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Influence of auxeticity of reinforcements on the overall properties of viscoelastic composite materials

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ABSTRACT

This work aims to analyze the damping response of viscoelastic composite reinforced by elastic auxetic heterogeneities by means of micromechanical modeling. The linear viscoelastic problem can be transformed into the associated elastic one via the Carson-Laplace transform (C-LT). Loss factors are taken into account by the introduction of the frequency-dependent complex stiffness tensors of the viscoelastic phases. The micromechanical formalism, based on the kinematic integral equation, leads to the computation of effective storage modulus and its associated loss factor in the quasi-static domain. The possibility to enhance viscoelastic (VE) properties of a polymeric material such as PVB is examined through several mixing configurations. Thus, the use of elastic auxetic heterogeneities is analyzed in comparison with classical elastic and viscoelastic reinforcements. The model predictions for VE phases, confirm the possibility to improve the global material stiffness. Also, it is shown in the particular case of elastic and spherical heterogeneities, by a proper choice of phases' stiffness ratio Q, that auxetic reinforcements represent a good compromise to have simultaneously enhanced stiffness and loss factor response in composite materials.

1. Introduction

Damping is one of the most important characteristics when a high capacity to absorb acoustic and vibration energies is desirable for a material. Thus, in aeronautics or automotive industries, materials with a high damping capacity are often requested (Wang et al., 2004). The viscoelastic behavior is important due to the intrinsic dissipation of dynamic strain energy in a material by conversion to heat. Nowadays, the use of polymeric matrix composite materials and multiphase polymeric systems, like Polyvinyl Butyrate (PVB), has been steadily increased (Koutsawa et al., 2009). Also, it has been observed that the best approach for modeling the macroscopic behavior of complex materials would be one that takes into account their intrinsic multiscale structure (Haberman, 2007). Therefore, in the design and the enhancement of viscoelastic composite materials, the micromechanics appears to be a powerful and precious tool.

Micromechanics describes the relationship between the global continuum properties of a material and its micro constituents or heterogeneities constituting the composite microstructure. The micro constituents are randomly dispersed and orientated with different shapes (Hlavacek, 1975, 1976) in the matrix phase. The transition from the micro- to the macro-scale is performed through a Representative Volume Element (RVE) in the sense introduced by Kröner (1977a,b). From Jarzynski (1990), it is well established that embedding some kind of heterogeneities into a material can increase its damping properties. Several works were dealt with the use of micromechanics formalism as homogenization tools in the area of viscoelastic material description (Alberola and Mele, 1996; Christensen, 1969; Gibiansky and Lakes, 1997; Hashin, 1970). Based on the composite sphere model of (Hervé and Zaoui,

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1993, 1995; Remillat, 2007) provided a framework to design composite materials with enhanced damping properties. He showed that the homogenized bulk modulus can be increased with high volume fraction of inclusions while the loss factor is given by that of the matrix regardless of the volume fraction, if the inclusion is either very stiff or very soft. Furthermore, Haberman (2007) used the self-consistent model proposed in Cherkaoui et al. (1994) to compute the effective moduli of a viscoelastic material containing coated spherical inclusions. In his analysis, losses are taken into account by introducing the frequency-dependent complex shear modulus of the viscoelastic matrix and the mode conversion appears through the localization tensors that govern the micromechanical behavior near the inclusions. Based on the multi-coated model developed by Lipinski et al. (2006) for anisotropic medium, (Koutsawa, 2008) studied in the quasi-static domain, the properties of viscoelastic composite material in which are embedded viscoelastic multi-coated heterogeneities. He has shown that by a suitable choice of the composite phases, one can design materials with very good stiffness and a good damping power in all frequency ranges. Also, he observed that the unusual negative stiffness behavior, first discussed by Lakes (2001), leads to advantageous changes in damping capacity of viscoelastic material. Negative stiffness is to be distinguished from negative Poisson's ratio (NPR). The NPR characterizes auxetic materials, which remain thermodynamically stable. Since the first works concerning synthetic auxetics carried out by Lakes (1987), many interests are focused on auxetic composites due to their technological applications in the design of innovative materials and structures (Stavroulakis, 2005). Various manufactured auxetic materials were reported in the literature. Case of polyester foam developed by Lakes (1987) and expanded polytetrafluoroethylene (PTFE), reported by Evans (2001), can be cited. Interesting applications of auxetic materials reside in the enhancement of viscoelastic properties and the deformation behavior (Yang, 2004). Due to interesting properties mentioned above, auxetics tend to be used to improve the macroscopic behavior of different structures. At the level of the structure, Scarpa et al. (2000) have shown, through the static and free-vibration simulations on sandwich beams with different core cellular materials, that it was possible to obtain both enhanced stiffness per unit weight and modal loss factors using two-phase cellular solids with a re-entrant skeleton (See Ref. (Scarpa et al., 2006) for more). Indeed, the possibility to achieve high stiffness and low loss, or high loss and low stiffness is well known (Gibiansky and Lakes, 1997; Wang et al., 2004). That is the case of the PolyVinyl Butyrate (PVB). Due to its important loss factor in acoustic frequencies, this material is used in technological applications such as laminated safety glass. In the same time, PVB remains very inapt in terms of stiffness. Therefore, this weakness limits its application in other technological domains where combination of high stiffness and high energy loss are required.

