HYBRID CORK-POLYMER COMPOSITES FOR IMPROVED STRUCTURAL DAMPING PERFORMANCE

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Abstract

Damping and stiffness are two key structural properties that tend to be mutually exclusive; stiff materials have low damping, whereas highly damped materials lack rigidity. The present work aims to investigate the effectiveness of cork material in improving the product of the stiffness and damping ratio of composite materials for structural applications. In this study, cork is incorporated into a carbon-epoxy composite using two methods: as a single constrained layer and micron-scale particulate inclusions. Damping performance is evaluated in terms of loss modulus which is the product of stiffness and loss factor, $E\eta$. The loss modulus captures the reduction in stiffness, due to the introduction of a lossy material to improve the damping properties. Damping performance is found to increase with the introduction of cork material either as a constrained layer and particulates in the matrix at the first four natural frequencies. This presents the opportunity, particularly with the highly customizable particulate hybrid composite, for tailored structural materials with superior damping performance without degrading stiffness.

1. Introduction

Vibration is usually undesirable in structural applications, as it can lead to fatigue damage and ultimately early failure of structures. Furthermore, vibration leads to acoustic emissions that are detrimental to consumer comfort in commercial components and may compromise strategic operations in military applications. Increased structural damping has the potential to mitigate the effects of vibration and increase the performance and life of a component.

The need for damping is prevalent in the aerospace, automotive, marine and power generation industries. Any cyclically moving component, such as an engine or turbine will generate vibration. Additionally, aerodynamic and hydrodynamic effects such as flutter and buffeting result in vibration that is potentially damaging to wing structures and hydrofoils. The choice of damping material must be carefully selected not only to consider operational conditions but also the potentially harsh environment of bespoke applications, such as extreme temperature ranges, oxidative atmospheres, a range of excitations at various frequencies and large, cyclic loads.

Due to their superior strength to weight ratio, composites are more frequently being employed in high-performance, structurally critical applications. Damping performance of composite structures has traditionally been overlooked, with the focus primarily being on mechanical performance. As the

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design envelope for composites expands, damping will play a more crucial role in material selection and component design.

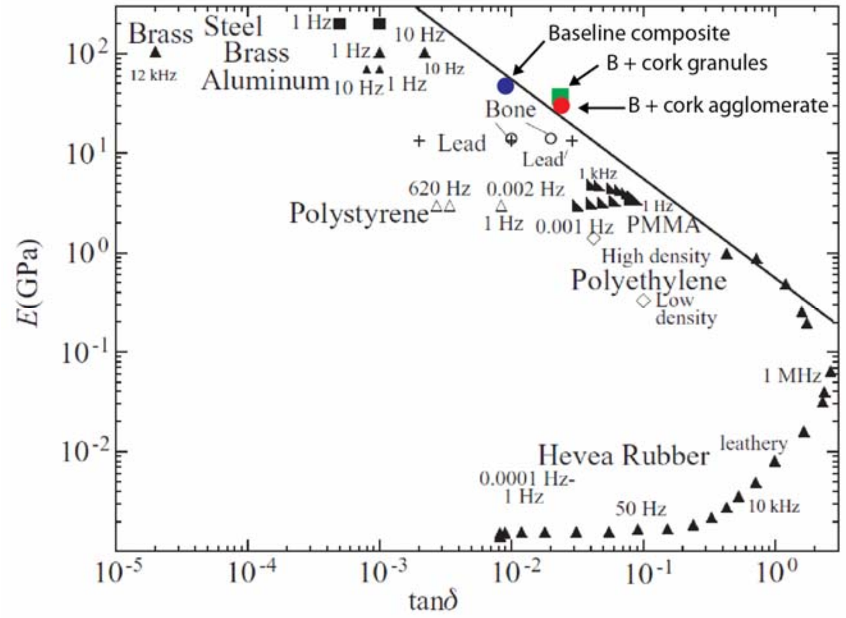

Figure 1. Stiffness-loss map showing the damping performance of typical materials [1] and experimentally determined baseline composite and cork-hybrid composite at frequencies corresponding to the fourth bending mode of vibration (Table 3).

