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Structural composite materials tailored for damping

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Abstract

This paper reviews the tailoring of structural composite materials for damping. By the use of the interfaces and viscoelasticity provided by appropriate components in a composite material, the damping capacity can be increased with negligible decrease, if any, of the stiffness. In the case of cement–matrix composites, the use of silica fume as an admixture results in increases in both the damping capacity and the storage modulus. In the case of continuous fiber polymer–matrix lightweight composites, the use of submicron-diameter discontinuous carbon filaments as an interlaminar additive is more effective than the use of an interlaminar viscoelastic layer in enhancing the loss modulus when the temperature exceeds 50 °C. Surface treatment of the composite components is important. In the case of steel reinforced concrete, the steel reinforcing bar (rebar) contributes much to the damping, but appropriate surface treatment of the rebar further enhances the damping.

Keywords: Disordered systems; Polymers; Elastomers and plastics; Surfaces and interfaces; Elasticity; Anharmonicity

1. Introduction

The development of materials for vibration and acoustic damping has been focused on metals and polymers [1]. Most of these materials are functional materials rather than practical structural materials due to their high cost, low stiffness, low strength or poor processability. Thus, this paper uses practical structural materials, such as concrete, as the starting point in the development of materials for damping. This development involves tailoring through composite engineering and results in reduction of the need for nonstructural damping materials.

Composite materials are widely used for structures due to their strength and stiffness. Damping in structures is commonly provided by viscoelastic nonstructural materials. Due to the large volume of structural materials in a structure, the contribution of a structural material to damping can be substantial. The durability and low cost of a structural material add to the attraction of using a structural material to enhance damping. By the use of the interfaces and viscoelasticity provided by appropriate components in a composite material, the damping capacity can be increased with negligible decrease, if any, of the storage modulus. The attaining of a significant damping capacity while maintaining high strength and stiffness [2–4] is the goal of the structural material tailoring described in this review paper.

Vibrations are undesirable for structures, due to the need for structural stability, position control, durability (particularly durability against fatigue), performance, and noise reduction. Vibration reduction can be attained by increasing the damping capacity (which is expressed by the loss tangent, tan δ) and/or increasing the stiffness (which is expressed by the storage modulus). The loss modulus is the product of these two quantities and thus can be considered a figure of merit for the vibration reduction ability.

Damping of a structure can be attained by passive or active methods. Passive methods make use of the inherent ability of certain materials (whether structural or nonstructural materials) to absorb the vibrational energy (for example, through mechanical deformation, as in the case of a viscoelastic material), thereby providing passive energy dissipation. Active methods make use of sensors and actuators to attain vibration sensing and activation to suppress the vibration in real time. The sensors and actuators can be piezoelectric devices [5–10]. This review is focused on materials for passive damping, due to its relatively low cost and ease of implementation.

Materials for vibration damping are mainly metals [11–13] and polymers [14–16], due to their viscoelastic character. Rubber is commonly used as a vibration damping material [17,18]. However, viscoelasticity and molecular movements are not the only mechanism for damping.

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Defects such as dislocations, phase boundaries, grain boundaries and various interfaces also contribute to damping [19], since defects may move slightly and surfaces may slip slightly with respect to one another during vibration, thereby dissipating energy. Thus, the microstructure greatly affects the damping capacity of a material. The damping capacity depends not only on the material, but also on the loading frequency, as the viscoelasticity as well as defect response depend on the frequency [20]. Moreover, the damping capacity depends on the temperature [20].

