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A Passive Approach to the Development of High Performance Composite Laminates with Improved Damping Properties

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Abstract

This paper explores the use of a viscoelastic material as a passive and straightforward solution towards the development of a hybrid composite material with improved damping properties. A cork based composite was selected as viscoelastic material due to its low weight combined with excellent damping properties, showing a great potential for vibration control. Two forms of specimens were considered: 1) a sandwich consisting of carbon-epoxy facesheets and a cork agglomerate core; 2) a carbon-epoxy laminate with embedded cork granulates. The experimental determination of the loss factor was based on the bandwidth method, being a determinant step to obtain relevant dynamic properties of the material for the development of an accurate computational model based on the different types of geometries. Results are encouraging about the possible use of cork based composites as a viable passive solution to improve the damping properties of high performance composites according to the design requirements for particular applications.

Keywords: sandwich components, viscoelastic material, composite material, structural damping, loss factor, cork.

1 Introduction

High performance composite laminates are used as structural materials in a wide range of applications with demanding stress-to-weight ratios, such as in the case of aeronautical components. However, the elevated stiffness of most composites implies a reduced loss tangent which is an effective measure of the damping capabilities of this type of materials. This can cause higher displacement levels in the event of dynamic loading conditions, which can eventually promote cyclic dependent damage mechanisms (like fatigue) and even a catastrophic failure of a structure in extreme conditions. In these situations it is mandatory to modify the physical structure of the system to reduce both the amplitude and time of response to an external excitation. Active damping systems have been gaining a raising interest as a possible solution to vibration control, in particular those using smart materials and structures with adaptive features [1]. Recent investigations [2-5] confirmed the advantages of using adaptive structures for vibration control purposes induced by aeroelastic phenomena, the most part combining high performance composite and metallic materials with bonded smart actuators, such as piezoelectric materials. However, active systems typically have limited strain/force response capabilities requiring a considerable amount of energy, which makes this a rather inefficient solution.

Passive damping seems to have greater advantages in terms of energy efficiency and reliability of machines/structures than active damping, since this approach is based in simple solutions regarding the use of structural modifications, isolation techniques and/or damping materials [6]. This latter option typically requires viscoelastic materials with an intrinsic capacity of dissipating mechanical energy. Most of the times, these materials are combined with high strength/stiffness FRPs in the form of a hybrid composite, which has been explored by some researchers during the past few decades. In fact, constrained layer treatment has been proposed by some researchers since the early 1950s [7, 8] as a successful technique to enhance the damping properties of composite laminates, resulting from the energy absorption induced by shear strain between the damping layer and the high-stiffness constraining layers. Ungar et al. [8] suggested a multiple constrained layer treatment where the increase of damping can be quite considerable at low frequencies, especially for a large number of layers. These authors also found that the damping characteristics of a damping layer treatment are determined by the sum of all constraining layers, whereas their relative thicknesses have only a small effect. Based on this first evidence about the benefits of constrained viscoelastic damping, other authors explored the influence of different parameters of the materials aiming at improving their energy absorption capabilities [9-12]. More recently, the utilization of advanced optimization procedures based on the development of specific computational models resulted into the optimization of modal loss factors of sandwich plates with elastic laminated constraining layers, as in the case of the work of Araújo et al. [13], where the thicknesses and laminate layer ply orientation angles were considered as design variables.

The inclusion of viscoelastic layers within composite laminates can also be done through a co-curing process. In this case, the anisotropy of the fiber-reinforced constraining layers favors the damping mechanisms due to the higher capacity of energy dissipation of composites compared with conventional isotropic materials (such as metallic layers). This latter approach has been followed in recent years as a consequence of a better trade-off between the improvements of damping characteristics with little reduction in strength and/or stiffness of composite structures [14], which in turn are gaining a raising position in high performance applications, such as airframes and space structures.

The main objective of the present paper is to study a passive damping system based on the addition of a single layer of a viscoelastic material to a primary structure. In this case, a CFRP laminate with a cork agglomerate layer placed in the middle plane was considered. The reason for considering cork as the viscoelastic material follows from the excellent energy absorption properties of this natural material, which were confirmed in previous works regarding the characterization of cork based composites under static and dynamic loading conditions [15].

A FEM analysis was undertaken to assess the influence of the cork agglomerate layer in the dynamic response of the material, in particular in the improvement of the loss factor. Numerical results were confirmed with experimental data obtained from dynamic testing of this sandwich type configuration of the material.

