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A procedure for the evaluation of damping effects in composite laminated structures

Riccardo Vescovini, Chiara Bisagni *

Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy

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ABSTRACT

The paper presents an approach based on experimental tests and numerical simulations for taking into account damping effects during the design and the analysis of composite structures. The experiments are conducted using the Dynamic Mechanical Analysis (DMA) and unidirectional coupons are tested to characterize the damping properties of the plies. Starting from these results, first order shear deformation theory is applied to determine the damping properties of the laminate, which are then used in the context of a numerical procedure based on finite element analyses and strain energy method. The results are presented for an aircraft stiffened panel, illustrating the evaluation of the specific damping capacities of the structure, and performing direct transient analyses to investigate the effect of damping on the panel response to pulse loadings.

1. Introduction

Damping is an important aspect related to the behaviour of composite structures. Indeed, the response to dynamic loads is affected by the damping characteristics in terms of vibrations, load distributions and deformed configurations.

While the advantages offered by composite materials are well known with regard to the elastic properties and strength-to-weight ratios, the potentialities related to the damping characteristics have been less investigated. Up-to-date, quite a few methods are available to account for damping effects on composites and, often, the approaches are more of empirical nature. In the context of transient modal dynamic analyses and mode-based steady state dynamic analyses, modal damping is commonly assumed on the basis of the experience or, when available, of experimental tests at sub-component or full size level. If this approach is adopted, the inherent contribution to modal damping due to the material cannot be distinguished from that due to joints, frictions and parasitic damping. For this reason, the development of new strategies to quantify the contribution of the material itself to the modal damping is a necessary step to gather insight into the potential benefits offered by the use of composites, and to allow the tailoring of the structures to meet the desired damping properties.

A review of studies on damping in composite materials is found in [1]. In general, two main approaches are found in the literature to characterize the damping of composites: the correspondence principle [2], sometimes referred to as complex-stiffness method or elastic–viscoelastic principle, and the strain energy method [3]. The first of the two approaches consists in converting the linear elastic equations into their viscoelastic counterpart by the substitution of the elastic moduli with the complex ones. The second approach considers the specific damping capacity (SDC) as the ratio between the weighted sum of the energy dissipated by each single element and the total strain energy stored in the structure.

Several works are found in the literature implementing the correspondence principle. Simply supported plates were studied by Alam and Asnani [4] by means of a semi-analytical procedure based on trigonometric expansion of the three displacement components. The formulation was applied to the analysis of plates with cross- and angle-ply lay-ups, and the effects of the material properties, the number of layers and the angles of orientation were investigated. Three different plate theories were considered by Ohta et al. [5] in the context of a procedure based on the corresponding principle and the method of Ritz. The corresponding principle was applied by Meunier and Shenoi [6] to the analysis of sandwich plates, implementing a semi-analytical procedure based on high-order shear deformation theory and Hamilton's principle.

Earlier works on the damping characterization of composite structures based on the strain energy method are the ones of Adams and Bacon [7], and Ni and Adams [8], who represented the energy dissipation by sub-dividing the contributions of the different stress components. The use of the strain energy method

* Corresponding author.
E-mail address: chiara.bisagni@polimi.it (C. Bisagni).

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was applied by Hwang and Gibson [9] with respect to its application at micro- and macro-mechanical levels. Closed-form expressions were derived by Adams and Maheri [10] for the evaluation of the flexural damping of composite beams using the Adams–Bacon criterion, and the accuracy of the analytical predictions was supported by the comparison with experimental results. Other analytical solutions were developed by Yim and Jang [11] for the analysis of laminated beams. Adams and Maheri [12] derived closed-form solution for the evaluation of dissipative properties of beams, while finite element analyses and the Ritz methods were employed for the study of plates [13,14].

A comparison between the accuracy of the correspondence principle and the strain energy method is found in the work of Berthelot and Sefrani [15], where the numerical predictions are compared with the experimental measurements of damping of glass and Kevlar unidirectional composites. The results highlight a good agreement of the strain energy approach with the experiments.

In the context of the various implementations of the strain energy method, a comparative study is presented by Billups and Cavalli [16], where the accuracy of the approaches of Adams and Bacon [7], Ni and Adams [8], Adams and Maheri [12] and Saravanos and Chamis [17,18] is assessed.

The present work discusses a procedure which can be used to evaluate the modal damping at panel level starting from the experimental characterization of the damping properties at ply level. An overview of the procedure is presented in Fig. 1.

The experimental measurements are based on Dynamic Mechanical Analysis (DMA) tests and allow for a quick and convenient characterization of the material properties, while the numerical analysis is faced using the commercial finite element code Abaqus together with Python scripting.

