Negative-Poisson's-Ratio (NPR) Microstructural Material by Soft-Joint Mechanism

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ABSTRACT

A counterintuitive material of a negative Poisson's ratio (NPR) is presented. Its material structure design is realized by the result from topology optimization and a compliant mechanism. The NPR structural material has the composite configuration of resin and elastomer. Taking advantage of the stiffness from the resin and the compliance from the elastomer, the NPR structural materials are made and tested. Their performance has been compared to the theoretical prediction and two single-material-based configurations.

Keyword: negative Poisson's ratio, structural material, PDMS, composite

1. INTRODUCTION

MicroElectroMechanical Systems (MEMS) has presented an approach via micromanufacturing technologies to implement tiny structures and devices. The capability of creating microstructures is important when an accumulation of constituent microstructures can alter the physical properties of materials in bulk. Although the bulk materials from macroscopic investigations have their own homogenous properties, their homogeneities disappear when the same materials are examined in microscale. By tailoring the underlying microstructures, the desired mechanical properties of materials may be controlled. Therefore, material design using periodical microstructures has drawn much interest in the research community in recent years [1-5].

To demonstrate this concept, we are focusing on a material design with a special mechanical property. We present such example by making a counterintuitive material with a negative Poisson's ratio (NPR). Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the stretching direction. Most materials resist a change in volume so that its cross section becomes narrower when stretching. These materials usually have positive Poisson's ratios. However, the materials with re-entrant structures will have negative Poisson's ratios and some intuitive examples of them have been demonstrated [4, 6]. Other design approaches from topology optimization for better performances of NPR material designs have also been reported [5]. However, most of these examples of NPR material design suffers from its silicon based construction which is costly and only suitable for small strain applications [6].

A compliant mechanism based material design methodology is studied in this paper. Unlike the conventional single material approach of the compliant mechanism construction, two types of materials, one for rigidity and the other for compliance, are used in our design. The optimized material designs are realized by the micro-molding processes, which are aided by the stereolithography of a Rapid Prototyping (RP) machine. Then, the resulting microstructural materials are measured and characterized for verification and comparison.

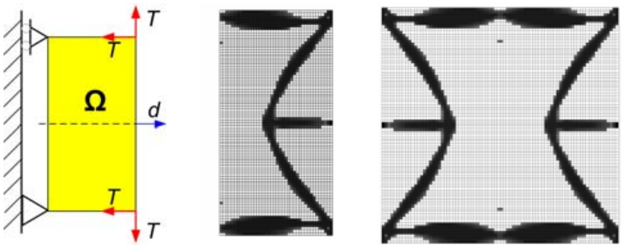
2. TOPOLOGY DESIGN

The NPR material developed here is low-cost and can sustain large strains. The design methodology starts with a design problem - when the loads are horizontally and vertically applied, the center of the right edge produces a maximum horizontal expansion, as shown in **Fig.1(a)**. The upper left corner is limited to vertical displacement only and the lower left corner is fixed completely. When the horizontal and vertical loads are applied to the upper and lower right corners of the design domain, the center of the right edge is expected to produce a maximum horizontal expansion. This design problem is readily transformed into a topology optimization problem with a volume constraint as follows:

Maximizing: $\boldsymbol{d}$

Subject to: $$V = v_e \sum_{i=1}^{N} \rho_i \leq \overline{V} \qquad (1)$$

where $\boldsymbol{d}$ is the horizontal displacement at the center of right edge. V denotes the total volume, $\overline{V}$ represents the upper bound of the allowable volume, v_e is the element area, ρ_i is the element density and N is the total number of elements. The details of this approach can be found in the work by [7, 8]. In this paper, the design domain Ω is discretized into 80x40 finite elements and the volume constraint is chosen as 30%. The vertical and horizontal applied loads are set to be equal. Symmetric constraint is set along the horizontal centerline to get an up-and-down symmetric structure. The optimized design is identified as a compliant mechanism after 10 iterations as shown in **Fig. 1(b)**. The structure in design domain Ω is mirrored along the left vertical boundary to get a left-and-right symmetric structure as shown in **Fig. 1(c)**.



(a) (b) (c)

Fig. 1: Our design methodology:
(a) the design domain (Ω) with boundary and loading conditions;
(b) the optimization result, and
(c) the final optimal structure.

For the topology optimization problem with volume constraints, the solution is generated and identified as a compliant mechanism with a re-entrant honeycomb cell for the maximum transverse expansion. The gray levels of the elements represent their compliance levels. The darker regions signify higher stiffness while the brighter regions signify higher compliance.

A compilation of these re-entrant honeycomb cells can result in a microstructural material with maximum transverse expansion. The design is optimal and its theoretical model can be interpreted as a cluster model of pin-joint mechanism in **Fig.2** to represent the properties of the microstructural material. However, the fabrication itself is challenging. A single material based design cannot truly reflect the optimized solution. Thus, a composite material configuration of a compliant material for the brighter elements and a rigid material for the darker elements is employed.