2 Numerical analysis

2.1 Viscoelastic model

It is well known that the response of a general mechanical system with *n* degrees of freedom can be represented by Equation (1).

$$[\mathrm{M}]\ddot{X} + [\mathrm{C}]\dot{X} + [\mathrm{K}]X = [\mathrm{F(t)}] \tag{1}$$

where [M], [C], [K] are the mass, damping and stiffness system matrices; [F(t)] is the external load vector to be considered in the numerical model; $\ddot{\mathrm{X}}$, $\dot{\mathrm{X}}$ and X are the acceleration, velocity and position vectors.

Also, from the Rayleigh damping model, the energy dissipation of this system can be expressed by a damping matrix [C] with symmetric coefficients, which in turn can be related to the mass and stiffness matrices using the following relationship:

$$[\mathrm{C}] = \alpha\,[\mathrm{M}] + \beta\,[\mathrm{K}] \tag{2}$$

Here, α is the mass proportional damping factor and β is the stiffness proportional damping factor. These matrices can be determined from a numerical model implemented using a conventional finite element model (FEM) code, as in the present situation. In the formulation of Rayleigh damping, the mass proportional damping effect is considered to be dominant in the lower frequencies, whereas the stiffness proportional damping is dominant at the higher frequencies. In this work, it is assumed that $\beta \ll 1$ due to the relative low frequencies to be expected during the operation of the structural component to be developed. It can be found [15] that for a given mode *i* the mass proportional damping factor using the related damping model is given by the following expression:

$$\alpha_i = 2 \cdot \omega_i \cdot \xi_i = \omega_i \cdot \eta_i \tag{3}$$

In the above equation ω_i is the damped natural frequency for the *i*th vibration mode. It is quite clear that for a given finite element model with certain mass and stiffness matrices, the results of the dynamic analysis depend hugely on the values given to parameters α and β. Therefore, it is of significant importance that the numerical values assigned to the mass coefficient should be based on experimental data obtained for the particular specimen geometry and types of materials considered in this analysis.

As mentioned before, viscoelastic materials possess a capacity to both store and dissipate mechanical energy. The mechanical properties of these materials can be described by a combination of a real and a complex component. In fact, the elastic and viscous stresses are related to material properties through the ratio of stress to strain, which is either called the storage modulus (if elastic stresses are considered) or loss modulus (in the case of considering viscous stresses). The ratio of the viscous modulus to the elastic modulus is the tangent of the phase angle shift between the stress and strain vectors, i.e., tan δ, which is a commonly used parameter for assessing the damping capability of most materials. In the particular case of the cork agglomerates used in this work, the main mechanical properties which were considered for the development of the numerical model were provided by the material's manufacturer, Amorim Cork Composites, having being obtained by a dynamic mechanical thermal analysis technique (DTMA).

2.2 Numerical model

The numerical model was based in the finite element method, being developed using the commercial FEM code ABAQUS®. The main objective of the numerical analysis was to obtain the dynamic response of a rectangular flat plate representative of the sandwich with a cork agglomerate core. Results were compared with a plain CFRP laminate aiming at determining the influence of the viscoelastic layer in the variation of the loss factor.

The plate was considered fixed at one end and subjected to an impulsive concentrated load of 1N applied at the centre of the free tip, as shown in Figure 1(a). This load was simulated using a very short period of application, in this case 0.05s. The load value was chosen to be small enough as to avoid large displacements allowing the validity of linear theory to be maintained. A mesh quality performance evaluation was carried out using a convergence analysis of the natural frequencies of the component as the targeting output. Results were compared considering meshes with different amounts of elements in order to settle a compromise between accuracy and computing time. At the end, a structured mesh with a total of 990 shell type elements was used. For illustration purposes, Figure 1(b) presents the mesh used to obtain the second mode of vibration of the plate under bending.

The plate geometry was representative of a 450mm x 60mm laminate specimen with a $[0_2\ 90_2\ 0_2\ 90]_s$ stacking sequence. It should be noted that the thickness of each layer of CFRP after curing is around 0.15 mm.

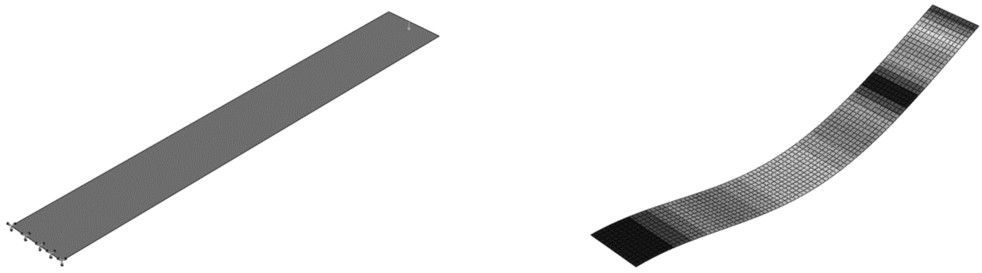

Figure 1 – Flat plate model: a) load and boundary conditions; b) mesh and representation of the second mode of vibration.

