisson's ratio is also known in polymer gels, ferroelastic ceramic near phase transition temperatures and in In-Sn alloy near a morphotropic phase boundary [6–9]. Bi-material strips, made from two different materials with different thermal expansion coefficients, give rise to bending deformation in response to a temperature change [10,11]. A 2D-lattice made from bi-material ribs can thus achieve either convex or concave shape for the individual cells upon temperature change. It is therefore feasible to design lattice structures with ribs made from bi-material strips so that the structure Poisson's ratio is tunable from positive to negative in the temperature range of interest.

In this paper, a two-dimensional quadrilateral cellular structure made from bi-material strips was designed and its thermal deformation behaviors were studied via experimental, analytical and numerical approaches. The Poisson's ratio of the structure can be tuned from positive to negative (or vice versa) with a change in temperature. At any specific temperature change ΔT, the absolute value of Poisson's ratio decreased rapidly at first with an increasing compression strain ε_y and then more slowly as it approached a constant of approximately 1 when $\varepsilon_y > 0.1$. A maximum absolute value of the Poisson's ratio of approximately 12 was found at $\varepsilon_y = 0.001$ at a 10 °C temperature change.

2. Numerical analysis and theory

The thermal deformation behaviors of a unit cell structure made of bi-material ribs with alternating orientation have been studied using the commercial finite element software ANSYS. The unit cell structure model is shown in Fig. 1(a, b). At 22 °C, all strips of the unit cell structure are kept straight. Different colors represent different materials. The materials' parameters of the bi-material were defined based upon experimental data (Engineered Materials Solutions "P675R" strip). The density, Young' s modulus, Poisson's ratio and thermal expansion coefficient for the lower and higher thermal expansion materials are 8100 kg m^{-3}, 140 GPa, 0.3, 1.3×10^{-6} K^{-1} and 7300 kg m^{-3}, 199 GPa, 0.3, 30×10^{-6} K^{-1}, respectively. The density, Young' s modulus, Poisson's ratio of the crossbeam are 8930 kg m^{-3}, 119 GPa, 0.33, respectively. Geometrical parameters are H=92mm, L=92mm, h_1=0.25mm, h_2=0.4mm. Swept meshes of 18780 elements (Solid 186, 20 nodes) were applied. Temperature was set to vary from −20 °C to 60 °C with an incremental step of 10 °C. At each specific temperature, the displacement of the central node on the top surface

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* Corresponding author.
E-mail address: lidong@mail.neu.edu.cn (D. Li).

http://dx.doi.org/10.1016/j.matlet.2016.06.054
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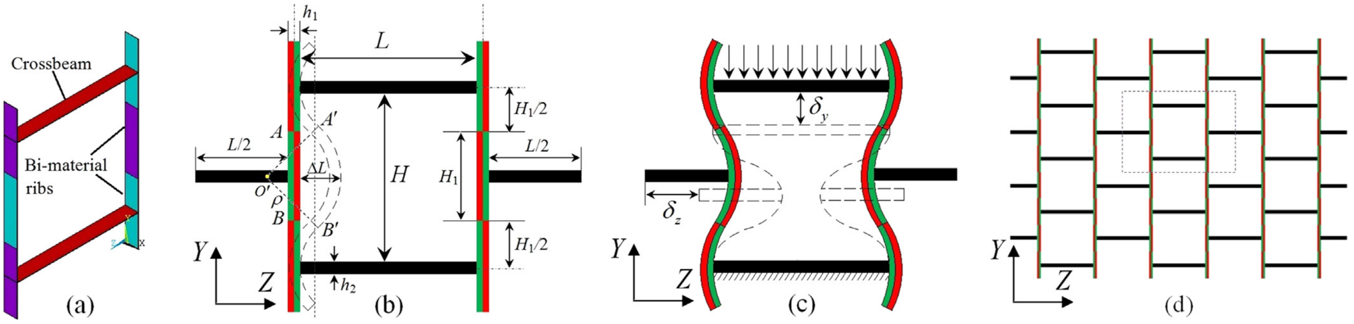

Fig. 1. (a) ANSYS model of a unit cell structure made of bi-material ribs with alternating orientation at 22 °C. All strips are kept straight at 22 °C. Geometrical parameters defining the unit cell structure in the y-z plane are shown in (b); the material with lower thermal expansion coefficient is shown in green, and the one with higher coefficient is shown in red. (c) at a temperature higher than 22 °C, the unit cell structure exhibited a concave shape due to bending of the bi-material strips. The unit cell structure was then compressed in order to determine the structure's Poisson's ratio by referring to the vertical and lateral displacements, δ_y and δ_z. (d) 2D lattice structure made from repeating the unit cell structure, and a zoom-in view of the unit cell structure dash line marked in (d) is shown in (*a*-c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the upper crossbeam was recorded as the deflection of upper crossbeam, and multi-loading steps were applied to calculate the Poisson's ratios of the unit cell structure at different strain levels (Fig. 1(c)). The bottom surface of the lower crossbeam was fixed with all degrees of freedom being constrained. The compressive strain ε_y was set from 0.001 to 0.11 on the top surface of the upper crossbeam in the vertical direction, and the Poisson's ratios (ν_{yz}) were calculated at each strain level by

$$\nu_{yz} = -\frac{\varepsilon_z}{\varepsilon_y} \tag{1}$$

where, $\varepsilon_y$and ε_z refer to the strains in the *Y*- and *Z*-directions, $\varepsilon_y=\frac{\delta_y}{H}$, and $\varepsilon_z=\frac{\delta_z}{L}$.