The dynamic mechanical response of a material is measured by its dynamic modulus, E^* [1]. This complex property has real and imaginary parts known as the storage (E') and loss (E'') moduli. The ratio between the loss and storage moduli is designated as the loss factor, tanδ, where δ is the phase angle that represents the lag between stress and strain of a viscoelastic material under cyclic loading.

For load-bearing structures, any increase in damping performance needs to cause minimum or no degradation in stiffness. Therefore, a good measure of overall structural damping is the product of stiffness and loss factor, Etanδ ($E\eta$), which is called loss modulus. In general, materials tend to exhibit either good mechanical properties or good damping. $E\eta$ is therefore useful in finding an optimal compromise for overall performance. A stiffness-loss plot for typical materials is shown in Fig. 1. The goal is to design a material to have high mechanical performance and offer high damping (top right of Fig. 1).

A solution to improving damping in composite materials is through hybridisation. Hybrid composites are invaluable as they allow their material structure to be tailored for a particular application. Structurally, composites can be improved by introducing mechanically superior fibres to an existing material, for example, the addition of carbon fibres to a glass fibre laminate [2,3]. Conversely, hybrid composites have the potential to reduce cost in components through the introduction of less expensive materials to non-critical regions. Improvements in damage tolerance can be achieved through the addition of particulate inclusions. This has been shown to improve the fracture toughness of composites significantly [4–6]. For improved damping, several solutions have been explored and reviewed [7–10]. It is possible to tailor constituent materials, including the fibres, matrix and interface regions. The material architecture can be optimised through the variation of ply stacking sequence in laminates and weave design in textile composites. The addition of viscoelastic materials has also shown promise through the addition of constrained layer damping materials and particulate inclusions within the matrix material.

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Constrained layer damping has been shown [11–16] to increase damping performance in composite laminates due to energy dissipation as a result of viscoelastic shearing of the constrained layer. Typically, materials with excellent viscoelastic properties are selected as the constrained layer to maximise damping properties. Additionally, damping properties in composites can be significantly improved [4–6,17–22] through the addition to the resin of particulate material. Particulate inclusions improve damping properties through dual mechanisms. The first is due to the viscoelastic nature of the particles and the second is due to the potential for interfacial sliding between the particle and the resin.

Cork has a high damping capacity and high coefficient of friction, consequently it is commonly found in soles of shoes, packaging and handling of tools. Cork is obtained from the bark of a species of oak, the Quercus Suber. The cellular structure (Fig. 2b) of cork provides an effective mechanism for the dissipation of energy.

Here, an investigation into the structural damping performance of cork-polymer hybrid composites is presented. Hybridisation is achieved through two methods: an interleave layer of cork agglomerate; and discreet cork particles. In both cases, the cork is inserted at the laminate mid-plane.

2. Materials

A Sigmatex 650gsm 2x2 twill weave T300-3k carbon fibre fabric with West System 105 epoxy and 206 slow hardener was selected as the baseline composite. Panels were manufactured in a 0/90 configuration with a total of four plies and processed by vacuum assisted resin infusion and cured for 24 hours at room temperature.

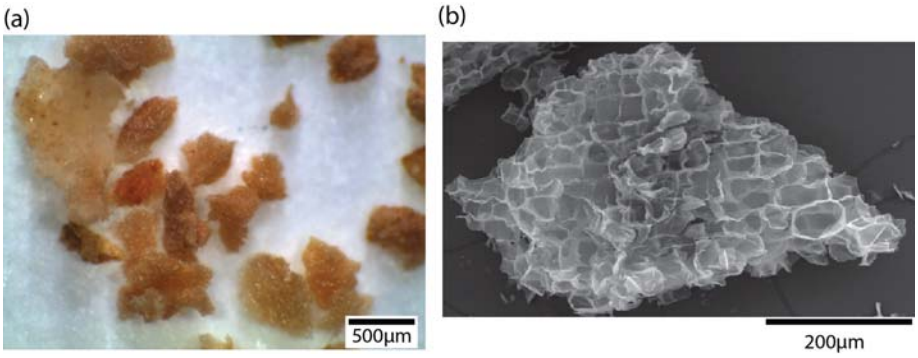

Figure 2. (a) Micrograph of several cork granules; and (b) SEM image showing the cellular structure of a single granule.

