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A simplified approach to model damping behaviour of interleaved carbon fibre laminates

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ABSTRACT

Interleaving a viscoelastic layer within a laminate has been individuated as an efficient architecture for increasing damping performance of plane structures. A semi-analytical model based on the first order shear deformation theory accounting for the out-of–plane strain contributions to the energy dissipation in composite laminates with interleaved architecture is proposed. Two different configurations for the interleaved composite laminate architecture have been manufactured and tested in bending. The elastic and dissipative material functions for the elongational and shear modes have been experimentally characterised for the constituents of the interleaved laminates: the unidirectional lamina and the damping layer material. These constitutive material behaviours have been used for the model calculations. A satisfactorily agreement between the experimental data and predicted results has been found for the bending behaviour of the different architectures.

1. Introduction

Advanced fibre reinforced composites are commonly used in weight sensitive structural applications due to their high stiffness to weight ratio. However, due to the weight reduction itself the polymer matrix composite structures exhibits a very low vibro-acustic damping in respect to standard metallic structures. The current designing practice is characterized by a sequential methodology, where structure optimization is primarily performed with respect to the stiffness and the strength. The fulfilment of relevant functional requirements such as the thermal and the acoustical insulation is later addressed with weight penalties for the structure. The necessity of a multidisciplinary design approach addressing the transition from the metallic to the composite fuselage aircraft that includes not only mechanical issues but also the vibration suppression and thermal insulation features has been illustrated by a series of papers by Van Tooren et al. [1]. The detrimental effect on the structural efficiency resulting by the application of a viscoelastic layer to the fuselage skin panel for the improvement of the acoustical insulation has been discussed in the latest paper of the series leaving room to further improvement. In particular, the local addition of the viscoelastic materials to the vibrating structure has been the standard procedure to control vibration amplitude for composite fuselage panels [2–5]. This latter architectural solution implemented by a retrofitting design procedure leads to relevant waste of the weight gain resulting from the use of composite materials. As matter of fact, the flexibility of composite materials gives the chance to design and manufacture final elements which are simultaneously compliant to both structural and vibro-acoustic requirements of a primary structure. The development of multifunctional design tools integrating structural and damping features enables a next step toward the exploitation of the composite material benefits and applications.

The structural damping in the case of a composite fuselage represents a multiscale top-down with specific functionality determined by the behaviour of the stringers reinforced skin, which, in turn, is associated to the panel damping behaviour owning its features to its laminate architecture and constituent materials itself.

Different disciplines are involved to develop design tools for the various dimensional scales. From the bottom-up perspective, robust governing equations for the structural and viscoelastic behaviour of constituents materials to be passed through the different dimensional scales are needed to perform reliable dynamical structural analysis of proper bounded sub elements and, in turn, to be implemented into the whole fuselage barrel design.

In particular, the insertion of viscoelastic layer within the laminate has been individuated [6,7] as the most promising

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architecture for increasing damping performance of plane structures. In particular, the dynamical behaviour of elementary structures (beam, plates) based on the interleaved viscoelastic layer architecture has been intensely investigated and a plenty of models have been proposed for the evaluation of the damping loss factor at the structure mechanical resonances (modal analysis). The pioneering works of Ross et al. [8] have investigated the constrained layer configurations where a metallic plate have been added with a viscoelastic layer upper constrained by a thin metallic layer. They focused on the evaluation of the flexural modal damping properties of the hybridised plate structure where mechanical energy dissipation was assigned only at the viscoelastic layer. Based on this method, Cupial et al. [9] have been developed later a method for calculating the modal in-plane flexural loss factor of a composite panel with a viscoelastic interleaved layer by the use of first order shear deformation theory where the composite layers were considered orthotropic. A considerable effort has been made by the group of Saravanos that in a series of papers introduced a real multiscale model for the modal behaviour of an interleaved hybrid composite starting from constituent materials. In particular, in Saravanos et al. [10], the increasing in damping properties of composite plates by embedding viscoelastic layers in the material stacking sequence was considered and discussed. A semi-analytical method has been further proposed by Saravanos [11] to solve the dynamical motion of the hybrid interleaved laminate involving high-order and discrete layer theories to include transverse shear effects in laminates. Eventually, Berthelot [12] proposed a generalised method for modal damping calculation in the case of composite plates and beams based on the Ritz method where the transverse shear effects are introduced trough equilibrium condition on laminate thickness.

