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Damping properties of bi-dimensional sandwich structures with multi-layered frequency-dependent visco-elastic cores

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ABSTRACT

The aim of this paper is to present a finite element model based on first order shear theory (zig-zag approach) to compute the damping characteristics of sandwich structures with multi-layered frequency-dependent viscoelastic cores. The model is validated versus a layerwise finite element model and used to study damping and rigidity of a laminated glass configuration with a multi-layered visco-elastic core composed of acoustic PVB and PVB. It is shown that the rigidity index of the structure (defined as the adimensionalized inverse of the maximal transverse displacement under a static load) evolves linearly with the viscoelastic layers' thicknesses and quadratically versus elastic layer's thickness. The first mode damping and resonant frequency show a non monotonous behaviour. In particular, the existence of an optimal faces thickness for damping is shown while a quadratic behaviour of frequency versus acoustic PVB layer thickness is reported.

1. Introduction

Viscoelastic sandwich structures are commonly used as damping devices in many domains such as aeronautics, aerospace, mechanical and civil engineering. They play a key role in vibration control, shocks absorption and noise reduction. They are made of two identical elastic and stiff layers separated by at least one soft viscoelastic layer. Due to the difference between in-plane displacements of the elastic layers and to the low viscoelastic core stiffness, the latter experiences a strong shear which is known to be responsible of the damping properties of viscoelastic sandwich structures. The study of sandwich structures started in 1959 with the work of Kerwin [1] that has been further improved by Ungar [2] in 1962. Analytical methods were first developed to estimate damping properties (loss factor and resonant frequencies) of sandwich beams and plates with simple boundary conditions. These can be found in the works of DiTaranto and Blasingame [3], Mead and Markus [4] and Rao [5]. Since then, many investigations have been devoted to vibration analysis of viscoelastic structures and especially damping properties computation. In the finite elements framework, several works in the literature have been devoted to model viscoelastic structures [6–12]. However, modelling frequency dependent viscoelastic sandwich structures implies dealing with nonlinear problems because of the frequency dependence of the stiffness matrix. Unfortunately, legacy finite elements codes such as Abaqus or Ansys are not able to solve these nonlinear problems efficiently. Numerical methods such as the modal strain energy method [13] and the asymptotic numerical method [14] have been developed in order to solve the resulting nonlinear problem. An overview of the different methods of resolution can be found in [15]. Recently, the research has focused on multilayer or laminated sandwich structures for their improved multifunctional properties in terms of mechanical damping, rigidity, acoustics, etc. Araujo et al. [16] presented a finite element model for damping analysis of anisotropic laminated viscoelastic sandwich structures. Li and Narita [17] studied the optimal design of symmetrical laminated thin plates comprised of fiber-reinforced layers and viscoelastic layers by varying the material fibers orientation. Nguyen et al. [18] developed a higher-order zig-zag theory for viscoelastic laminated composite plates for efficient temporal response computation. Yang et al. [19] performed vibration analysis of multilayer thick sandwich cylindrical shells with a viscoelastic core under arbitrary boundary conditions investigating the effect of fiber orientation angle and thickness. Akoussan et al. [20] presented a finite element model for multilayer orthotropic viscoelastic sandwich structures along with a resolution method based on asymptotic numerical method. Bouayed and Hamdi [21]

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proposed a shell finite element model for vibroacoustic studies of multilayers car windscreens while providing a good review of the past finite element models for multilayers structures. However, to the author's best knowledge, most of the studies that can be found in the literature on multilayer viscoelastic sandwich structures do not consider the possibility of having multi-layered viscoelastic cores made of different types of viscoelastic materials. For example, windscreens vibro-acoustical damping properties can be enhanced by using multi-layer viscoelastic layers made of a plastic layer sandwiched by two PVB layers [22]. Furthermore, the noise damping properties of security laminated glass can be enhanced by sandwiching a high stiffness polymer layer by two low stiffness but high damping polymer layers [23]. In the present work, the authors propose a finite element model based on the zig-zag approach to model a five layered sandwich beam with a viscoelastic core made of two different layers of viscoelastic materials. The model is thought as a tool to study different properties of sandwich structures with multi-layered frequency dependent viscoelastic cores. An application to a five layered laminated glass is considered and the impact of the relevant parameters studied. In Section 2, the model kinematics along with the assumptions made are presented. Then, in Section 3, the variational formulation of the problem using the principle of virtual work is derived. In Section 4 the finite element model is detailed along with the resolution technique. In Section 5, the finite element model is validated for frequency dependent and frequency independent viscoelastic cores. In Section 6, the model is used to compare some relevant design characteristics (damping, frequency and rigidity) of a laminated glass structure with a multi-layered viscoelastic core.