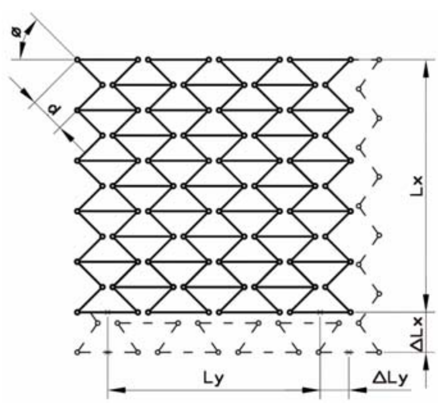


Fig. 2: The pin-joint mechanism cluster model interpreted from topology optimization.

3. FABRICATION

To make this composite configuration for the compliant mechanism material, a fabrication method utilizing stereolithography and elastomer-molding is proposed. This method constructs the structural material of two basic elements: (1) the stiff element (the darker region in **Fig.1**) made of a resin-elastomer composite, and (2) the compliant element (the brighter region in **Fig.1**) made of elastomer only, as shown in **Fig. 3**. The composite element has the resin as the 'bone' of the structure that provides the necessary rigidity. On the other hand, the compliant elements made of elastomer act as soft joints, allowing the desired deformation in the structure. The combination of these two elements produces the desired deformation behavior of the NPR mechanism.

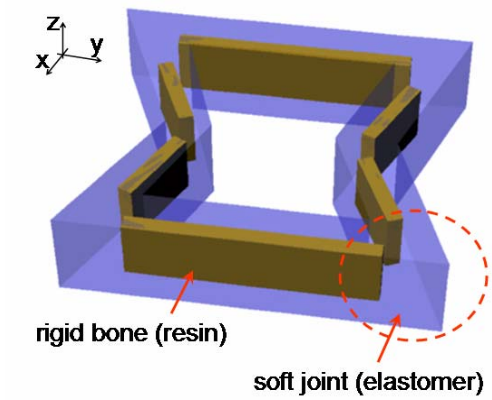


Fig. 3: A basic cell unit of structural material, including rigid bones in resin-PDMS composite and elastomer soft joints.

The process of making a NPR structural material is illustrated in **Fig. 4**. A dual-template approach is used, where both templates are made of Accura® SL resin materials. The lower template consists of cavities, which act as the mold while the upper template has the rigid bones fixed by tethers (step-1, 2). These tethers are designed to provide enough strength, to allow the bones to be placed into the elastomer. The resin material is generated by using the stereolithography machine (Viper Si2 TM SLA® system, 3D Systems Inc).

An elastomer of poly-dimethylsiloxane, or PDMS (Sylgard 184, Dow Corning), consisting of the base and the curing agent in a 10:1 ratio, is well mixed and degassed. An appropriate amount of PDMS, calculated by a CAD program to maintain the uniformity of the structure thickness, is poured into the mold (step-3). The bones in the upper template are then inserted into the PDMS in the mold of the lower template. The whole structure is then cured in air (step-4).

Once cured, the composite resin-bone and the PDMS soft joints are obtained. The final structure will be revealed after breaking the tethers and peeling resin-PDMS material from the lower template (step-5). A structured material of 4 x 6 unit cells (~30 x 30 mm) can be obtained. Each cell is 5 x 5 mm. The cross section of a resin bone is 0.5 x 0.5 mm and the whole the resin-PDMS composite is 1.5 x 1.5 mm in cross section.

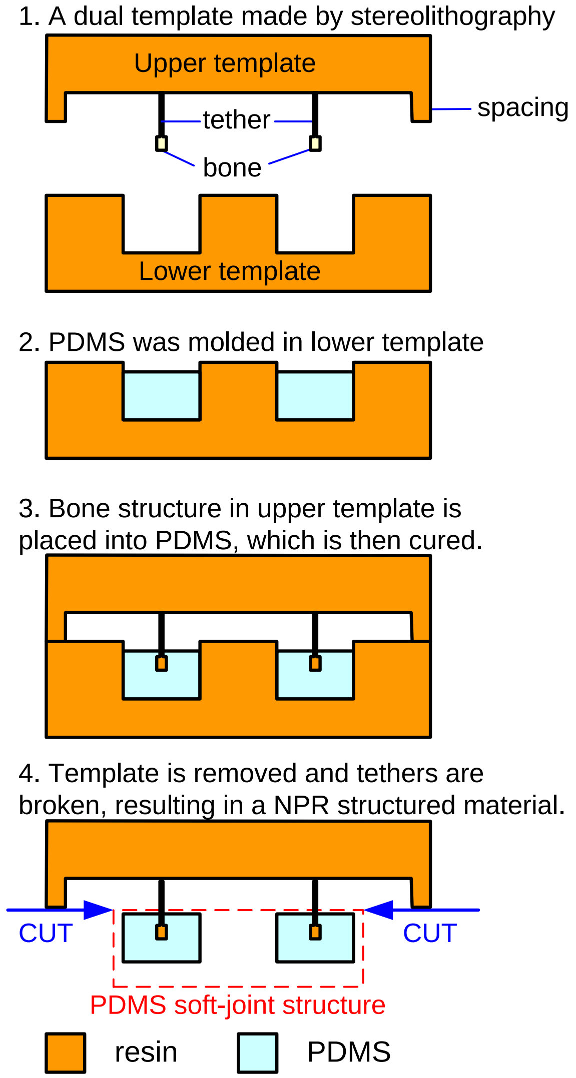
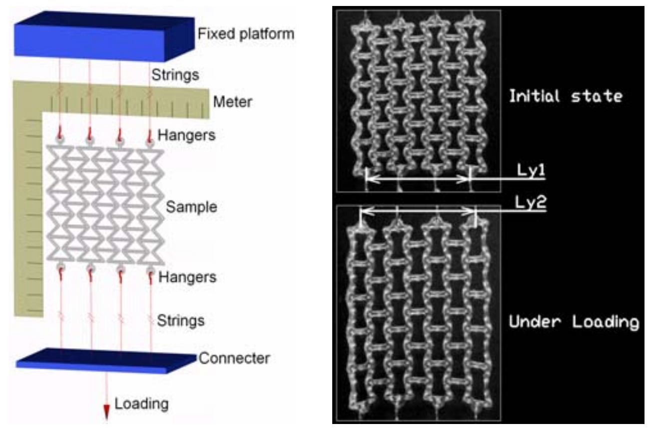


