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Microstructure effects in wavy-multilayers with viscoelastic phases

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ABSTRACT

Microstructure effects in wavy-multilayers have been an important object of investigation due to several technological applications of this microstructure architecture found in practice, which includes bio-inspired materials. The investigated microstructure consists of stiff elastic wavy layers embedded in substantially softer viscoelastic matrix. The soft matrix does not produce much resistance as the wavy crimp pattern unfolds due to applied transverse loads, producing a stiffening effect, which depends on the local bending stiffness (or moment of inertia) controlled by the layer thickness. This microstructure effect has already been investigated in previous works considering elastic-plastic and non-linear elastic phases, in the infinitesimal and finite deformation domains, respectively. In this work, we further extend this investigation, employing the generalized FVDAM theory for the analysis of periodic materials with viscoelastic phases. As previously documented, this microstructure effect is negligible in the infinitesimal elastic domain, but it is significantly magnified along the time, when the viscoelastic effects take place. Different volume fractions and amplitude-to-wavelength ratios are considered for the analyzed multi-layers. The outlined discussion about the results of the conducted investigation becomes clear the importance of that stiffening effect for the design of viscoelastic wavy-multilayers.

1. Introduction

The multilayered composites, or simply multilayers, are important materials with lamellar architectures very commonly found in the nature, as well as, manufactured by the man for several technological applications. Composed of alternating layers made of two or more materials, multilayers can be found or built in different scales, with a myriad of combinations of both geometry configurations and constituent phases. They include biological tissues, artificial bio-inspired materials, thin metallic, ceramic and hybrid laminated structures designed for a large range of applications, such as in mechanical, optical, magnetic and electronic systems (Salonitis et al., 2010; Guinovart-Sanjuán et al., 2016; Adams and Bell, 1995).

Most of studies reported in the literature have focused on flat-layer laminates, in contrast with the relatively little publications on the behavior of multilayers with wavy microstructures. In the case of man-made multilayers, for instance, the layer waviness often develops as an undesirable fabrication defect or, in contrast, it is deliberately induced to attain specific material properties (Adams and Bell, 1995; Grenestedt and Hutapea, 2002). Wavy microstructures are also exhibited in a variety of natural biological systems, such as tissues, with essential functions (Liao and Vesely, 2003).

In spite of the technological potential of wavy multilayers, important local and macroscopic mechanical effects induced by the architecture waviness have not been yet addressed or explored. A clear understanding how local properties of the constituent phases, as well as, the arrangement and geometry of the layers, influence the macroscopic structural level is an essential requirement for the development of new generation of engineered multilayer materials and their applications. Micromechanical techniques are important tools to provide this fundamental understanding. For instance, well-conceived micromechanical theories allow to capture the influence of phase localized effects, such as, plastic flow, damage or failure occurring at different scales, on the macroscopic mechanical response of the material. The use of micromechanical techniques leads to substantially reduced time and costs to develop new heterogeneous materials with targeted performance characteristics by circumventing the traditional trial-and-error approach (Huet, 1990; Michel et al., 1999).

For the case of materials with periodic microstructures, including periodic multilayers with wavy architectures, Fig. 1, the

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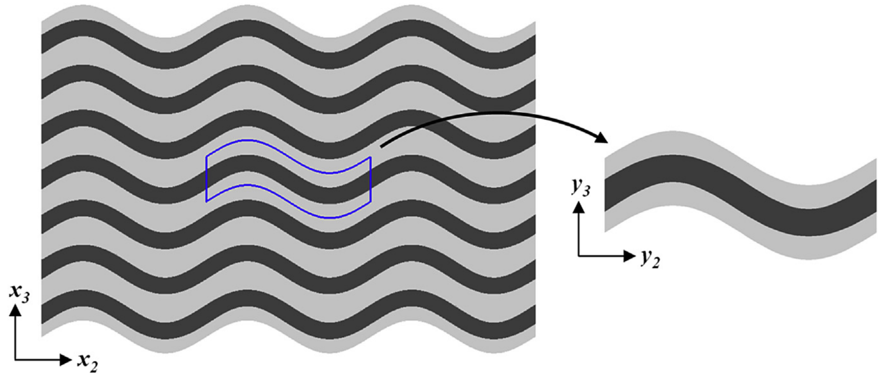