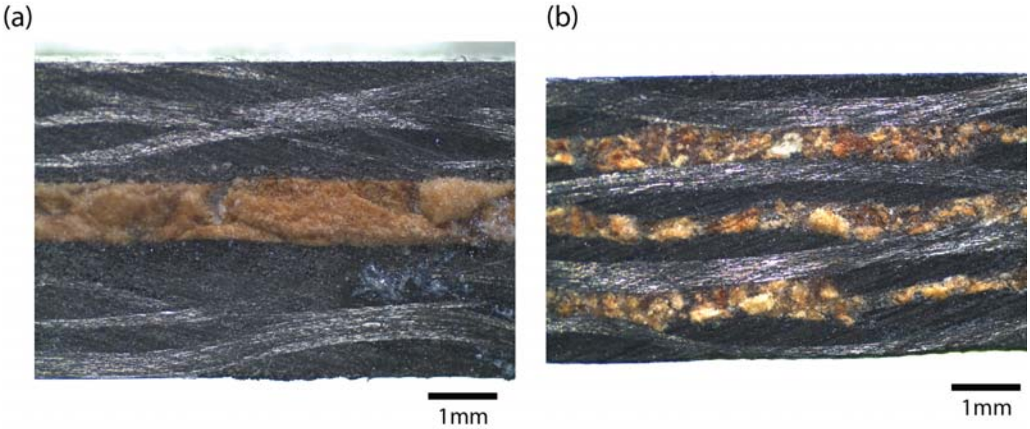

Figure 3. (a) Cork agglomerate hybrid composite; and (b) cork granule hybrid composite.

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Hybridization was achieved using either cork granules, ranging 100-500μm in size (Fig. 2), or a 1mm thick NL25 cork agglomerate provided by Amorim Cork (Portugal). A single cork agglomerate sheet was placed at the composite mid-plane (Fig. 3a), whereas the granules were dispersed evenly between each ply to give a total weight fraction of approximately 5% (Fig. 3b).

3. Experimental Setup

The mechanical and damping performance of each material was evaluated through flexural and vibration-damping testing. These simple tests will provide a measure of damping performance ($E\eta$) for the bending modes of vibration.

Table 1. Geometric and constituent properties of hybrid composites.

Material	Thickness (mm)	Fraction of damping material
Baseline	2.8	-
Base + NL 25 cork	4.2	0.25 (by volume)
Base + cork granules	3.9	0.05 (by weight)

3.1 Flexural Testing

Three-point bend test specimens were manufactured for each material, each measuring 155x13mm (length x width). The thickness of each panel is given in Table 1. Testing was conducted on a 50kN Instron test machine in line with ASTM standard D7264. The support span of each material was calculated using a span to thickness ratio of 32:1. Specimens were tested to failure at a loading rate of 1mm/min. The displacement at the half-span was measured using a linear variable differential transformer (LVDT), the force was measured by the test machine. The flexural modulus was calculated by the following equation:

$$E = \frac{PL^3}{4bh^3\delta}, \tag{1}$$

where P denotes the applied force, L the support span, b the width, h the thickness, and δ the mid-span deflection.

3.2 Vibration-damping testing

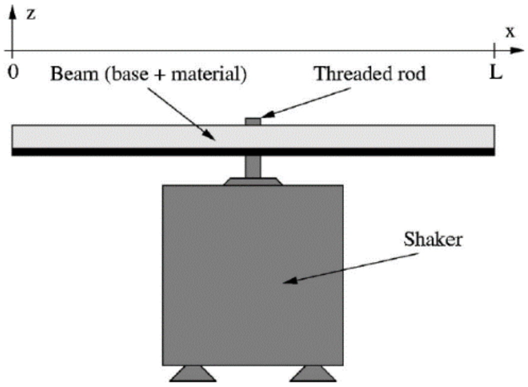

Figure 4. *Butterfly* beam setup for vibration-damping testing proposed by [24].

