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Stiff, strong, zero thermal expansion lattices via material hierarchy

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ABSTRACT

For engineering applications where tight dimensional tolerances are required, or for applications where materials are subjected to a wide range of temperatures it becomes desirable to reduce a material's coefficient of thermal expansion. By carefully designing lattice microstructures, zero thermal expansion can be achieved. This work describes lattice microstructures that achieve zero expansion by utilizing either the Poisson effect to negate thermal expansion, or a curved, bi-material rib morphology. Previously described microstructures were composed of solid material constituents. The lattices presented here have structural hierarchy in which lattice ribs contain oriented porosity. This gives rise to improved strength and modulus, and provides additional design freedom associated with anisotropy.

1. Introduction

Low or even zero thermal expansion coefficients are desirable for materials requiring precise dimensional tolerance or subjected to environments with large temperature fluctuations. It is possible to achieve thermal expansion that is large positive, zero, or large negative by lattices with curved bi-material ribs [1,2]. Zero expansion lattices based on this concept have been designed [3] with improved ratio of stiffness to density [4]. Lattices containing straight ribs can in principle be fully stretch-dominated and have an optimally high ratio of stiffness to density. Two-dimensional lattices with two kinds of ribs and rotating joints were introduced by Steeves et al. [5]. Zero expansion lattices constructed of curved, hexagonal honeycomb cells, with inserts consisting of three spars, made of a second dissimilar material are described by Jefferson et al. [6]. Two-dimensional and three-dimensional lattices containing nested tubes were analyzed by Lehman and Lakes [7].

The nested tube morphology consists of ribs that consist of two tubes with differing coefficients of thermal expansion (CTE) oriented concentrically, following the structural strut design of Baird [7,8]. Zero expansion is achieved via nested tubes as follows. The difference in material thermal expansion creates a thermal stress which acts to stretch the lower CTE material circumferentially, for an increase in temperature. This circumferential extension in turn leads to a Poisson contraction in the axial direction. By carefully choosing material properties and volume ratios it is possible to fully compensate for the thermal expansion in the axial direction to achieve zero expansion. For a decrease in temperature the reverse is true, a circumferential constriction results in an axial extension negating axial thermal contraction. Two configurations exist, with the same analysis and principles applicable to both. The first configuration is to have the smaller CTE material press fitted over the larger expansion material. This ensures that the two materials remain in contact as the temperature increases. Material separation may occur for sufficiently large temperature decreases. Another configuration would be to press fit the larger CTE material over the smaller expansion material, ensuring contact for all temperature decreases, with possible material separation for sufficiently large temperature increases.

Prior analysis of lattices based on nested tubes considered both isotropic and anisotropic materials as well as two material boundary conditions [7]. The first boundary condition assumes that the constituent materials are perfectly bonded, whereas the second boundary condition assumes perfect slip condition. Previously described material structures could only achieve zero thermal expansion with the use of either the perfect slip assumption or the use of a negative CTE material. Both of these restrictions entail limited applicability. Most commonly used materials have positive thermal expansions, and the perfect slip assumption is an ideal condition. One may approximate such a condition by segmenting the larger CTE material into rings, or a wrapping of helical wire [9].

The present analysis describes zero expansion morphologies composed of positive CTE materials. Strength and stiffness of these lattices are enhanced by structural hierarchy. Structural hierarchy refers to structure within structure. Honeycombs and foams with structural hierarchy can be designed with compressive strength to density ratio orders of magnitude greater than values for con-

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ventional structures [10]. The present zero-expansion lattices are designed using ribs that themselves have oriented porosity. Lattices are considered based on nested hierarchical tubular ribs as well as lattices based on curved bi-material ribs.

2. Material properties

Several materials were considered throughout this analysis. Four isotropic metals were chosen including Invar, aluminum, steel, and brass. These materials were selected for their commonality and typical use as structural materials. Invar is well known for its small coefficient of thermal expansion. Additionally two anisotropic, unidirectional fiber composites were also considered, a graphite fiber epoxy composite and a Kevlar fiber epoxy composite. The fibers are aligned in the longitudinal direction with respect to the matrix, while the transverse direction is considered to be orthogonal to the axis of the fibers. The material properties used for each material are shown in Table 1 in which E is Young's modulus, v is Poisson's ratio, and α is thermal expansion. The properties used are obtained as follows. The properties of Invar were obtained from Woolger [11]; the properties for Kevlar epoxy and graphite epoxy composites are from Agarwal and Broutman [12] The thermal properties for aluminum and steel are obtained from the ASM International Materials Properties Database Committee [13], while the mechanical properties of aluminum and steel are from Cook and Young [14]. The properties of Brass are those of yellow brass and were obtained from Beer et al. [15].

