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

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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 $\varepsilon_y = 0.001$ for a 10°C temperature change.

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

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.

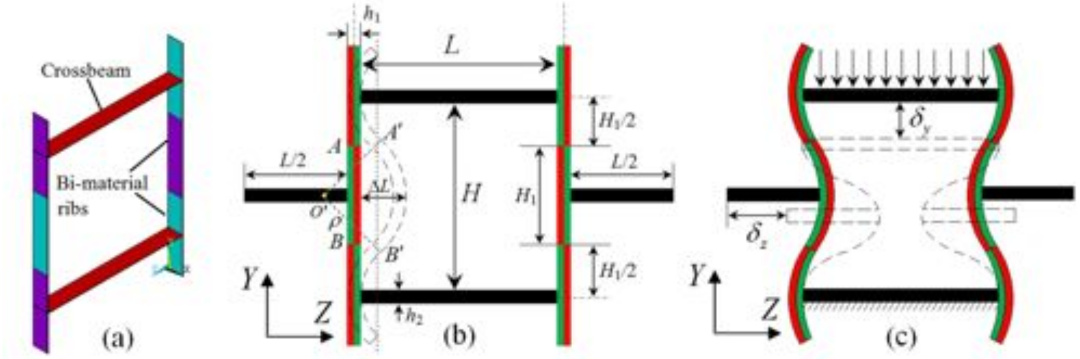
In this paper, a two-dimensional quadrilateral cellular structure made from bi-material strips was designed and its thermal deformation behaviors were studied via experimental, analytical and numerical approaches. The Poisson's ratio of the structure can be tuned from positive to negative (or vice versa) 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}, 140GPa, 0.3, $1.3\times10^{-6}K^{-1}$ and 7300 kg m^{-3}, 199GPa, 0.3, $30\times10^{-6} K^{-1}$, respectively. The density, Young' s modulus, Poisson' s ratio of the crossbeam are 8930 kg m^{-3}, 119GPa, 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, multi-loading steps were applied to calculate the Poisson's ratios of the unit cell structure at different strain levels (Fig. 1c). 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, ε_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],

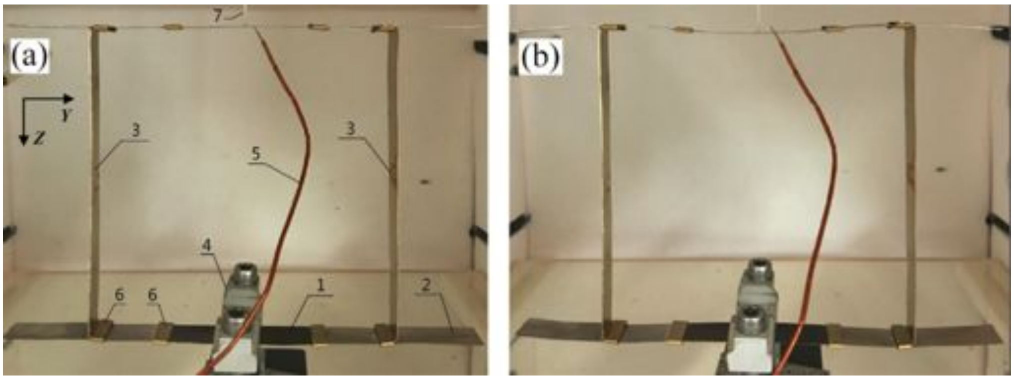
$$\frac{1}{\rho} = \frac{(\alpha_2-\alpha_1)(T-T_0)}{\frac{h}{2}+\frac{2(E_1I_1+E_2I_2)}{h}\left(\frac{1}{E_1a_1}+\frac{1}{E_2a_2}\right)} \tag{2}$$

where, ρ is the curvature radius (see Fig. 1b), h is the thickness of the bi-material strip, T refers to the environment (final) temperature, and T_0 refers to the initial temperature. 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 ΔL, the radius of the curvature ρ and the strip length H_1 is $H_1^2 = 8\rho\Delta L$. Therefore, the maximum deflection ΔL can be obtained as

$$\Delta L = \frac{H_1^2}{8\rho} = \frac{H_1^2}{8}\frac{\left(\alpha_2 - \alpha_1\right)(T - T_0)}{\frac{h}{2} + \frac{2\left(E_1 I_1 + E_2 I_2\right)}{h}\left(\frac{1}{E_1 a_1} + \frac{1}{E_2 a_2}\right)} \tag{3}$$

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 92mm, a width of 10mm and a thickness of 0.4mm. 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.



