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On the trade-off between damping and stiffness in the design of discontinuous fibre-reinforced composites

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Abstract

Quasi-static models are first developed, by using a *forced balance approach*, to define the effects of selected microstructural parameters, e.g. fibre aspect ratio, fibre off-axis angle and fibre volume fraction, on the damping and stiffness of a class of polymeric, discontinuous fibre-composite systems. Simultaneous optimization of damping, stiffness and weight of a class of such material is then carried out by using the so-called *inverted utility function method*. The obtained results show that discontinuous fibre-reinforced composites have superior design flexibility as compared with those pertaining to continuous fibre-reinforced composites. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

It is well known that lightweight fibre-reinforced polymer composite materials have higher specific strength and stiffness when compared with conventional structural materials such as metals. Much effort has been devoted to the improvement and optimization of these properties as pertaining to various classes of composite microstructures. Good vibration damping properties are also particularly important for composite structures to acquire [1] when they are used under dynamic loading, e.g. in aerospace structures. Due in part to the extensive accumulated experience with conventional structural materials, such as metals, which in general have poor internal damping, the potential for the improvement and optimization of damping in fibre-reinforced composites has not yet been fully realized. Meanwhile, the full use of discontinuous fibre-reinforcement has not yet been fulfilled in composite material applications. This may be due to the direct accomplishment of higher specific strength and stiffness in the more familiar continuous fibre composites.

The damping properties of continuous fibre composites have been studied by a number of researchers [2,3]. There are relatively few publications on damping of discontinuous fibre composites. However, studies reported by, for instance, McLean and Read [4] and Gibson et al. [5] indicate that vibration damping of polymeric fibre-reinforced composites may be significantly improved, and possibly can be readily optimized by using, as a reinforcement, discontinuous fibres rather than continuous ones. In this context, studies carried out by, e.g. Gibson and Yau [5], Gibson et al. [6], Sun et al. [7], and Suarez et al. [8] have confirmed that the damping factor of polymeric discontinuous fibre-composites is a frequency dependant, and it relates strongly with the microstructure's particulars, e.g. fibre aspect ratio, fibre volume fraction and fibre off-axis angle. The research work of Gibson and Yau [5] and Gibson et al. [6], for instance, indicates that by varying the fibre aspect ratio and fibre orientation, superior damping and stiffness could be achieved separately. This observation implies that the optimum conditions, in terms of microstructural parameters, for damping may not be necessarily the same for stiffness. Consequently, it is important to study the influence of the various governing microstructural parameters as pertaining to both damping and stiffness. The optimization, in terms of the microstructure, of this trade-off between damping and stiffness is the main intention of this paper. In this context, the general procedure of the *force-balance approach* [7] is used to formulate an analytical optimization model, whereby a multi-objective optimization functional is established to optimize the mentioned two properties simultaneously. For this purpose, both the composite laminate and its constituents are assumed to behave in a linear viscoelastic

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manner. Hence, the elastic-viscoelastic correspondence principle [9-11] is assumed to be applicable. The composite laminate is considered to be uniaxially loaded in tension with the loading direction coinciding with the longitudinal axis *x* of the laminate.

In the force-balance approach, the expression for the elastic stiffness of a discontinuous fibre-composite is derived from the average fibre stress using Cox's analytical model concerning fibre stress distribution [12]. In this paper, the analytical model by Cox [12] is followed and extended to include time-dependent behaviour, whereby the elastic – viscoelastic correspondence principle is used to obtain the expressions for the viscoelastic complex moduli from their elastic counterparts. In the case of sinusoidal loading, the expression for the complex modulus would involve both the storage modulus and the associated-with loss modulus. Here, the following complex moduli are dealt with

$$E_x^* = E_x' + iE_x'', \qquad E_f^* = E_f' + iE_f'',$$

$$E_m^* = E_m' + iE_m'', \qquad G_m^* = G_m' + iG_m''$$
(1)

where E and G indicate, respectively, the moduli under tensile and shear loading. Meantime, and the over-prime designates the storage modulus and the double over-prime identifies the loss modulus. Meantime, the corresponding damping (or loss) factor is defined as the ratio between the loss modulus and the associated-with storage modulus, i.e.