2.1. Zero expansion via oriented porosity and the Poisson effect

Hierarchical tubular rib based lattices contain a tube with oriented porosity along its axis. This tube is then incased by a second material which has porosity oriented circumferentially. The porosity can be distributed randomly or periodically, but it is assumed to be homogeneously distributed within the material. Fig. 1 depicts this zero expansion morphology. A no slip boundary condition is assumed.

Oriented porosity in the lattice rib gives rise to tunable anisotropy of the rib material, a useful design variable, and also enhances the ratio of strength to weight. Anisotropy is achieved with the addition of oriented cylindrical pores.

The structural hierarchy can alter the mode of failure, resulting in improved strength. Both plastic yield and Euler buckling modes are considered for octet-truss lattices of zero expansion tubes. Deshpande et al. describe the octet-truss and its mechanical properties [16]. An octet-truss lattice made of nested tube elements is shown by Fig. 2 [7].

The material Young's modulus along the axis of the pores is proportional to the material density, whereas in the transverse direction the elastic modulus is proportional to the relative density to the third power [17]. This difference is due to the mode of deformation for each direction. Along the axial direction the solid material's deformation is stretch dominated, but in the transverse direction, the deformation is primarily bending dominated [17]. By changing the relative density of each constituent material, the degree of anisotropy can be adjusted. Eqs. (1) and (2) explicitly state the Young's moduli along the axial and transverse directions.

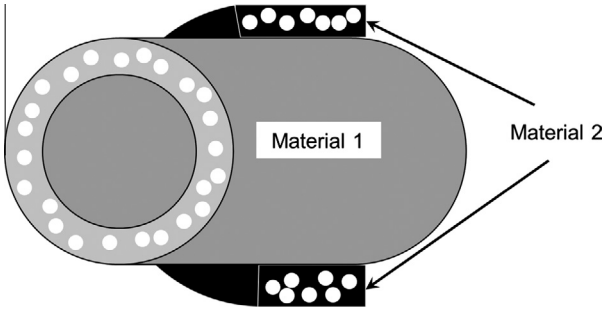

Fig. 1. Shows the bi-material, concentric tube with oriented porosity in the form of tubular channels oriented longitudinally in material 1 and oriented circumferentially in material 2.

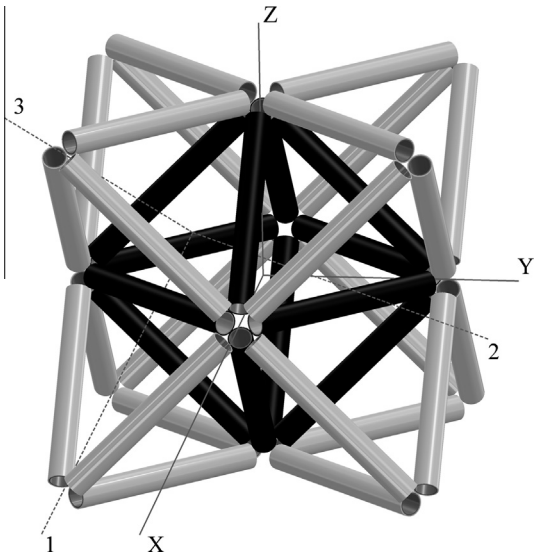

Fig. 2. Depicts an octet-truss lattice structure composed of nested tube rib elements. All elements are identical. The inner octahedron elements are shown in black while the exterior tetrahedral elements are depicted in white for visual clarity.

$$E_A = C_1 \frac{\rho}{\rho_S} E_S \tag{1}$$

$$E_T = C_2 \left(\frac{\rho}{\rho_S}\right)^3 E_S \tag{2}$$

The subscript s indicates the material property (density or elastic modulus) corresponding that of the solid material (density or elastic modulus). The constants of proportionality (C_1 or C_2) depend on the geometry of the pores. Because the pores are perfectly aligned in the axial direction the constant C_1 is simply equal to one. The tan-

Table 1
Provides a list of material properties used throughout the analysis. For fiber reinforced composites the L subscript indicates the direction along the fibers while T denotes transverse to the direction of the fibers. Steel, brass, aluminum, and Invar are considered isotropic and are only defined by one Young's modulus and one CTE.

Material property	Steel	Brass	Aluminum	Invar	Unidirectional graphite fiber epoxy composite	Unidirectional Kevlar fiber epoxy composite
E_L (GPa)	200	105	70	140	159	83
E_T (GPa)	–	–	–	–	10.9	5.6
v_{LT}	0.3	0.35	0.33	0.28	0.38	0.34
α_L (μstrain/K)	12	20.9	22.2	1	0.045	−3.3
α_T (μstrain/K)	–	–	–	–	20.2	35