Fig. 1. A wavy lamellar material containing a highlighted unit cell of the periodic microstructure with amplitude-to-wavelength ratio of 0.1 and stiff-phase volume fraction of 0.40 (dark region).

micromechanical analysis is typically based on the concept of repeating unit cell (RUC), which represents the basic building block that characterizes the material microstructure (Michel et al., 1999). The effective or homogenized properties of the periodic composite material are obtained through the response of the RUC under combined periodic displacement and traction boundary conditions (Michel et al., 1999; Ostoja-Starzewski, 2006; Maghous and Creus, 2003; Saroukhani et al., 2015). This RUC boundary-problem is mostly solved using the finite-element method (Huet, 1990; Zohdi and Wriggers, 2008).

The homogenized version of the parametric finite-volume theory applied to periodic materials, so-called Finite-Volume Direct Averaging Micromechanics (FVDAM) theory, has demonstrated to be an attractive alternative to the finite-element approach in the solution of periodic RUC problems. The efficiency of this theory has been rigorously verified by extensive comparison of its results with solutions generated using analytical approaches and finite element techniques (Cavalcante et al., 2008, 2011, 2012). It has been successfully applied to homogenization of periodic composite materials with microstructures characterized by RUCs with different geometries and constituent phase behaviors. For instance, using the original work by Cavalcante et al. (2007), Gattu et al. (2008) developed and applied with success the framework of the parametric FVDAM for homogenization of periodic materials with elastic phases, followed by the implementation of thermal and plastic effects by Khatam and Pindera (2009a, 2009b). More recently, a generalized version of the parametric FVDAM has been constructed (Cavalcante and Pindera, 2014a, 2014b) and after extended to homogenization problems of periodic materials with viscoelastic phases by Cavalcante and Marques (2014).

In this work, the generalized FVDAM is applied to investigate viscoelastic microstructure effects in periodic multilayer materials. The investigated microstructure consists of stiff elastic wavy layers embedded in substantially softer viscoelastic matrix, Fig. 1. The soft matrix does not produce much resistance as the wavy crimp pattern unfolds due to applied transverse loads, producing a stiffening effect, which depends on the local bending stiffness (or moment of inertia) controlled by the layer thickness. Here, the mentioned effect is investigated through the creep functions of sequential unit cells generated by subdividing a stiffer thick layer within the unit cell, with a fixed geometry, into progressively thinner ones and redistributing the thinner layers uniformly in a manner that the volume fractions of the two phases are preserved (Fig. 2).

This microstructure effect has already been investigated in previous works considering elastic-plastic and non-linear elastic phases, in the infinitesimal and finite deformation domains, respectively (Khatam and Pindera, 2010, 2012; Cavalcante and Pindera, 2014b). As previously documented, this microstructure effect is negligible in the infinitesimal elastic domain, but it is significantly magnified along the time, when the viscoelastic effects take place. Different volume fractions and amplitude-to-wavelength ratios are considered for the analyzed multilayers. The outlined discussion about the results of the conducted investigation becomes clear the importance of that stiffening effect for the design of viscoelastic multilayers. To the best knowledge of the authors, there are not works published about the mentioned effect for time-dependent wavy-multilayer materials.

Fig. 2. Unit cells of the lamellar material comprised of sinusoidal architectures (amplitude-to-wavelength ratio of 0.1) with a fixed volume fraction of the hard phase layers of 0.40 (dark region), which are subdivided into progressively thinner plies.

2. Summary of the viscoelastic homogenization using the generalized FVDAM theory

This section presents a brief summary of the homogenization