Composite materials are multiphase materials obtained by artificial combination of different materials, so as to attain properties that the individual components by themselves cannot attain. An example is a lightweight structural composite that is obtained by embedding continuous carbon fibers in one or more orientations in a polymer matrix [21]. The fibers provide the strength and stiffness, while the polymer serves as the binder. Another example is concrete, which is a structural composite obtained by combining (through mixing) cement (the matrix, i.e. the binder, obtained by a reaction, known as hydration, between cement and water), sand (fine aggregate), gravel (coarse aggregate) and optionally other ingredients that are known as admixtures. Short fibers [22] and silica fume (a fine SiO_2 particulate) [23,24] are examples of admixtures. In general, composites are classified according to their matrix material. The main classes of composites are polymer–matrix [25], cement–matrix [23], metal–matrix [26,27], carbon–matrix [28,29] and ceramic–matrix [30,31] composites, which have all been investigated in terms of the damping behavior.

Polymer–matrix and cement–matrix composites are the most common, due to the low cost of fabrication. Polymer–matrix composites are used for lightweight structures (aircraft, sporting goods, wheel chairs, etc.), in addition to vibration damping, electronic enclosures, asphalt (composite with pitch, a polymer, as the matrix), solder replacement, etc. Cement–matrix composites in the form of concrete (with fine and coarse aggregates), steel reinforced concrete, mortar (with fine aggregate, but no coarse aggregate) or cement paste (without any aggregate) are used for civil structures, prefabricated housing, architectural precasts, masonry, landfill cover, thermal insulation, sound absorption, etc. Carbon–matrix composites are important for lightweight structures (e.g. space shuttle) and components (e.g. aircraft brakes) that need to withstand high temperatures, but they are relatively expensive due to the high cost of fabrication. Carbon–matrix composites suffer from their tendency to be oxidized ($2C+O_2 \rightarrow 2CO$), thereby becoming vapor. Ceramic–matrix composites are superior to carbon–matrix composites in the oxidation resistance, but they are not as well developed as carbon–matrix composites. Metal–matrix composites with aluminum as the matrix are used for lightweight structures and low-thermal-expansion electronic enclosures, but their applications are limited by the high cost of fabrication and by galvanic corrosion.

Among the metal-based structural materials, steel [32] and aluminum [33] alloys are dominant. Steel is advantageous in the high strength, whereas aluminum is advantageous for its low density. For the purpose of damping, zinc [26] and magnesium [27] alloys are particularly attractive. For high temperature applications, intermetallic compounds (such as TiAl and NiAl [34]) have emerged, though they suffer from their brittleness. Metal–matrix composites such as those containing ceramic particles [26,35,36] are superior to the corresponding metal matrix in the high modulus, high creep resistance and low thermal expansion coefficient, but they are expensive due to the processing cost. Moreover, they may not be much better than the corresponding metal in the damping capacity [26,35,36]. The metal matrix and the dislocations induced by the thermal expansion mismatch between filler and matrix tend to govern the damping behavior. A complication is that a strong filler–matrix interface is undesirable for damping, but is desirable for stiffening.

Among the cement-based structural materials, concrete is dominant. Although concrete is an old material, improvement in the long-term durability is needed, as suggested by the degradation of bridges and highways all over the US. The improvement pertains to decrease in the drying shrinkage (shrinkage of the concrete during curing or hydration), as the shrinkage can cause cracks. It also pertains to a decrease in the fluid permeability, as water permeating into steel reinforced concrete can cause corrosion of the reinforcing steel. Moreover, it pertains to improvement in the freeze–thaw durability, which is the ability of the concrete to withstand temperature variations between temperatures below 0° (freezing of water in concrete) and those above 0 °C (thawing of water in concrete).

Among the polymer-based structural materials, fiber reinforced polymers [37,38] are dominant, due to their combination of high strength and low density. All polymer-based materials suffer from their inability to withstand high temperatures. This inability can be due to the degradation of the polymer itself or, in the case of a polymer–matrix composite, due to the thermal stress resulting from the thermal expansion mismatch between the polymer matrix and the fibers.

Vibration damping is desirable for most structures. It is commonly attained by attaching to or embedding in the structure a viscoelastic layer [39–43]. However, due to the low strength and modulus of the viscoelastic material compared to the structural material, the presence of the viscoelastic material (especially if it is embedded) lowers the strength and modulus of the structure. A more ideal way to attain vibration damping is to tailor the structural material itself, so that it maintains its high strength and modulus while providing damping.