Modelling the composite material viscoelasticity has followed two alternative approaches: the Correspondence Principle (CP) and Strain Energy Method (SEM) (see Chandra et al. [13,14]). In particular this latter approach has related the total damping of a composite material or a composite structure to the damping of each constituent phase and the fraction of the total strain energy stored in this phase. According to this approach, for any system of linear viscoelastic elements, the loss factor can be expressed as a ratio of product summation of individual element loss factor and strain energy stored in each element to the total strain energy. Ni et al. [15] developed a model for flexural damping behaviour of a composite laminate based on the classical plate theory by using the "Strain Energy Method" (SEM). Saravanos proposed later in 1989 a micromechanics approach for the calculation of the lamina loss factor including the out-of-plane effects through high order thick laminate theory [16]. Yim et al. [17] have been used the equilibrium equations to account for the transverse shear stresses in predicting the modal loss factor. Melo and Radford [18] proposed the use of the dynamical mechanical analysis method to characterize the composite lamina constitutive equation based on the Strain Energy Method (SEM) by the introduction of only four viscoelastic independent parameters for each lamina as function of temperature [19]. The DMA based approach allows to investigate the effects of temperature and frequency on viscoelastic properties of composites by the experimental study on global lamina properties.

In the present work, the in-plane standard strain energy approach is extended taking into account the shear contributions related to the transverse shear stress components according to Rolfes-Rhower model.

Taking advantage of the SEM formalism, which could be applied to different dimensional scale, a simplified modelling approach is presented to model the elastic and the dissipative properties of composite laminates. A detailed experimental campaign was carried out to measure the in-plane and the out-of-plane elastic and dissipative properties for the unidirectional "unit" lamina of the composite and for the viscoelastic damping layer. Obtained material functions were input to the model to compute the elastic and damping behaviour of hybrid laminates, characterised by three different configurations. Comparison of the model predictions with the experimental data works out very satisfactorily thus the damping behaviour of different hybrid configurations can evaluated without further verification tests.

The proposed approach allows the evaluation of the complete viscoelastic behaviour of an hybrid laminate based on the first order deformation theory. In particular, the analytical formulation of the energy loss due to the transversal shear modes has been developed. The method allows a semi analytical solution in respect to the actual numerical solutions [11,14]. The prosed approach requires that the constitutive viscoelastic components of the lamina are the only needed fundamental material properties to describe the overall behaviour of the hybrid laminate. To this aim, direct measurements of the lamina properties have been carried out by dynamical mechanical tests. In- and out plane properties were measured by bending and torsional tests, respectively. A fairly good agreement of the model predictions with the bending behaviour of different hybrid architectures has been achieved.

2. Dissipative behaviour of composite laminate

An elastic solid is deformed with strains (ε, γ) and loaded with stresses (σ, τ) when external forces are applied. The work of external forces is stored as strain energy, U, according to the following relationship:

$$U = \frac{1}{2}\int_V \underline{\sigma}\cdot\underline{\varepsilon}\,dV \tag{1}$$

with $\underline{\sigma}$, $\underline{\varepsilon}$, respectively, the stress and strain tensors and dV representing the unit volume element. The total energy stored within the material can be computed as the sum of the energy stored in all constituent phases of the elastic body, as:

$$U = \frac{1}{2}\sum_{V_i}\left(\int_{V_i} \underline{\sigma}\cdot\underline{\varepsilon}\,dV\right) \tag{2}$$

The mechanical energy dissipated by a material, is measured by the Specific Damping Capacity (SDC), which represents the ratio between the dissipated and total energy, as follows:

$$\psi = \frac{\delta U}{U} = 2\pi\tan\delta = 2\pi\eta \tag{3}$$

The derivation of the eq. (2) could be find elsewhere [20]. The strains and stresses generated by external forces, dissipate energy by different mechanisms, therefore damped energy can be evaluated for corresponding tensor element by summation of each term, as follows:

$$\delta U = \frac{1}{2}\int_V \underline{\psi}(\underline{\sigma}\cdot\underline{\varepsilon})\,dV \tag{4}$$

where ψ is the material *specific damping capacity* (SDC) as defined in eq. (3).

The global laminate stiffness matrix could be calculated starting from stiffness matrix Q for each layer as follows (commonly referred as Kirchhoff-Love model [21]):