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Vibration-damping testing was conducted in accordance with ASTM standard E0756 with the test setup modified from a fixed-free configuration to a free-free *butterfly* beam setup (Fig. 4). This was to alleviate problems associated with the root section in the standard Oberst beam test [24]. Five specimens of each material measuring 350x10mm (length x width) were manufactured and tested (thicknesses given in Table 1). The amplitude versus displacement response was obtained between 0 and 5kHz using the mechanical impedance method, where the specimen is forced to vibrate using an electrodynamic shaker device, while the response is being measured by a laser vibrometer. The structural loss factor (η) was calculated at the location of each natural frequency using the half-power bandwidth method. Once a resonant frequency was identified (e.g. Fig. 5a), the width of the peak was measured 3dB lower than the peak value (Fig. 5b). The loss factor, η, is calculated using the following equation:

$$\eta = \frac{\Delta f}{f_n} \tag{2}$$

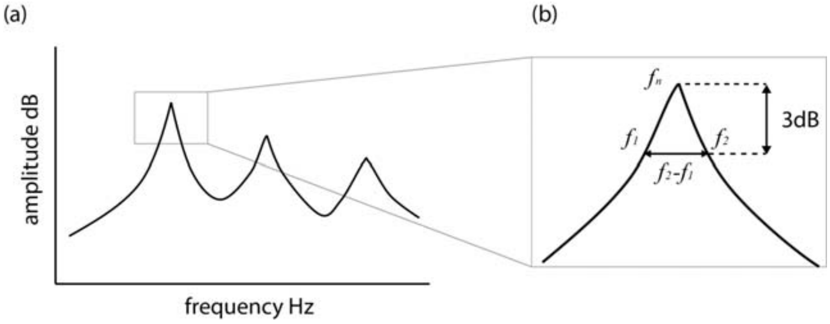

Figure 5. (a) Typical frequency response of a material and (b) half-power bandwidth method to obtain loss factor.

4. Results

Table 2. Flexural properties of hybrid and baseline test cases with properties in brackets normalised against the baseline.

Material	E (GPa)	Coefficient of variation	σ_{strength} (MPa)	Coefficient of variation
Baseline	46.3 (1.00)	0.066	449 (1.00)	0.053
Base + Cork agglomerate	29.2 (0.63)	0.022	160 (0.36)	0.088
Base + Cork granules	37.4 (0.81)	0.037	349 (0.78)	0.031

The flexural modulus and strengths for each material specimen, averaged over the five test specimens, are given in Table 2. The values shown in brackets are normalised against the baseline composite. The coefficient of variation (standard deviation divided by mean value) is also presented. The hybrid composites show a modest reduction in mechanical properties in terms of both stiffness (19-37%) and strength (22-64%) in comparison with the baseline material. The cork granule hybrid composite provides the best performance of the hybrid materials with a reduction of 19% in stiffness and 22% reduction in strength. The cork granule hybrid composite also has the added advantage of being the most customisable, since the amount and location of cork granules added to the baseline can easily be varied to tailor mechanical performance.

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Table 3. Natural frequencies (f_n) of the first four bending modes of vibration of hybrid and baseline test cases.

Material	Mode I (Hz)	Mode II (Hz)	Mode III (Hz)	Mode IV (Hz)
Baseline	87.99	536.13	1479.98	2843.16
Base + Cork agglomerate	132.71	693.95	1644.73	2765.23
Base + Cork granules	118.28	736.52	1988.56	4114.77

Table 4. Loss factor (η) of hybrid and baseline test cases for the first four bending modes of vibration. Properties in brackets normalised against the baseline.