The main objective of the present work is to examine the effect of inserting auxetic inclusion phases in polymeric matrix on the enhancement of viscoelastic properties of composite materials. This work constitutes a theoretical support in the investigation of the use of auxetic materials as composite reinforcements. First candidate tested has been the PVB. The correspondence principle is first recalled to express the viscoelastic properties of phases in the time/frequency domain. The micromechanics approach used here is based on the kinematic integral equation formalism of Dederichs and Zeller (1973). By this formalism, various strain localization tensors can be obtained. The use of these tensors leads to several well-known micromechanics schemes tested to obtain the overall properties of the composite constituted by the PVB matrix and auxetic reinforcements. Finally, systematic analysis of various microscopic and overall parameters on the resulting viscoelastic properties is presented.

2. Fundamentals of viscoelasticity in time/frequency domain

Solution of some viscoelastic problems can be derived from the elastic-viscoelastic correspondence principle. Moreover, in the time domain, a Carson-Laplace transform (C-LT) may be applied to transform the time variable t into its corresponding one p. The viscoelastic problem is therefore converted into its associated elastic one. This principle has been widely used to tackle viscoelastic problems (Christensen, 1979).

The general form of the linear viscoelastic stress-strain relation is given by Christensen (1979):

$$\begin{cases} \boldsymbol{\sigma}(t,\boldsymbol{x}) = \int_{-\infty}^{t} \mathbf{R}(t-\tau,\boldsymbol{x})\dot{\boldsymbol{\varepsilon}}(\tau,\boldsymbol{x})d\tau \\ \boldsymbol{\varepsilon}(t,\boldsymbol{x}) = \int_{-\infty}^{t} \mathbf{J}(t-\tau,\boldsymbol{x})\dot{\boldsymbol{\sigma}}(\tau,\boldsymbol{x})d\tau \end{cases}, \tag{1}$$

where $\dot{\boldsymbol{\varepsilon}}(t,\boldsymbol{x}) = \frac{\partial \boldsymbol{\varepsilon}}{\partial t}(t,\boldsymbol{x})$, $\dot{\boldsymbol{\sigma}}(t,\boldsymbol{x}) = \frac{\partial \boldsymbol{\sigma}}{\partial t}(t,\boldsymbol{x})$. Functions $\mathbf{R}(t,\boldsymbol{x})$, $\mathbf{J}(t,\boldsymbol{x})$ are called relaxation and creep functions respectively while $\boldsymbol{\varepsilon}(t,\boldsymbol{x})$, $\boldsymbol{\sigma}(t,\boldsymbol{x})$ denote the local strain and stress tensors and $\boldsymbol{x}$ the position vector. Using the C-LT defined by:

$$\mathcal{C}(\mathbf{f}(t,\boldsymbol{x})) = \hat{\mathbf{f}}(p,\boldsymbol{x}) = p\int_0^{\infty} e^{-pt}\mathbf{f}(t,\boldsymbol{x})dt, \tag{2}$$

one can demonstrate that previous expressions of the viscoelastic constitutive relations (1) become:

$$\begin{cases} \hat{\boldsymbol{\sigma}}(p,\boldsymbol{x}) = \hat{\mathbf{R}}(p,\boldsymbol{x})\hat{\boldsymbol{\varepsilon}}(p,\boldsymbol{x}) \\ \hat{\boldsymbol{\varepsilon}}(p,\boldsymbol{x}) = \hat{\mathbf{J}}(p,\boldsymbol{x})\hat{\boldsymbol{\sigma}}(p,\boldsymbol{x}) \end{cases}. \tag{3}$$

Now, $\hat{\mathbf{R}}(p,\boldsymbol{x})$, and $\hat{\mathbf{J}}(p,\boldsymbol{x})$ are the C-LT of the relaxation and creep functions, respectively. In the frequency domain, the C-LT relaxation function $\hat{\mathbf{R}}(p,\boldsymbol{x})$ can be replaced by the complex moduli $\hat{\mathbf{L}}(\mathbf{i}\omega,\boldsymbol{x})$ such as (Christensen, 1969; Hashin, 1970):

$$\begin{aligned} \hat{\mathrm{L}}_{klmn} &= \hat{\mathrm{R}}_{klmn}(p,\boldsymbol{x})\big|_{p=\mathbf{i}\omega} \\ &= \mathbf{i}\omega\int_0^{\infty}\hat{\mathrm{R}}_{klmn}(t,\boldsymbol{x})\exp(-\mathbf{i}\omega t)dt \\ &= \mathbf{i}\omega\mathcal{F}(R_{klmn}(t,\boldsymbol{x})) \end{aligned} \tag{4}$$

where $\mathcal{F}$ represents the Fourier transform. Then, the strain-stress relation can be written in the time/frequency domain as:

$$\hat{\sigma}_{kl}(\mathbf{i}\omega,\boldsymbol{x}) = \hat{\mathrm{L}}_{klmn}(\mathbf{i}\omega,\boldsymbol{x})\hat{\varepsilon}_{mn}(\mathbf{i}\omega,\boldsymbol{x}). \tag{5}$$