Materials and Design 147 (2018) 134–145

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

The role of anisotropy on the static and wave propagation characteristics of two-dimensional architectured materials under finite strains

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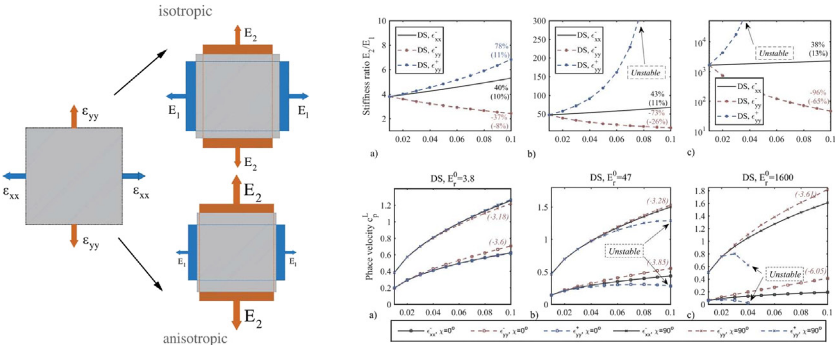
HIGHLIGHTS

- Analyze the role of initial anisotropy on the architectured material's static properties
- Distinguish between the effects of finite normal and shear strains
- Investigate the correlation between initial material anisotropy, loading direction and material instability
- Identify the structural and loading prerequisites for optimal wave propagation tuning within anisotropic media

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 December 2017
Received in revised form 26 February 2018
Accepted 14 March 2018
Available online 16 March 2018

Keywords:
Nonlinear analysis
Metamaterials
Anisotropy
Wave propagation
Shear strains
Normal strains

ABSTRACT

In the current work, we analyze the role of anisotropy on the static and wave propagation characteristics of architectured materials. In particular, we study the mechanical behavior of nearly isotropic, moderately and highly anisotropic metamaterials under finite shear and normal strains. Thereupon, we quantify the effect of finite deformations with respect to their magnitude and loading direction, relating the metamaterials' initial degree of anisotropy to its finite strain static attributes. We distinguish between the effect of finite shear and normal strains, noting that highly anisotropic material designs do not uniquely entail shear strain sensitive structural behaviors. Contrariwise, we observe that finite normal loads in certain loading directions can lead to instabilities at rather low strain magnitudes already for moderately anisotropic material designs. Moreover, we show that strain-induced instabilities can be detected as negative phase velocity increments before the stiffness matrix loses its positive definiteness. What is more, we demonstrate that anisotropy and non-reciprocity can be used as mechanisms for wave propagation tuning. We provide evidence that for enhanced tuning capabilities to be observed, inner material density variations need to be exploited. The latter require the application of normal rather than shear strains, as shear deformations are volume preserving.

1. Introduction

The advancement of additive manufacturing has led to a new paradigm in the design of materials [1,2]. A new class of artificial materials arose with static and dynamic properties that natural materials

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https://doi.org/10.1016/j.matdes.2018.03.039

commonly cannot exhibit and has been named as metamaterials [3]. Anticipating the subsequent developments and analyses, the wording metamaterials is here employed to designate inner architectures of network materials giving rise to both unusual static and dynamic effects associated to rather extreme mechanical properties or behaviors not encountered for common materials. Up to now a considerable amount of works has been dedicated to a class of metamaterials named auxetics, because of their property to laterally expand when stretched [4]. Different inner material configurations have been shown to yield an auxetic behavior, indicative examples being chiral, hexa and tetrachiral repetitive unit-cell arrangements [5–7]. Auxetics have found a wide range of applications in different fields, primarily due to their reduced overall structural weight [8].

Lately, the need to go beyond auxetics in order to satisfy current anisotropic material design requirements in different engineering fields has been highlighted (Fig. 1). In particular, in the realm of civil engineering, the development of highly anisotropic artificial materials has been directly associated with the design of optimal wind morphing structures [9]. What is more, various mechanical engineering branches (such as the ceramic and automotive industry) are in need of lightweight artificial materials with direction dependent static attributes [10–15]. The interest in anisotropic material designs arises not only due to particular stiffness requirements, but also because of specific volumetric behaviors. In particular, a near-zero Poisson's ratio values have been noted to favor nano-engineering applications [16]. Furthermore, certain biological members such as tendons and ligaments are in need of biocompatible substitute materials that exhibit Poisson's ratio values well above the isotropic limits [17,18] in order to emulate native tissue mechanics [19].

However, anisotropic material designs are particularly sensitive to the magnitude of the applied strain. Their material properties strongly depend on the applied deformation, commonly exhibiting a highly nonlinear constitutive law behavior [20,21]. As a result, different constitutive models have been developed to describe their large strain mechanical properties [22]. To that extent, both discrete and continuum homogenization approaches have been elaborated to allow for a complete characterization of the network material's mechanical behavior upon finite deformations [23–25]. Moreover, homogenization methods dedicated to the nonlinear response of composite materials have been presented [26,27]. Homogenization schemes have been complemented by the development of problem specific finite element (FE) models, used to investigate the deformation behavior of three-dimensional anisotropic architectured media, such as textiles [28–30].