2.3 Experimental testing

2.3.1 Material

A high strength unidirectional carbon prepreg with modified epoxy resin was used to fabricate the composite laminates. As mentioned before, the viscoelastic layer was positioned in the middle-plane of the specimen considering two distinct configurations of the material: 1) a microsandwich typology with a 1mm thick NL10® cork agglomerate core (provided by Amorim Cork Composites); 2) a very thin cork dust layer embedded in the laminate during the manual ply-up staking operation (cork dust was mixed with an epoxy resin system to obtain an uniform layer). The main mechanical properties of the cork agglomerate core can be found in Table 1, whereas the characteristics of the different types of laminates are shown in Table 2.

Specimens were cured through an autoclave process according to the recommendations of the manufacturer of the prepreg material. During the stacking procedure, special care was put in the introduction of the cork based viscoelastic layer (either in the form of a cork agglomerate or a dispersed cork dust layer), ensuring that an extra amount of epoxy resin was used to provide an adequate adhesion between the viscoelastic and constraining layers.

Density	140 [kg/m3]
Poisson's ratio	0.1
Tensile strength	0.6 MPa
Shear modulus	5.9 GPa
Loss factor (at 1kHz)	0.022

Table 1 – Mechanical properties of the cork agglomerate core

Specimen	Stacking sequence	Thickness (mm)
CFRP	$[0_2\ 90_2\ 0_2\ 90]_s$	2.2
CFRP with a core cork layer	$[0_2\ 90_2\ 0_2\ DCL\ 0_2\ 90_2\ 0_2]$	3.2
CFRP agglomerate with a cork dust layer	$[0_2\ 90\ CCL\ 90\ 0_2\ 90]_s$	2.5

Table 2- Configuration of the laminate plates

2.3.2 Testing procedures

Dynamic testing aimed at determining the loss factor for different configurations of the material, as described in the previous section. The bandwidth method was used for this purpose, which consists of determining the frequencies at which the amplitude of two consecutive points (Z1 and Z2, having Figure 2 as reference) in the response curve of a dynamic system will equal $1/\sqrt{2}$ of the amplitude of a peak in that response.

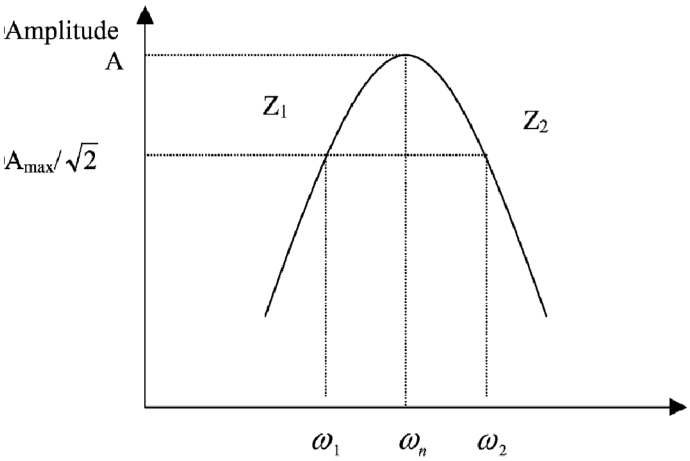

Figure 2 – Half-power bandwidth method.

The bandwidth at these points is known as half-power bandwidth. The half-power points for small damping corresponds to the frequencies $\omega_1 = \omega_n(1-\xi)$ and $\omega_2 = \omega_n(1+\xi)$ where ξ is the damping ratio mentioned above. The frequency interval between this two points is $\Delta\omega = \omega_2 - \omega_1$. The loss factor is defined by Equation (4):

