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Influence of first to second gradient coupling energy terms on the wave propagation of three-dimensional non-centrosymmetric architectured materials

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ABSTRACT

In the current work, we analyze the role of the coupling energy between the first and second order gradient kinematic terms on the wave propagation characteristics of three-dimensional (3D) architectured materials with a non-centrosymmetric inner structure. To that scope, we elaborate an energy based method that computes the network material's unit-cell total deformation energy, based on its full linear 3D beam kinematics. We use a continualization method to provide the effective second gradient constitutive law, where a coupling energy tensor of order five appears, due to the lack of a center of inversion. Thereupon, we consider the case study of a pyramid shaped unit-cell periodic microstructure. We formulate the dynamic equilibrium equations and compute the architectured materials' wave propagation attributes. We analyze the effect of the coupling energy terms on the propagating longitudinal and shear modes, presenting the corresponding phase velocities for different directions of propagation. We compute the influence of the coupling energy terms on the wave propagation characteristics as a function of the propagation direction. We observe considerable differences between second gradient media description with and without the consideration of the coupling energy term contributions for propagating modes along the non-centrosymmetric inner material direction. We assess the effect of coupling energy over a wide range of propagating directions, deriving useful overall conclusions its role in the wave propagation characterization of 3D architectured media.

1. Introduction

Additive manufacturing has led to a new paradigm in material design, in which the inner organization of matter plays a central role (Cui, Smith, & Liu, 2010). Architectured materials constitute a new class of artificial materials with static and dynamic characteristics that are typically not encountered in natural materials (Maldovan, 2013; Reda, Karathanasopoulosn, Elnady, Ganghoffer, & Lakiss, 2018). They are used in a wide range of engineering applications, amongst others in vibration control, energy absorption (Clayes, Deckers, Pluymers, & Desmet, 2016; Mei et al., 2012) and noise reduction (Bacigalupo, & Gambarotta, 2014; Reda, Ganghoffer, & Lakiss, 2017).

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In the last years, a lot of attention has been given to the static behavior of architectured materials. In particular, an emphasis has been posed in the design of 2D unit cells with tailored stiffness attributes. Designing materials of controlled mechanical properties has opened new possibilities in a series of engineering applications, such as in morphing and mechanical engineering, wave propagation and vibration (Xu, Shen, Zhou, Huang, & Xie, 2016). For the computation of the effective mechanical properties of architectured media, homogenization methods have been commonly employed. The determination of a homogenized material behavior constitutes the first step towards the characterization of its wave propagation characteristics (Bacigalupo & Gambarotta, 2014; Reda et al., 2017). The latter can be obtained by computing the material's dynamic attributes at the scale of their representative building blocks (Lachenal, Daynes, & Weaver, 2013).

Artificial materials demonstrate not only uncommon static properties, but also peculiar dynamic mechanical attributes. A primal design objective has been to obtain inner material architectures that favor the development of bandgap frequency regions. Different lattice configurations have been shown to provide wave propagation isolation characteristics. More specifically, triangular and hexagonal honeycomb lattices have been identified to exhibit isolation properties (Karathanasopoulos, Reda, & Ganghoffer, 2017), while tetrachiral honeycombs have been shown to permit a veering of certain modes. The latter have found direct application in both passive and active vibration control (Bacigalupo & Gambarotta, 2017). Recently, architectured materials that make use of inner folding mechanisms have attracted researcher's attention for their ability to control elastic waves (Bacigalupo & Gambarotta, 2016).

The use of resonant elements has been associated to material designs of enhanced dynamic properties. More specifically, resonant internal units have been related to acoustic band gaps (Collet, Ouisse, Ruzzene, & Ichchou, 2011; Liu, & Hu, 2010; Lu, Feng, & Chen, 2009; Pennec, Djafari-Rouhani, Larabi, Vasseur, & Hladky-Hennion, 2008) along with a tuning capability at low frequencies (Bigoni, Guenneau, Movchan, & Brun, 2013). Their wave propagation characteristics are highly sensitive to their inner material topology, with different inner architectures to exhibit utterly different dynamical properties (Bacigalupo & De Bellis, 2015).

Whereas a relatively large number of works has been so far devoted to the analysis of two-dimensional (2D) unit-cell structures, three-dimensional (3D) unit-cell material designs have received much less attention. The wave propagation characterization of 3D materials with an inner architecture entails a high computational cost for typical numerical methods, such as finite element methods (Lee, Mace, & Brennan, 2007; Mace, Duhamel, Brennan, & Hinke, 2005; Mencik & Ichchou, 2008). The identified numerical difficulties have highlighted the need for effective continuum models to be employed, in which the inner material architecture is represented through an effective continuum behavior. In the low frequency regime, a primal prerequisite for the effective continuums' method applicability is the considerably lower unit-cell size with respect to the wave length, or equivalently the limitation to the low frequency regime (Mencik & Duhame, 2015; Silva, Mencik, & Arruda, 2015).

It needs however to be noted that not all effective continuum descriptions suffice to characterize wave propagation. In particular, it has been experimentally proven that most waves are dispersive, that is, each wavenumber travels with a different phase velocity (Erofeyev, 2003; Jakata &Every, 2008). In the low frequency range, in order to study the wave propagation of the effective continuum media, enriched second gradient elasticity descriptions need to be used that account for microstructural effects descriptive of the dispersive wave behavior (Aifantis, 1996). This requires the incorporation of both first and second order contributions in their mechanical description (Pasternak & Mühlhaus, 2005). Gradient-enriched theories can sufficiently capture dynamic behaviors overlooked by classical elasticity, in which second gradient terms are neglected. A second-order strain gradient theory has been developed in Shaat and Abdelkefi (2016), based on the strain energy density depending upon the conventional strain in addition to the first and the second strain gradients (Mindlin, 1965). This theory aims mathematically to capture physical phenomena not included in Cauchy elasticity, including surface tension and cohesive forces (Mindlin, 1965). Size effects may be modeled through the introduction of higher order strain gradients in the respective constitutive equations. This suggestion has been taken up, among others in Aifantis (1984, 1987, 1992, 1995, 1996), where the authors consider the issue of size-dependent properties by building on earlier proposals for gradient elasticity and plasticity. Several homogenization methods towards second order gradient continua have been developed in the literature (Alibert, Seppecher, & dell'Isola, 2003; Forest, 1998, 2002; Misra & Singh, 2015; Placidi, Andreaus, Della Corte, & Lekszycki, 2015; Rahali, Ganghoffer, Chaouachi, & Zghal, 2015; Reda, Rahali, Ganghoffer and Lakiss (2016b, 2016c)). What is more, different homogenization methods have been proposed to obtain a second gradient continuum description of periodic discrete materials (Placidi, Andreaus, Della Corte, & Lekszycki, 2015; Rahali, Ganghoffer, Chaouachi, & Zghal, 2015; Reda, Rahali, Ganghoffer, & Lakiss, 2016). However, the development of homogenization method that not only accounts for first and second order contributions, but also incorporates the effect of their inner coupling, remains up to now a scientific challenge.

1.1. Constitutive laws for non-centrosymmetric solids

The inherent assumption of central symmetry has been done systematically in most models of repetitive network materials, so that the unit cell has been assumed to be invariant with respect to coordinate inversion as a consequence of the existence of a center of symmetry within the unit cell. However, some network materials are constructed in such a way that they do exhibit structural non-centrosymmetry (they lack a center of symmetry), a type of anisotropy which is expected to bring specific behaviors not encountered for centrosymmetric structures; typical examples of non-centrosymmetric solids