DMA tests are initially performed on unidirectional specimens with different angles of orientations, including on-axis and off-axis configurations. From the experimental results, the damping properties are evaluated at ply level by identifying the specific damping capacities Ψ_{11}, Ψ_{22} and Ψ_{12}. Then, the laminate damping matrices are derived referring to the first order shear deformation theory. At the end of this step, the accuracy of the characterization is checked by comparison of the numerical predictions with the DMA tests performed on specimens made by laminates with different plies orientation.

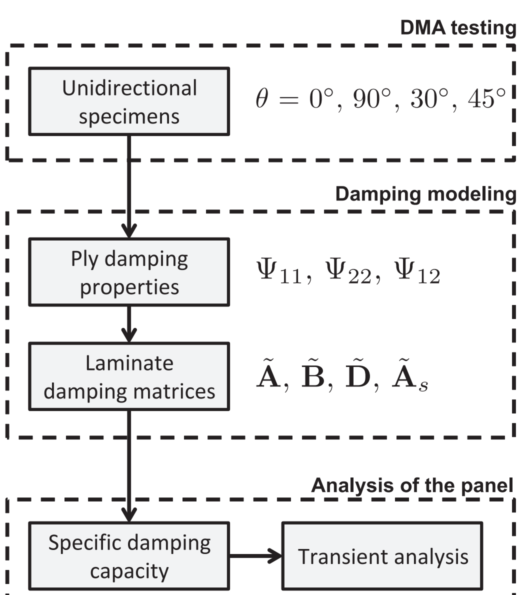

Fig. 1. Overview of the procedure.

The analysis is then performed at panel level. In particular, finite element analyses are conducted to determine the panel SDC as well as the distribution of the dissipated energy. Finally, the modal damping is used in the context of a Rayleigh damping approximation to perform direct transient analyses, and to assess for the effects of damping to a suddenly applied load. In particular, the dynamic buckling behaviour of the panel is investigated referring to the modified Volmir criterion [19]. Indeed, while it is well known that the ratio between the dynamic and the static buckling is usually different from the unity [20–22], the investigation of the effects due to damping have been quite rarely assessed. The Volmir criterion identifies the critical conditions according to the maximum value of the out of plane displacement during the time history, and is consequently affected by the damping properties of the structure.

Compared to other works in the literature, whose focus is the study of beams or plates, the present effort aims to extend the range of applicability of the strain energy method to aircraft subcomponent structures. The analysis procedure is developed to account for structures characterized by the presence of regions with different stacking sequences, as well as lay-ups with plies of different materials and/or thicknesses.

Furthermore, the investigation of the dynamic effects on the buckling of the structures has been widely investigated [20–22], but quite rarely the effects of damping have been accounted for.

2. DMA testing

The experimental characterization of the ply damping properties is performed using the DMA. The tests were conducted with the TA Instruments DMA 2980 machine at the laboratory of the Department of Aerospace Science and Technology of Politecnico di Milano.

The DMA is a technique to measure the properties of materials loaded with a periodic stress excitation. During the test, a sinusoidal stress is applied, and the strain is measured. The phase lag between the applied stress and the measured strain is used to estimate the material specific damping capacity, while the amplitudes of the stress and of the strain are used to evaluate the storage and the loss modulus. One of the main advantages of DMA testing is due to the fact that it just requires use of coupons.

The material under investigation is a carbon/epoxy. In particular, specimens at 0°, 90°, 30° and 45° are tested, two for each angle of orientation considered.

Various types of fixtures are available for the DMA, such as the three point bending, the single and the dual cantilever configurations. In a previous investigation by Bisagni and Catapano [23], three point bending and dual cantilever configurations were compared, allowing to observe that more reliable results are achieved in terms of specific damping capacity if the cantilever fixture is used. This conclusion is probably due to the non-perfect adherence between the specimen and the fixture in the case of three point bending. For this reason, dual cantilever conditions are used in the present investigation. A picture of the DMA equipment is reported in Fig. 2 and illustrates the specimen boundary and loading conditions. As seen from the figure, the specimen is fixed at the ends by two screws with a tightening torque of 40 N mm, while the central probe, which is controlled by a pneumatic system, is responsible for the load introduction.

The overall dimensions of the specimens are 60 mm × 10 mm, while the effective length, measured as the clamp-to-clamp distance, is 37.5 mm.

The coupons are realized by the stacking of six plies of unidirectional material with same angle of orientations, for a nominal thickness equal to 0.75 mm, as the result of the stacking of six plies