$$2\xi = \frac{\Delta\omega}{\omega_n} \tag{4}$$

An instrumented impact hammer (Dytran Instruments, Dyna Pulse) was used to excite the beams that were free in space (suspended by two nylon threads on a rigid frame). The frequency response was obtained in a range of frequencies from 10Hz to 1500Hz with an accelerometer (Brüel&Kjær 4374) located on the opposite side of the hammer hot point (on the lengthwise direction). A spectrum analyzer (CSI 2120) and an accelerometer conditioner (Brüel&Kjær 2635) were also used. The hammer impact characteristic was obtained from a sensor placed on the hitting face. A total of four tests were made for each type of specimens and a series of ten shots was performed in each specimen which were acquired by the transducer considering a valid shot whenever the coherence value was close to unity. The data were processed on a computer using two software programs: Vibpro® and LabView®. The first code is used for pre-processing purposes of the data and to obtain the representation of the frequency response. The latter code is used to determine the loss factor related to different frequencies using a routine created by the authors, consisting in an algorithm that automatically extracts points at 3dB below each peak, [17]. This process allows also for manual adjustment whenever the automatic routine fails the detection of the resonant peak. All the calculations were made taking into consideration -3dB and -6dB variations, since these two thresholds allowed confirming the coherence of the loss factor for each frequency, therefore validating in some way each acquisition.

3 Results and discussion

Figure 3 shows the variation of the loss factor as a function of frequency for the different configurations of materials. The lower frequency limit (80Hz) is imposed by the first mode of vibration of the plate in the test setup. However, these results should be considered with some reserves due to the reduced accuracy of the testing equipment for low frequencies.
For a better interpretation of the results all the values regarding each specimen are included in this figure so the difference between the loss factor variations as a function of the frequency can be visualized more easily by observing the distances comprised within the same cloud of points for a given frequency.

From the observation of these results it becomes clear that there is a damping effect caused by the viscoelastic layer within the laminate regardless the type of material (i.e., cork agglomerate core or cork dust layer). This damping effect is visibly higher close to the upper limit of the frequency rage (1300Hz), where an average 50% increase in the loss factor was found for specimens with cork agglomerate core. On the other hand, this value is approximately halved for those specimens with cork dust layers. Nevertheless, the damping benefit resulting from the inclusion of the viscoelastic layer (whichever its form) is evident for frequencies above around 200-400Hz, as the cork based laminates appear to have an increasing trend of their corresponding loss factor in opposition to plain CFRP laminates, which shows a damping capacity decrease for higher frequencies.

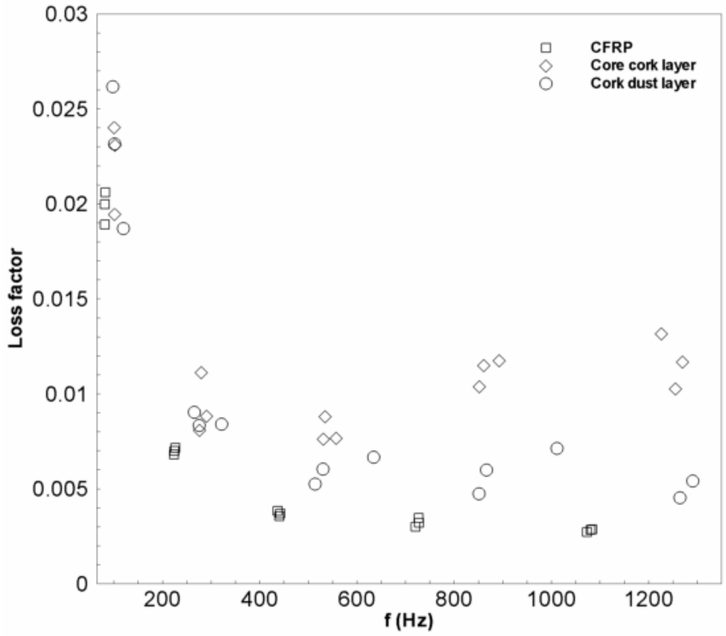

Figure 3 - Loss factor variation as a function of frequency (as obtained from experimental testing)

The enhancement of the damping properties resulting from the utilization of a viscoelastic layer within the composite laminate was corroborated by the results of numerical analysis. The numerical predictions of the dynamic behavior of both CFRP laminates and sandwich specimens in the form of the maximum displacement as a function of frequency considering the bending mode response is presented in Figure 4. This image does not include the response of those specimens with a damping layer in the form of a cork dust film, since the numerical results for this type of material showed some inconsistencies which need further working. Nevertheless, it becomes clear that the damping effect of the cork agglomerate core has a consequence in the reduction of the displacement field for all the vibration modes shown in this figure. On the other hand, the inclusion of the viscoelastic layer has a direct effect in the natural frequency values for the two types of materials, since the response regarding the laminates with improved damping properties is clearly shifted to the right in the graph. Table 3 presents the results of the natural frequencies for the different bending modes of CFRP laminates with and without the cork layer. It is evident that the use of this type of viscoelastic material is a straightforward solution to increase the natural frequencies according to the design requirements of a certain structure, in part due to the higher laminate thickness caused by the introduction of the viscoelastic layer. It is interesting to mention though that this shifting effect of the eigenvalues is more pronounced in the lower limit of the frequency range considered in the numerical analysis, as a frequency increase varying from around 70% to 10% was found for the lowest and highest frequency value, respectively.