$$\eta_{\rm c} = E''_x / E'_x, \qquad \eta_{\rm f} = E''_{\rm f} / E'_{\rm f}, \qquad \eta_{\rm m} = E''_{\rm m} / E'_{\rm m},$$
 $\eta_{G_{\rm m}} = G''_{\rm m} / G'_{\rm m}$
(2)

2. Influence of selected microstructural parameters

Among the many microstructural parameters, of the dealt-with composite laminate, that may be considered for the optimization process, we narrowed down our attention to three parameters, namely, θ , V_f and l/d, representing, respectively, the fibre off-axis angle with respect to the longitudinal axis x of the laminate (the loading direction), the fibre volume fraction and the fibre aspect ratio. While the optimization model is presented below in a generalized manner, the particular case of E-glass/epoxy composite, Table 1, is being dealt with as an illustration.

For a wide range of applications of composite materials, the fibre volume fraction varies within the range of 50– 70%. Meanwhile, an observation was made by Cox [12] that, for short fibre-reinforced composite materials, the reduction of the effective longitudinal modulus due to the load transfer from fibre to fibre is considered to be significant only for fibre aspect ratios less than 100. Therefore, we set below the fibre volume fraction to vary within the range from 50 to 70% and the fibre aspect ratio to vary within the range from 1 to 100.

The obtained results indicate that with the increase in the fibre off-axis angle, e.g. by setting θ as 0, 40, 60, 80 and 90°,

Table 1

Selected material properties of Scotchply 1002 matrix epoxy and E-glass fibres at room temperature (adopted after Gibson and Plunkett [14])

Material properties	Epoxy	E-glass
Young's modulus (GPa)	3.79	72.4
Shear modulus (GPa)	1.38	30.3
Damping factor	0.015	0.0014
Shear damping factor	0.018	0.0014
Poisson's ratio, ν	0.36	0.2
Specific Gravity, g	1.23	2.54

and plotting the non-dimensional ratios η_x/η_m and E'_x/E'_m against the fibre volume fraction V_f and the fibre aspect ratio l/d, the values of the ratio η_x/η_m are increasing, while those for E'_x/E'_m are decreasing. Meantime, when the fibre off-axis angle reaches a value between 40 and 60°, both η_x/η_m and E'_x/E'_m curves change their directions, which demonstrate that for a fibre off-axis angle θ within the range of 40–60°, both the ratios η_x/η_m and E'_x/E'_m reach their extreme values (maximum and minimum, respectively) almost simultaneously. Figs. 1 and 2 show, for instance, the results obtained by setting the fibre off-axis angle θ as 40 and 60°, respectively.

Meanwhile, by setting the fibre aspect ratio as 5, 20, 40, 80 and 100, one observed that the damping ratio η_x/η_m decreases monotonously as the fibre aspect ratio increases and for value of l/d > 15, the rate of decrease in value slows down until the fibre aspect ratio reaches 20, whereby the value of the ratio η_x/η_m maintains a constant value afterwards. Also, the ratio E'_x/E'_m also increases sharply until the fibre aspect ratio l/d reaches a value of about 20. With the fibre aspect ratio ranging from 20 to 60, the ratio E'_x/E'_m increases slowly with the increase in the fibre aspect ratio l/d and seems to have a constant value from l/d = 60upwards. Figs. 3 and 4 demonstrate the results when l/d is set as 5 and 80, respectively.

On the other hand, by setting the fibre volume fraction $V_{\rm f}$ as 50, 60 and 70%, one was able to identify that with the increase in the fibre volume fraction, both the ratios $\eta_x/\eta_{\rm m}$ and $E'_x/E'_{\rm m}$ change almost linearly, with the values of the ratio $\eta_x/\eta_{\rm m}$ are monotonously decreasing and those for $E'_x/E'_{\rm m}$ are monotonously increasing. Fig. 5 shows, as an example, the obtained results for the case when $V_{\rm f}$ is 50%.

From the above numerical results, one concludes that in order to increase the damping of a discontinuous fibrereinforced composite, it is necessary to sacrifice the stiffness of this material. It is also apparent that, among the three microstructural variables considered, the fibre off-axis angle θ has the most significant influence on the damping and stiffness of short fibre-reinforced composites.

3. Optimization

The subject of the trade-off between damping and stiffness is presently gaining more and more attention

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