4. RESULTS AND DISCUSSION

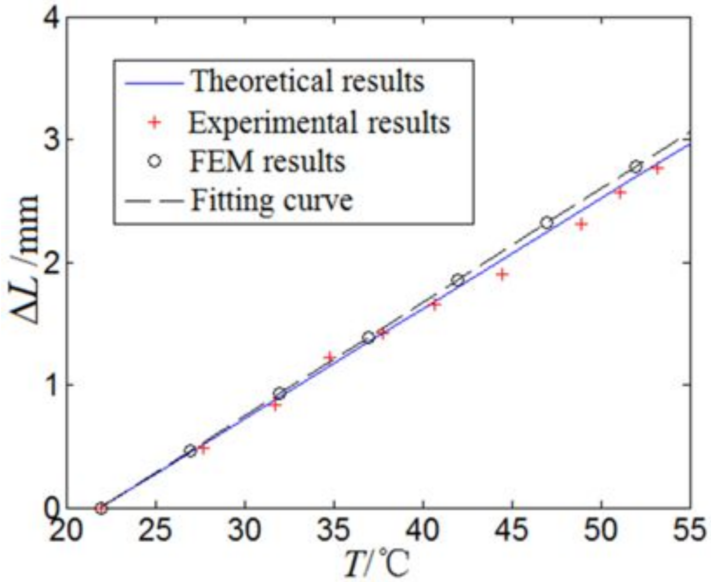
4.1. Thermal deformation

The thermal deformation behaviors of the specimen at both 22°C and 50 °C were shown in Fig. 2. Analytical, FEM and experimental results for the relationship between temperature and the maximum deflection （□*L*） are shown in Fig. 3. A linear relationship between temperature and □*L* is observed in the temperature range accessed in the present study (20 -55°C).

The least square method was used to curve fit the FE simulation results as

$$\Delta L = 0.095T - 2.033 \tag{4}$$

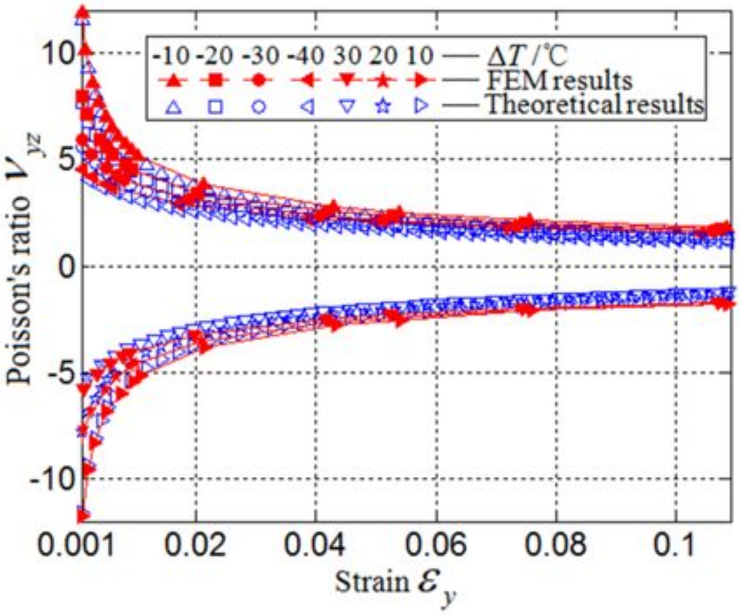
where, *T* is the environmental temperature. It can be seen that the analytical and numerical predictions are in excellent agreement with the measurements, which suggested the validity of the FE model proposed.