2. Kinematic model

The five layered sandwich structure is assumed to be symmetric as depicted on Fig. 1. The first layer is elastic of thickness h_f, the second layer is viscoelastic of thickness h_{c_1} and the central layer is viscoelastic of thickness h_{c_2}. By symmetry, the fourth layer is viscoelastic of thickness h_{c_1} and the fifth layer is elastic of thickness h_f. Strain and displacement fields in each layer described by a "zig-zag" model has been adopted: the displacement field in the elastic layer derives from an Euler-Bernoulli approach whereas a Timoshenko model characterizes strain and displacement field in the viscoelastic layers. The present analysis is based on the following assumptions [24,25]:

- All the materials are assumed linear, homogeneous and isotropic.
- There is no shear in the elastic layers.
- The transverse displacement is assumed to be the same for all plies.
- The Young's modulus of the viscoelastic layers is complex frequency dependent, but the Poisson ratio is assumed to be constant.
- No slipping occurs at the interfaces between the different layers.
- The elastic layers have the same Young's modulus and mass density.

Fig. 1. Five layered sandwich beam structure.

In the following, x denotes the longitudinal coordinate, z the vertical coordinate and t the time. In all the paper, we shall use the following convention $\frac{\partial g}{\partial x} = g'$ and $\frac{\partial g}{\partial t} = \dot{g}$, with g a function of (x, t). Regarding all the above assumptions, the displacement field and associated deformation in the elastic layer can be expressed as:

$$U_i(x,z,t) = u_i(x,t) - (z - z_i)w', \tag{1}$$
$$W_i(x,z,t) = w(x,t), \quad i = 1,5 \tag{2}$$
$$\varepsilon_i(x,z,t) = u_i' - (z - z_i)w''. \tag{3}$$

where u_i is in-plane displacement of the ith layer and $w$the common transverse displacement.

On the other hand, the displacement field and associated deformation in the viscoelastic layer can be expressed according to Timoshenko theory:

$$U_i(x,z,t) = u_i(x,t) + (z - z_i)\beta_i(x,t), \tag{4}$$
$$W_i(x,z,t) = w(x,t), \quad i = 2,3,4 \tag{5}$$
$$\varepsilon_i(x,z,t) = u_i(x,t)' + z\beta_i(x,t)', \tag{6}$$
$$\xi_i(x,z,t) = \beta_i(x,t) + w(x,t)', \tag{7}$$

where ξ_i is the shear strain, $\beta_i$is the rotation of the mid-plane of a viscoelastic layer i. The second viscoelastic layer in the structure's core is taken as the central layer $u_3 = u$. Furthermore, requiring the continuity of the displacement field at the interfaces between the different layers results in the following relationship:

$$u_1 = u_2 + \frac{h_{c_1}\beta_2 - h_f w'}{2},$$
$$u_2 = u_3 + \frac{h_{c_2}\beta_3 + h_{c_1}\beta_2}{2},$$
$$u_4 = u_3 - \frac{h_{c_2}\beta_3 + h_{c_1}\beta_4}{2},$$
$$u_5 = u_4 - \frac{h_{c_1}\beta_4 + h_f w'}{2}.$$

By setting $u_3 = u$ and using the symmetry hypothesis (which gives $\beta_2 = \beta_4$), the above displacement field can be rewritten as a function of the displacement of the central layer:

$$u_1 = u + h_{c_1}\beta_2 + \frac{h_{c_2}\beta_3 - h_f w'}{2}, \tag{8}$$
$$u_2 = u + \frac{h_{c_1}\beta_2 + h_{c_2}\beta_3}{2}, \tag{9}$$
$$u_4 = u - \frac{h_{c_2}\beta_3 + h_{c_1}\beta_2}{2}, \tag{10}$$
$$u_5 = u - h_{c_1}\beta_2 - \frac{h_{c_2}\beta_3 - h_f w'}{2}. \tag{11}$$

3. Variational formulation

The virtual work principle is applied to establish the equation of motion of the five layered sandwich beam. The virtual work principle components of a symmetric five layered sandwich beam can be expressed as the sum of the different virtual works of all the layers:

- In the elastic layers
$$\int_0^L (N_i \delta u_i' + M_i \delta w'')dx = -\rho_f S_f \int_0^L \ddot{w}\delta w dx. \tag{12}$$
- In the visco-elastic layers
$$\int_0^L (N_i \delta u_i' + M_i \delta\beta_i' + T_i(\delta\beta_i + \delta w'))dx = -\rho_{c_i} S_{c_i} \int_0^L \ddot{w}\delta w dx, \tag{13}$$