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Multilevel hierarchy in bi-material lattices with high specific stiffness and unbounded thermal expansion



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ABSTRACT

Dual-material concepts that expand or contract as desired upon changes in temperature exist but have their limitations. One upon which we focus here is the trade-off caused by the inherent thermo-elastic coupling that they feature, a condition that makes desired changes in thermal expansion penalize elastic stiffness, and vice versa. In this paper, we present hierarchical bi-material lattices that are stiff and can be designed to attain a theoretically unbounded range of thermal expansion without (i) impact onto elastic moduli and (ii) severe penalty in specific stiffness. Through a combination of theory, numerical simulations and experiments, we demonstrate the thermomechanical performance of eight hierarchical lattices, including two fractal-like hierarchical lattices with self-repeating units that are built from dual-material diamond shapes with low and high coefficients of thermal expansion (CTE). Results show that the achievable range of CTE can be enlarged by 66% through the addition of one order of hierarchy only, and that for a given CTE range the specific stiffness can be at least 1.4 times larger than that of existing stretch-dominated concepts. The concepts here introduced can open up new avenues towards multifunctional devices and structurally efficient materials with simultaneously customized thermal expansion and mechanical properties.

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1. Introduction

Architected materials can be designed to elicit extreme mechanical properties, often beyond those of existing solids [1]. They are very appealing for use in several fields of engineering including aerospace, automotive and biomedical [2–4]. In these applications, the target to maximize might be either structural, through attaining for example minimum mass at maximum stiffness [5,6], or functional, such as thermal dimension control [2], heat transfer [7], band gaps [8], mechanical biocompatibility [9], and others [1]. For lightweight structural applications, high stiffness is desired for preserving the structural integrity and resisting a variety of loading conditions. In contrast, high compliance is required to adapt under other loading conditions for more functional applications, such as energy absorption [10]. For functional applications, the coefficient of thermal expansion (CTE) has been the recent focus of intense research [11,12] aiming at obtaining large positive, zero or negative CTE via material architecture tuning.

The design freedom to adjust thermal expansion is particularly

advantageous in a large assortment of applications. On one hand, in extreme thermal environments, sensitive applications that require very fine precision, such as satellite antennas, space telescopes, and large array mirrors [4,13], call for materials with zero CTE so as to avoid undesired thermal deformation. On the other hand, there are other applications requiring materials with large positive or negative CTEs. These materials must induce responsive and desirable deformations under given changes in temperature [14], often, but not always, dictated by the surrounding environment, such as in morphing and adaptive structures [15,16], as well as MEMS [17]. The potential of periodic architected materials is also appealing because their repeating cell can be designed to concurrently maximize multiple performance requirements, notably structural and functional. Among many, examples of multifunctional lattices include those developed for aerospace components that can maintain precise dimensional tolerances under large temperature fluctuations and specific stiffness requirements [2,18].

This paper focuses on multifunctional lattices designed with the goal of providing unique control of thermal expansion and structural performance, at levels currently unmet by existing concepts. As with previous works [2,11,18–23], we deal with material architectures made of two materials, which can be designed to

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compensate the mismatched thermal deformation generated by each of the two materials. If exploited, this strategy enables the attainment of an overall thermal deformation that can be large positive, zero or large negative. Since dual material architectures achieve a tunable CTE through a purely mechanical, and thus temperature-independent, mechanism [4], their CTE is extremely dependent on the unit cell architecture and on the difference in CTE of their constituent solids [12,18]. To assess the potential of a given architected material in providing a range of CTE values via tailored selection of its material constituents and its cell topology, we need a quantitative metric. CTE tunability, (ΔCTE) has been recently used [23] to measure the maximum range of CTE values that a concept can achieve upon changes of its unit cell geometry from a given pair of materials. Whereas a single material has only one CTE value, hence no ΔCTE , the CTE of dual material concepts can be adjusted by geometric manipulation of the building block with the result of obtaining a range of CTE values. The difference between the minimum and maximum CTE that an architected material can offer is defined as ΔCTE . For a given concept, a large ΔCTE indicates ample freedom to tune the unit cell geometry, an asset that can release the dependence on the CTE ratio of the constituents (see [Supplementary Material A](#)).

Several dual-material concepts have been proposed in the literature, most notably by Lehman and Lakes [19,24], Steeves et al. [18], Hopkins et al. [25], Jefferson et al. [20], Sigmund et al. [22], and Xu et al. [23]. A number of these concepts, such as Lakes concept [26], while successful in demonstrating theoretically unbounded CTE tunability, feature a trade-off in structural efficiency [27]. The compromise between them emphasizes an inherent coupling between mechanical properties and thermal properties. This is typical of existing dual-materials concepts (See [Supplementary Material A](#)), for which CTE tailoring through architecture manipulation may result in severe reduction of mechanical performance. For example, some existing concepts show that the desired flexural deformation that a large CTE tunability would require is generally antagonist to the high specific stiffness that is distinctive of a structurally efficient architecture. This indicates that preserving high specific stiffness is in conflict with the need of enhancing ΔCTE , as manifest in stretch-dominated unit cells constructed by dual-material triangle (2D) or tetrahedron (3D), which offer a remarkable structural performance [2,18], but cannot achieve the sizeable CTE tunability of bend-dominated architectures [11,26]. Hence, the main issue we want to address in this paper: how to reduce the penalty that an increase in ΔCTE will generate on the elastic properties, so as to obtain the best compromise out of them.