Material	Mode I	Mode II	Mode III	Mode IV
Baseline	0.029 (1.00)	0.010 (1.00)	0.007 (1.00)	0.009 (1.00)
Base + Cork agglomerate	0.025 (0.87)	0.023 (2.37)	0.028 (4.08)	0.025 (2.65)
Base + Cork granules	0.030 (1.04)	0.007 (0.72)	0.010 (1.44)	0.023 (2.51)

Table 5. Damping performance ($E\eta$) of hybrid and baseline test cases with properties in brackets normalised against the baseline.

Material	Mode I (GPa)	Mode II (GPa)	Mode III (GPa)	Mode IV (GPa)
Baseline	1.34 (1.00)	0.46 (1.00)	0.32 (1.00)	0.42 (1.00)
Base + Cork agglomerate	0.73 (0.54)	0.67 (1.45)	0.82 (2.52)	0.73 (1.75)
Base + Cork granules	1.12 (0.84)	0.26 (0.57)	0.37 (1.15)	0.86 (2.06)

The vibration-damping test provides the amplitude-frequency plot for each material (shown schematically in Fig. 5). The peaks corresponding to the first four modes of vibration are clearly identifiable and allow calculation of the structural loss factors. The location of these peaks signify each resonant frequency. These are presented for each material in Table 3. The natural frequencies of each mode are relatively similar for each of the hybrid materials. This gives confidence that the relative additions of cork for each material are similar.

The damping loss factors for each mode are presented in Table 4. Normalised values (relative to the baseline composite) are shown in brackets. Qualitatively, it is clear that damping capability is enhanced by the presence of hybridisation. Each material provides at least double the loss factor for at least one mode, the most significant effect being observed for the cork agglomerate hybrid composite where mode III shows an increase of over four times the baseline value. This represents a significant improvement in damping properties.

Despite the significant improvement in structural loss factor demonstrated above, a more useful comparison of overall damping performance must also take into account the reduction in mechanical properties that naturally results when adding a mechanically inferior material. The product of flexural modulus and loss factor, $E\eta$, is a good performance indicator that incorporates both mechanical and damping behaviour. Values of $E\eta$ for each bending mode of vibration are presented in Table 5 for the baseline and hybrid composites. Despite the modest reduction in flexural modulus (Table 2) of the hybrid composites, their overall damping performance is generally better than the baseline composite,

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especially for the constrained damping layer material. Each hybrid material outperforms the baseline for at least one resonant frequency with the best performance seen for the cork agglomerate hybrid material at mode III. It must be noted that the cork granule composite generally performs worse than the agglomerate (Modes I & IV excluded), however, its material composition can be more easily tailored, via volume content and location of the particulates, than the constrained layer materials.

5. Discussion and Conclusions

The hybrid composites tested in this study show great potential in improving the damping performance of regular composite materials with only a modest reduction in mechanical properties. The interlayer material (NL25 cork agglomerate) showed the best improvement in damping properties. The cork particulate inclusions also showed promise at several frequencies and produce the smallest reduction in mechanical properties. This is due to the granules being encased in epoxy resin, rather than being a continuous damping layer with poor strength and stiffness. The result is less of the damping material carries load and thus the strength and stiffness are preserved.

Although the constrained layer damping material performed best, the cork granule hybrid composite shows great potential and it would be interesting to compare the damping performance of this material with different weight percentages of cork. Additionally, the location and size of the cork granules could be optimised. There is also far greater scope, when using particulate inclusions, for tailoring mechanical and damping properties for a particular application, whereas the constrained layer method is relatively inflexible by comparison. Future work will investigate this potential.

An important point to consider when digesting this rather limited study is the volume content of hybrid material from one configuration to the next. It is extremely difficult to control the amount of damping material being added to the baseline. As a result, the volume content of each hybrid material is not consistent. Any further study should seek to ensure the volume of the added damping material from one panel to the next is consistent, or isolate the constituent material properties from those of the structural composite.

Overall, this scoping study has shown that hybridisation can be successfully employed to improve the damping performance of composite materials. Shown in Fig. 1 are the stiffness-loss values for the baseline composite and the hybrid materials. This figure shows significant improvement in the damping properties provided by hybrid composites compared to typical materials. Upon further optimisation, hybrid composites show the potential to expand this envelope significantly further.

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