In the case of a composite material being the structural material, tailoring can be directed at (i) the interfaces in the composite, e.g. the fiber–matrix interface by fiber coating [44–46] or fiber surface treatment, and, in the case of continuous fiber composites, the interlaminar interface by the use of interlaminar additives such as metal particles [47], submicron-diameter carbon filaments [48] and viscoelastic polymer particles [49,50], (ii) the matrix by polymer blending in the case of polymer–matrix composites [51] and admixture (e.g. silica fume) use in the case of cement–matrix composites [23,24], (iii) the reinforcing fibers by the use of polymer fibers [52–55] and intercalated graphite fibers [56], and (iv) the use of additional fibers (i.e. fibers other than those for reinforcement), such as polymer fibers [57,58], coated fibers [46] and shape memory alloy fibers [59,60], to form hybrid composites. In particular, an additive or filler that is either viscoelastic [47,49] or small in unit size [48] is attractive. The small size results in a large filler–matrix interface area, thereby enhancing slippage at the interface during vibration.

In the case of continuous fiber composites, the reinforcing fiber orientation can be tailored to enhance damping. Examples are the use of zig-zag fibers (i.e. varying the ply orientation angle along the length of components like axially loaded struts) [61] and wave-like fiber orientations (i.e. fibers oriented in a continuous sine wave, with two layers that are 180° out of phase in the wave pattern sandwiching a viscoelastic layer) [62–65].

2. Cement–matrix composites

The most widely used structural composite is concrete—a cement–matrix composite. The dynamic mechanical properties of concrete have received much less attention than the static mechanical properties, in spite of the fact that dynamic loading conditions are commonly encountered in civil infrastructure systems. The dynamic loading can be due to live loads, sound, wind and earthquakes. The dynamic mechanical properties of concrete can be greatly affected by the admixtures [23,24,66–71].

The addition of silica fume (SiO_2 a fine particulate, ~0.1 μm size, preferably surface treated) as an admixture in the cement mix results in a large amount of interface and hence a significant increase in the damping capacity and storage modulus for both cement paste (nos. 1–4, Table 1)

Table 1
Damping capacity (tan δ) and storage modulus of cement-based materials at room temperature, as determined by flexural testing (three-point bending). Note that cement paste has no sand, whereas mortar has sand

		tan δ		Storage modulus (GPa)		Ref.
		0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz	
1	Cement paste (plain)	0.035	$<10^{-4}$	1.9	/	[23]
2	Cement paste with untreated silica fume[a]	0.082	0.030	12.7	12.1	[71]
3	Cement paste with treated[b] silica fume[a]	0.087	0.032	16.8	16.2	[71]
4	Cement paste with untreated silica fume[a] and silane[c]	0.055	/	17.9	/	[23]
5	Cement paste with untreated carbon fibers[d] and untreated silica fume[a]	0.089	0.033	13.3	13.8	[71]
6	Cement paste with untreated carbon fibers[d] and treated[b] silica fume[a]	0.084	0.034	17.4	17.9	[71]
7	Cement paste with treated[b] carbon fibers[d] and untreated silica fume[a]	0.076	0.036	17.2	17.7	[71]
8	Cement paste with treated[b] carbon fibers[d] and treated[b] silica fume[a]	0.083	0.033	21	22	[71]
9	Cement paste with untreated carbon filaments[d] and treated[b] silica fume[a]	0.089	0.035	10.3	10.9	[74]
10	Cement paste with treated[b] carbon filaments[d] and treated[b] silica fume[a]	0.106	0.043	11.3	11.4	[74]
11	Cement paste with untreated steel fibers[d] and untreated silica fume[a]	0.051	0.012	12.9	13.2	[74]
12	Cement paste with untreated steel fibers[e] and untreated silica fume[a]	0.046	0.011	13.0	13.6	[74]
13	Cement paste with latex[f]	0.142	0.112	/	/	[24]
14	Mortar (plain)	$<10^{-4}$	$<10^{-4}$	20	26	[70]
15	Mortar with treated[b] silica fume[a]	0.011	0.005	32	33	[73]
16	Mortar with untreated steel rebars	0.027	0.007	44	44	[73]
17	Mortar with sand blasted steel rebars	0.037	0.012	46	49	[73]
18	Mortar with untreated steel rebars and treated[b] silica fume	0.027	0.012	47	48	[75]