Fig. 4: Fabrication process flow for a NPR compliant mechanism material.

5. RESULTS AND DISCUSSION

Three different material designs are fabricated, measured and compared, based on the optimized compliant mechanism design. These material designs include (1) single-material of PDMS only (compliant material design), (2) single-material of resin only (rigid material design), and (3) resin-PDMS composite (boned material design).

A tensile test shown in **Fig. 5(a)** has been conducted to measure the transverse strain of these designs. Uniform forces are vertically applied on the samples. One end of the sample is fixed to the top of the testing platform; while the other end is pulled by various external loads. The connecting strings are long enough so that the tension forces in the strings can be assumed to be parallel to each other and perpendicular to the mechanism at all times. The weight of the structure can be neglected as it is comparably insignificant to the input tension forces. The total deformations of the structure, shown in **Fig. 5(b),** are captured and measured accordingly.



(a) (b)

Fig. 5: (a) NPR measurement setup and (b) its measurement results from a typical deformation of NPR material design.
(Note: L_{y1} indicates the initial transverse length and L_{y2} shows the transverse length under loading.)

The stress-strain curves for all three models are shown in **Fig. 6**. As expected, the rigid material design has the highest slope (i.e. the highest Young's modulus) and the soft material design has the lowest one, while the boned material design has the value in between.

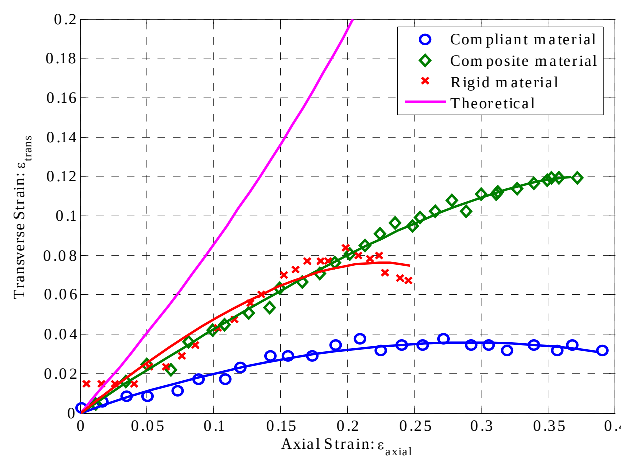


Fig. 6: Experimental results for strains in axial and transverse directions from the theoretical pin-joint model and three different material designs (compliant material, rigid material and composite material).

The slope of each curve in **Fig.6** can respectively represent the Poisson's ratios, as it is determined by the following:

$$Poisson's\ \ Ratio = -\frac{\varepsilon_{trans}}{\varepsilon_{axial}} = -\frac{Transverse\ \ Strain}{Axial\ \ Strain} \quad (2)$$

Fig. 6 shows that the theoretical cluster model of pin-joint mechanism produces a larger NPR effect, or a higher negative Poisson's ratio. The soft material design produces smallest negative Poisson's ratio. The boned material design and the rigid material design initially behave very similarly within the range of small strain. However, the boned material design can sustain a higher strain due to its compliant soft joint configuration, while the rigid material design fractured at a much lower strain level.

6. CONCLUSIONS

A compliant mechanism based material design with a negative Poisson's ratio has been presented. To realize the compliance of the design, a micro-molding process with elastomeric PDMS joints has been developed. Combining the stiffness of the resin material and the compliance of the PDMS, this compliant mechanism based material design performed well in the tensile test. The results have been compared with theoretical displacement and two single-material-based compliant mechanisms. It shows that the proposed design maintains better NPR properties within a large strain range and has the ability to recover its shape elastically after unloading. The extension of the proposed methodology to other structural and functional materials is currently under investigation.

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