This work proposes hierarchical lattice materials which feature enhanced CTE tunability regardless of the choice of the constituent solids, and enable thermal expansion control without incurring in severe loss of structural performance. Structural hierarchy is not new and for a long time now has been recognized as one crucial factor governing high stiffness, strength, and toughness in both natural and bio-inspired materials [28–30], and even more recently in the field of thermal expansion [19]. However, what has not been so far explored yet is how to exploit it to, first, amplify CTE tunability in architected materials, and then to decouple physical properties that are in conflict. The method adopted in this paper, as explained in Section 2, combines solid mechanics theory, finite element simulations and experiments on proof-of-concept lattices. The results presented in Section 3 demonstrate that initially coupled properties can be individually tuned in distinct hierarchical orders to obtain large CTE tunability without sensible loss in structural performance. Section 4 discusses the concept performance by drawing a comparison with a set of existing architected materials that are

stretch and bend dominated.

2. Methodology

Our focus here is on bi-material unit cells ([Fig. 1](#)) with high and low CTE, which are used to build hierarchical lattices (HL) including those made of self-repeating unit cells, i.e. fractal-like hierarchical lattices (fractal-like HL) and hierarchical lattices which feature at least two unit cells with different topologies, thus making the hierarchical lattice of a hybrid-type (hybrid-type HL) ([Fig. 2](#)). The following provides closed-form expressions and computational results of their thermomechanical properties, along with details on sample fabrication and CTE testing.

2.1. Unit cell model with a bi-material diamond shape

[Fig. 1a-I](#) shows the diamond that can attain a low-CTE performance (LD). Upon a uniform increase of temperature, red (α_{s1}) and blue (α_{s2}) elements in a LD deform at different rates, visualized in [Fig. 1a-II](#) as unbonded for explanation purpose. [Fig. 1a-II](#) displays the height increase, ΔH_{l1} , caused solely by thermal expansion in the blue elements. In the final configuration ([Fig. 1a-III](#)), rigid connections at the nodes cause a higher expansion in the red horizontal bar that turns the blue struts. As a result, the top vertex of the diamond springs back by ΔH_{l2} , a displacement that if desired can be conveniently designed to compensate ΔH_{l1} . By harnessing the values of α_{s1} and α_{s2} , or the skewness of the blue elements, θ , the CTE of a LD can be tuned to zero, or even negative, in the y -direction. Similarly, [Fig. 1b-I](#) shows the complementary version of the diamond in [Fig. 1a-I](#), where the switched material distribution yields a high-CTE diamond (HD). In [Fig. 1b-II](#), the expansion of the red elements bring about a height increase, ΔH_{h1} , and a width-wise gap, ΔW_h , which would appear if the blue bar, which exhibits less expansion, were visualized as unconnected. Also in this case, rigid connections ([Fig. 1b-III](#)) would compensate the visualized horizontal gap, ΔW_h , by a height increase of ΔH_{h2} , adding on to ΔH_{h1} , and this value of ΔH_{h2} can also be tuned by manipulating α_{s1} , α_{s2} and θ . From this explanation, we gather that the CTE in the y -direction depends on the thermal expansion ratio of the constituent materials, $\xi = \alpha_{s2}/\alpha_{s1}$, and the skewness angle, θ . If θ is given, the smaller the ξ , the lower (for LD) or higher (for HD) the CTE [18]; hence the greater the CTE distinction of the constituent solids, the higher the CTE tunability.

We now examine the general case of a LD ([Fig. 1a-I](#)) with an arbitrary skew angle, θ , and we derive its Young's moduli, from which those for HD can also be easily obtained. A small thickness ratio is considered, $t/l < 1/8$, that gives LD a low relative density, ρ^*/ρ_s , which is defined as the ratio of its real density over the density of the solid. For a generic dual-material unit cell, the relative density can be expressed as a function of the volume fractions of the constituents ([Supplementary Material B](#)), and more specifically for a LD (details in [Supplementary Material C](#)) can be written as:

$$\frac{\rho^*}{\rho_s} = \frac{\cos\theta + 2t}{\sin\theta l} \quad (1)$$

Using structural mechanics [31], the in-plane Young's moduli can be derived as ([Supplementary Material C](#)):

$$\frac{E_y^*}{E_{s2}} = \left(\frac{1}{2 \sin^3\theta} + \frac{E_{s2}/E_{s1}}{\tan^3\theta} \right)^{-1} \frac{t}{l} \quad (2)$$

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