When a bi-material strip is subjected to uniform heating, the curvature is expressed as [10],

$$\frac{1}{\rho} = \frac{(\alpha_2 - \alpha_1)(T - T_0)}{\frac{h}{2} + \frac{2(E_1I_1+E_2I_2)}{h}\left(\frac{1}{E_1a_1} + \frac{1}{E_2a_2}\right)} \tag{2}$$

where, ρ is the curvature radius (see Fig. 1(b)), h is the thickness of the bi-material strip, T refers to the environment (final) temperature, and T_0 refers to the initial temperature (T_0=22 °C) at which all strips of the unit cell structure are straight. E_1I_1, a_1, α_1 and E_2I_2, a_2, α_2 refer to the flexural rigidity, thickness, and thermal expansion coefficient of the metal strips with low and high thermal expansion coefficients used to make the bi-material strip. For a simply supported bi-material strip, the relationship between the maximum deflection $\triangle L$, the radius of the curvature ρ and the strip length H_1 is$H_1^2 = 8\rho\Delta L$. Therefore, the maximum deflection $\triangle L$ can be obtained as

$$\Delta L = \frac{H_1^2}{8\rho} = \frac{H_1^2}{8}\frac{(\alpha_2 - \alpha_1)(T - T_0)}{\frac{h}{2} + \frac{2(E_1I_1+E_2I_2)}{h}\left(\frac{1}{E_1a_1} + \frac{1}{E_2a_2}\right)} \tag{3}$$

3. Experimental

A large roll of bimetallic sheet with thickness of 0.25 mm was obtained from Engineered Materials Solutions “P675R”. Bi-material strips with a length of 50 mm and width of 10 mm were cut from the large roll and connected by brass clips. The crossbeam is made from brass with a length (L) of 92 mm, a width of 10 mm and a thickness of 0.4 mm. The specimen was clamped by a fixture in the middle of one bi-material strip and kept vertical in a furnace. A thermocouple was placed in contact with a bi-material strip to monitor the material's temperature. The deflection in the middle of the bi-material strip (i.e., Z-direction displacement) was measured using a linear variable differential transformer (LVDT; Trans Tek 240-000) through a hole on top of the furnace.

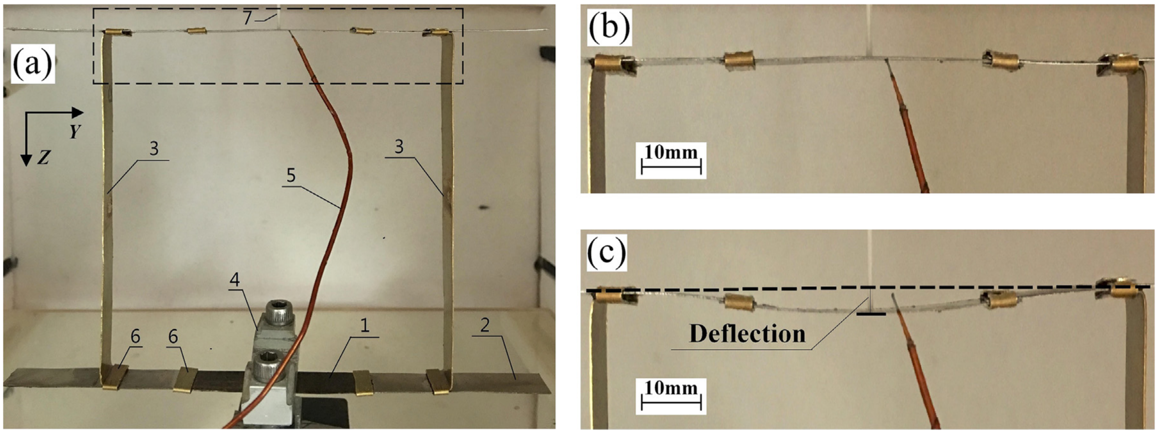

Fig. 2. (a) Photographic images of the manufactured structure at 22 °C (room temperature). A zoom-in view of the portion of the structure dash line marked in (a) is shown in (b) at 22 °C and (c) at 50 °C. In Fig. 2(a), 1- one side of the bi-material with high thermal expansion coefficient; 2- the other side of the bi-material with low thermal expansion coefficient; 3- crossbeam; 4- fixture; 5- thermocouple; 6- brass clip; 7- LVDT probe.