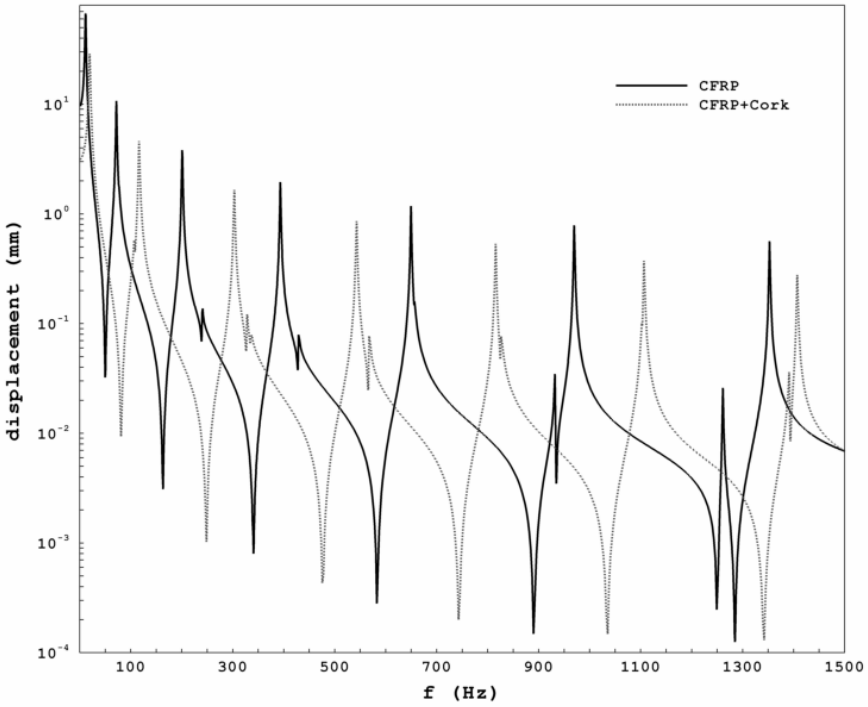

Figure 4 – Magnitude of frequency responses for CFRP laminates and cork agglomerate core specimens.

	CFRP	CFRP + cork layer
Vibration mode	f (Hz)	f (Hz)
1	11,4539	19,5629
2	71,8167	116,495
4	201,335	303,657
7	395,332	544,887
9	655,327	820,321
12	982,408	1115,55
14	1378,02	1421,93

Table 3- Variation of the natural frequencies regarding different vibration modes (bending) for CFRP laminates with and without cork damping layer

A final word about the properties of the cork based material considered in the numerical analysis is required: during the autoclave curing process, it was found that a marginal part of epoxy resin was transferred from the prepreg material to the interior of the cork core (which has a cellular type morphology). Therefore, a slight alteration of the nominal rigidity value provided by the manufacturer of the cork agglomerate should be accounted for to obtain accurate results in terms of comparative purposes between the numerical and experimental results. In this case, a 3% volume fraction of resin entrapped in the agglomerate was considered as a realistic value. Considering that the value of the Young modulus (E) for a typical epoxy resin system is around 3GPa, then the rigidity value of the cork agglomerate layer was corrected to 100MPa. However, this must be considered as a first approach to this problem, and further tests are necessary to accurately quantify the amount of resin entrapped in the cork layer during the fabrication process of the specimens.

4 Conclusions

Damping improvement of CFRP laminates based in the use of hybrid cork based composites has been addressed in this paper. Regardless the type of specimen configuration (i.e., sandwich with cork core or laminate with embedded cork granulate), experimental results were conclusive about the increase of the loss factor with reference to plain CFRP laminates. This effect is particularly noticeable for frequency values above 400Hz, and especially for the sandwich specimens with a cork core, where an average 50% increase in the loss factor was found.
Numerical results confirmed the damping capabilities of cork based sandwich type specimens, since the displacements of the frequency response, considering the first modes of vibration, were always smaller than the corresponding values regarding laminate specimens without viscoelastic layer.

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