4.2. Poisson's ratio

The relationships between the structure's Poisson's ratio and the compression strain ε_y determined from FE simulations at different temperature changes ($\Delta T = T - T_0$) are shown in Fig. 4. The Poisson's ratio of the unit cell structure can be tuned from positive to negative or vice verse by changing the temperature: if ΔT is positive, the cell shape will become convex and exhibit negative Poisson's ratio; if ΔT is negative, the cell shape will become concave and exhibit positive Poisson's ratio. 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 $\varepsilon_y > 0.1$. The maximum absolute values of the Poisson's ratio were found at $\varepsilon_y = 0.001$: the Poisson's ratios were 11.98, 7.93, 5.91, 4.82, -5.78, -7.68, -11.87 at ΔT=-10, -20, -30, -40, 30, 20, 10, respectively. The absolute value of Poisson's ratio decreased with an increasing ΔT. It can be seen that the FE simulation results matched well with the analytical predictions.

The lattice may be viewed as a planar honeycomb with orthotropic symmetry. In such materials, a large Poisson's ratio in one direction is associated with a small Poisson's ratio in the orthogonal direction. Poisson's ratio near zero has been utilized in structural honeycomb for sandwich panels used in aircraft; hexagonal cells are over-expanded to approach a rectangular shape [13].



5. CONCLUSIONS

A two-dimensional quadrilateral cellular structure made of bi-material strips was designed and its thermal deformation behaviors were studied via experimental, analytical and numerical approaches. Results show that the cell shape of the structure can become convex or concave with a change in the environment temperature, and hence the Poisson's ratio changes from positive to negative. The maximum deflections at the middle point of the bi-material strip at different temperatures were measured and compared with the analytical and numerical predictions. Excellent agreement was found between measurements and predictions. The Poisson's ratio of the unit cell structure can be tuned from positive to negative or vice versa by changing the 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^{o}C temperature change.

Acknowledgements

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References

[1] Gibson L J, Ashby M F, Schajer G S, Robertson C I, Proc. R. Soc. Lond. A, 382 (1982) 25-42.
[2] Lakes R S, Science, 238 (1987) 551.
[3] Wojciechowski K W, Physics Letters A, 137 (1989) 60-64.
[4] Li D, Dong L, Lakes R S, Phys. Status Solidi B, 250 (2013) 1983-1987.
[5] Li D, Dong L, Lakes R S, Materials Letters, 164(2016) 456-459.
[6] Hirotsu S, J. Chem. Phys. 94 (1991) 3949.
[7] Dong L, Stone D S, R.S. Lakes, Philos. Mag. Letts. 90 (2010) 23-33.
[8] Li D, Jaglinski T M, Stone D S. Lakes R S, Appl. Phys. Lett. 101(2012) 251903.
[9] Li D, Dong L, Lakes R S. Materials Letters, 143 (2015) 31-34.
[10] S. P. Timoshenko, J. Optical Soc. America, 11 (1925) 233-355.
[11] C S Ha, E Hestekin, J Li, M E Plesha, R S Lakes, Phys. Status Solidi B, 252 (2015) 1431-1434.

[12] B. M. Lempriere, AIAA Journal, 6 (1968) 2226-2227.
[13] Hexcel Corporation, HexWeb^{TM} honeycomb attributes and properties. (1999) 3-5.

Figure caption

Fig. 1 (a) ANSYS model of a unit cell structure made of bi-material ribs with alternating orientation at 22^{o}C. All strips are kept straight at 22^{o}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^{o}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.

Fig. 2 Photography images of the manufactured structure at (a) 22 ^{o}C (room temperature) and (b) 50 ^{o}C. (in Fig 2a, 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)

Fig. 3 The relationship between temperature and □*L*. Experimental and FEM results are represented by (+) and (o), respectively. The solid line in blue represents the analytical prediction, (- -) is the fitted curve for FEM results.

Fig. 4 The relationships between the Poisson's ratio and the compression strain ε_y at different ΔT. Symbols (-▲-), (-■-), (-●-), (-◀-), (-□-),(-□-), (-▶-) represent FEM results, and (□), (□), (□), (□), (□), (□), (□) represent analytical predictions at ΔT of -10□, -20□, -30□, -40□, 30□, 20□, 10□, respectively.