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Damping in composite materials: Properties and models

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ABSTRACT

The present review aims at gathering the available literature on damping in composite materials. A chronological review of test methods for damping estimation is presented in order to describe the timeline of the theoretical knowledge development in this field. In the last years many new material configurations have emerged that deserve investigation, such as nano-composites, hybrid laminates and sandwich materials. Damping models specifically meant for non-homogeneous materials are reported to provide a background for understanding this problem. Although not widely exploited yet, fibre reinforced polymers has the potential to be tailored for damping by acting on constituents, geometry and boundary conditions. Nano-composites, for instance, are shown to possess a high potential for damping purposes. New hybrid and sandwich-type structures are emerging as noise and vibration control solutions in lightweight applications. The effort devoted to mathematical and numerical model in view of Finite Element integration of damping properties is also addressed. Finally, the conclusions summarise the ideas of the authors on needed steps to advance the state-of-the-art in each of the described topic.

1. Introduction

The use of composite materials has constantly increased during the last decades. Several examples show that composite materials have entered the industry as a viable alternative to traditional materials. Aerospace and defence industries have been pioneers in this field but the attractive performance properties of composite materials have soon triggered their application for the production of sport equipment, boats, reinforcement components in civil engineering and energy applications. In the transport industry, aircraft design has taken the lead and the most recent aircrafts are made of composite for up to 60% of their weight. Automotive industry has been using composites for luxury and competition cars for several years and it is now employing them also in the series production of passenger vehicles.

Since their first appearance and applications, most researchers have focused on static characterisation and effective modelling of inhomogeneity and anisotropy and an extensive literature is available on this topic.

The use of composites for both primary and secondary structural components calls for a deeper understanding not only of their static characteristics but also of dynamic ones. In general, the use of static stiffness for the prediction of natural frequencies is acceptable. Damping properties, however, are difficult to assess and therefore difficult to account for in the design and analysis stage. To the knowledge of the authors, few reviews [1–3] have been published on this topic in the past with a more limited scope. Nonetheless, the damping of composite materials can be several orders of magnitude higher than that of traditional engineering materials, making them appealing also for components undergoing dynamic loading. The exploitation of material damping could also improve the general performance of composite structures compared to traditional vibration absorbing treatments. In fact, the weight of the treatments and the weight of the structures are in some cases comparable such that adding them to a base panel has a significant effect on the natural frequencies and mode shapes of the structure.

This review aims at gathering all the knowledge that has been gained in this field over the last years, treating both theoretical formulations and experimental procedures developed. The first part reviews the experimental techniques that have been developed to estimate damping in composite structures, followed by a description of the parameters affecting damping with the support of quantitative examples. The last section of part two covers the emerging hybrid composites and nano-composites. Finally, the last paragraph covers the approaches currently available to model

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damping, with particular focus to those typically employed for composite materials.

2. Experimental characterisation

Experimental measurements are essential in the study of damping of composite materials either for validation purposes or for material characterisation. However, proper techniques are needed to tackle the low weight and high stiffness. For example, standard *Dynamical Mechanical Analysis* (DMA) testing is most of the times not possible because of the high modulus [4]. Creep or relaxation tests can be used to determine linear viscoelastic models' parameters but they are usually time-consuming and require strict temperature and loading control [5]. A chronological review of test methods offers the reader the chance to follow the development of the knowledge in the field of damping. Since the beginning, the main concerns were related to the mass effect of traditional accelerometers and to supporting or clamping conditions. In Ref. [6], Sola and Jetté failed to validate their model because of non-perfect clamping conditions and accelerometers mass, both of which were not included in the model; Talbot and Woodhouse [7] found significant discrepancies between predicted and experimental values. The effect of different constraints on the modal damping is extensively studied by Maheri [8] on square plates. The way constraints act on damping is related to the variation in stiffness distribution. Such effect is shown also in Li and Narita [9]. Asymmetric constraining conditions may induce vibration coupling between normal and transverse stress components. The effect of coupling on damping has been studied by Hwang et al. [10,11] who quantified the contribution of coupling in terms of strain energy and found the optimal ply angle that maximises it. Zabaras and Pervez [12] accounted for the coupling between bending and shear in the formulation of the laminate stiffness matrix.

Most of the tests that will be described deals with unidirectional plies. As thoroughly explained in Ref. [13], the damping properties of orthotropic plies, which constitute the fundamental unit of laminates, is characterised by three damping coefficients along the material directions and on the plane they define. Such coefficients can be determined by analysing beams' vibrations and the frequency-dependent characteristic of the loss factor determined by varying the length of the beam.