Finite strains affect not only the static mechanical properties of materials, but also their wave propagation characteristics. While a relatively large number of works have dealt with the wave propagation analysis of architectured media and network material under small strains [31–34], large deformations wave analysis have comparatively received less attention, so that there still remains much to explore, both in terms of theoretical analysis and applications [35]. The effect of nonlinearities can be however prominent on the wave propagation characteristics of the structure analyzed [36]. Two types of nonlinearities can be primarily distinguished, namely: material and geometric nonlinearities [37,38]. The latter entail an amplitude dependent dispersion relation. Geometric nonlinearities relate to a deformation induced, modified inner material architecture that has been commonly modeled as a succession of incremental modifications of the materials' inner geometry [39]. The wave amplitude depends on the magnitude of the applied deformations; a physical behavior which has opened new frontiers in the so-called passive tuning of the dispersion diagram, going beyond a mere control of the dynamic and acoustic properties through the initial structural design [40].

Nonlinear periodic structures support a variety of wave solutions, which depend on the wave amplitude, on the wave interactions and on the type of nonlinearity. For example, solitary waves, harmonic waves and discrete breathers need to be used, depending on the wave propagation equation type [35,40–42]. In certain cases, specific constitutive law forms, such as cubic and quadratic constitutive relations have been employed to describe the nonlinear propagation of waves [38,42].

The dynamic characteristics of architectured media can be tuned through pre-stressing, a tuning mechanism that has been analyzed in different contributions [43–46,54]. It has been noted that there exists an initial deformation threshold for significant effects (such as partial bandgaps or instabilities) to be observed on the wave propagation characteristics; the threshold depends on the sensitivity of the initial inner material geometry on the magnitude of the applied strains [47]. Finite deformations control the tangent rigidity matrix in the case of large deformation and thus the materials' acoustic properties in a continuous manner. However, the feasible range of strains applied is limited by stability considerations: after a certain strain threshold, material instabilities arise [48–51]. Instabilities entail however wave propagation isolation in certain propagating directions. It is to note that, apart from the magnitude of the applied strains, highly anisotropic mass density distributions can be used to manipulate both the longitudinal [55] and flexural [56] wave

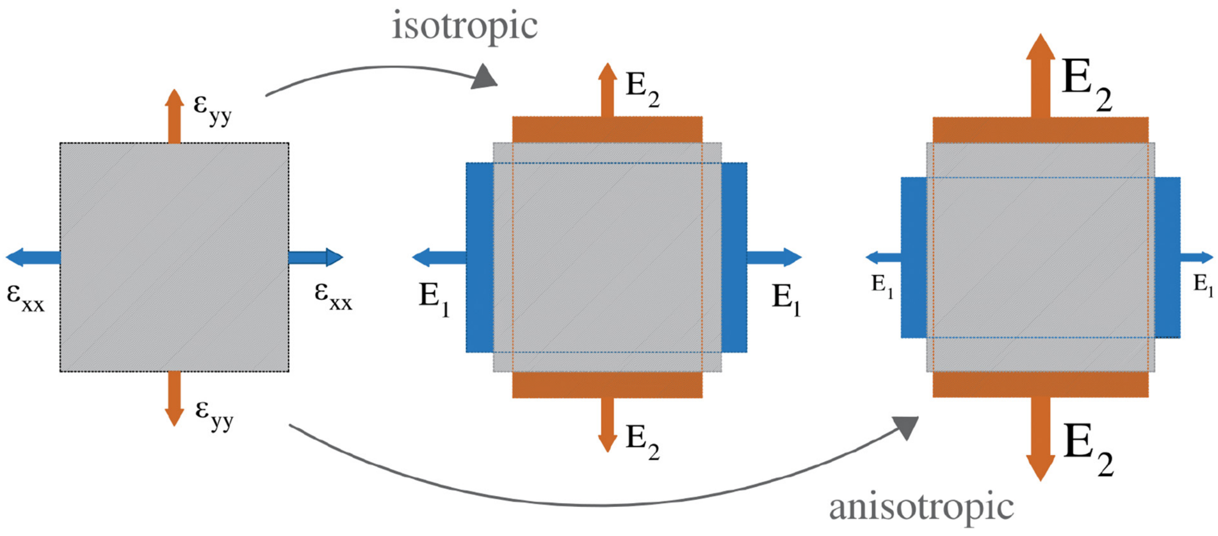

Fig. 1. Schematic representation of an anisotropic and isotropic two-dimensional material response upon the application of normal strains.