In 1972 Wright [14] tested glass and carbon reinforced polyester beams by suspending them at the fundamental mode node thus reproducing free–free conditions. Beams were excited by a sinusoidal force and displacements were measured by an optical contactless probe. The damping was then measured by recording the oscillation decay. Adams and Bacon [15] stressed the importance of using free–free vibration conditions to avoid extraneous damping mechanisms; moreover, to exclude the effect of amplitude-dependence steady state conditions are employed. These conditions are met by exciting a carbon fibre reinforced polymer (CFRP) beam electromagnetically by mounting a coil at its midpoint. The mode amplitude of the specimen is measured to obtain the energy stored and calculate the *Specific Damping Capacity* SDC. Due to the low relative weight difference between the coil and the specimen, the mass effect has to be taken into account. In a successive paper [16] they addressed the issue of air damping, that can become a relevant source of dissipation for big displacements of the beam, by suggesting *in vacuo* tests for low damped material such as CFRP. Possible sources of discrepancies between predicted and measured values are also proposed. Guild and Adams [17] recognised in the apparatus used by Adams and Bacon a source of uncertainty due to the clamping pressure of the coil on the beam that may introduce cracks which increase the damping capacity. They propose two new apparatuses, one for free–free vibration and one for cantilever vibration. Electromagnetic excitation of two coils in free–free tests and one coil in cantilever tests is used but the coil clamps are improved to be stiffer in order to exclude spurious contributions to damping. Using the same approach of Adams and Bacon, the SDC is calculated and similar trend are found with both methods though different values are obtained due to the different boundary conditions and possibly a different mass effect. In Ref. [18], Lin et al. tested supported glass and carbon reinforced epoxy plates. To limit the contribution of boundary conditions, soft rubber foam supports are placed under the expected position of the modes' nodes. Steady-state vibration and hammer impacts are used to estimate the SDC of the plates and non-contact transducers are employed to record the response. Suarez et al. [19] described random and impulse techniques to measure the viscous damping ratio with the half-power bandwidth method. The first makes use of an electromagnetic shaker and an eddy current probe, measuring the damping by means of the half-power bandwidth method. The impulse technique relies on an electromagnetic hammer to ensure a higher level of reproducibility. The main advantages of the first setup are: good control of the force level and no leakage, but the fixing and excitation conditions must be accurately controlled. The impulse method is more suitable for *in situ* testing, especially for health-monitoring purposes, being damping one of the most sensitive parameter to damage due to additional frictional dissipation occurring at cracks and delamination sites [20,21]. In Ref. [22], the apparatus is improved to allow extensional damping measures. Crane and Gillespie [23] developed a similar impulse technique apparatus, underlining the importance of avoiding standard accelerometers to reduce the contribution coming from the non-negligible mass addition, with respect to the specimen mass, and from the cables. The clamping system is enriched by guiding rails to avoid eccentric loading and possible uncontrolled vibration couplings. Maheri and Adams [24] used several contacting and non-contacting devices for both the excitation and the sensing to conclude that the laser sensor gives the most accurate displacement measures, which are then used to estimate the SDC. Gibson [25] reviewed different modal vibration techniques for the static and dynamic properties of composites at both specimen and component level. Vibration damping is proposed by Kyriazoglou [26] in the framework of a hybrid simulation methodology. In vibration damping beams are vibrated in free–free flexure in their fundamental mode; the vibration is driven by magnets attached at both ends; the excitation is a sinusoidal signal; tests are run *in vacuo* and displacement are measured by a laser vibrometer; finally, SDC is calculated. Vasques et al. [27] described direct and indirect method used for damping evaluation and proposed a novel test-rig for the characterization of damped materials. All the above mentioned methods are based on vibration testing which, according to Stevensons [28], prevent from distinguishing between material and structural damping.

Though focused on homogeneous materials, the paper by Vanwalleghem et al. [29] gives a detailed description of all the external factors possibly contributing to damping and provides guidelines on how to limit their effect.

3. Damping phenomena

Compared to metals, composite materials show generally a higher damping capacity. The main reason is the viscoelasticity of the polymeric matrix. As for stiffness and strength, also damping can be tuned by properly choosing composites constitutive parameters such as fibre aspect ratio, stacking sequence and constituents properties. However, in most cases optimal results for damping properties lead to insufficient performance in terms of