[a] 15% by mass of cement.
[b] Treated by silane coating.
[c] 0.2% by mass of cement.
[d] 0.5 vol.%.
[e] 1.0 vol.%.
[f] 30% by mass of cement.

and mortar (nos. 14 and 15, Table 1) [23,70,71,73]. The addition of latex (styrene butadiene in the form of a particle dispersion) as an admixture also enhances damping (nos. 1 and 13, Table 1), due to the viscoelastic nature of latex [24]. However, latex is much more expensive than silica fume.

The addition of either sand (nos. 1 and 14, Table 1) or 0.5 vol.% of a fibrous admixture in the form of 15 μm diameter untreated carbon fibers (about 5 mm long), 0.1 μm diameter carbon filaments (>100 μm long) or 8 μm diameter steel fibers (6 mm long) (nos. 2, 3, 5–12, Table 1) to the cement mix does not help the damping [68,69,71,74], due to the relatively high damping associated with the inhomogeneity within cement paste. However, the addition of 15-μm diameter silane-treated carbon filaments enhances the damping slightly, presumably due to the large interface area between the filaments and the cement matrix and the increased contribution of the interface to damping by the silane present at the interface (no. 10, Table 1) [74]. In spite of the ductility of steel compared to carbon, the steel fibers reduce the damping capacity (no. 11, Table 1) [74]. Thus, the interface area appears to be more important than the fiber ductility in enhancing damping. The addition of sand greatly reduces the damping capacity, due to the large proportion of sand compared to that of fibers or filaments. However, sand is inexpensive and is needed to diminish the drying shrinkage, and carbon fibers (particularly surface treated and used along with treated silica fume, which helps the fiber dispersion) are useful for increasing the storage modulus (nos. 2, 3, 5–8, Table 1), decreasing the drying shrinkage, increasing the flexural strength and toughness and rendering self-sensing ability [72].

Concrete is commonly reinforced with steel reinforcing bars (rebars in short). Both the loss tangent and the storage modulus of mortar are greatly increased by the use of steel rebar (preferably surface treated by sand blasting) in mortar (nos. 14, 16 and 17, Table 1) [73]. The addition of silica fume to steel rebar mortar further enhances the storage modulus (nos. 16 and 18, Table 1) [75].

Comparison of nos. 15 and 18 in Table 1 shows that the steel rebars enhance both loss tangent and storage modulus of silica fume mortar. However, comparison of nos. 2, 11 and 12 shows that the addition of 8-μm diameter steel fibers to silica fume cement decreases the loss tangent and has almost no effect on the storage modulus. Thus, steel rebars are much more useful than steel fibers for damping and stiffening. This may be due to the presence of surface deformation patterns on the steel rebars and the smoothness of the steel fiber surface. The importance of surface roughness is supported by the effect of sand blasting the steel rebars. The sand blasting enhances both loss tangent and storage modulus, as shown by comparing nos. 16 and 17 [73].

Silane coating [71] is an effective surface treatment, due to the hydrophilicity enhanced by silane and the fact that the cement mix is water-based. The enhanced wettability results in better dispersion in the cement mix. The treatment applied to silica fume enhances the loss tangent and storage modulus. When it is applied to carbon fibers, the storage modulus is increased, with negligible effect on the loss tangent.

Silane can be introduced to silica fume cement in two ways: (i) as a coating on silica fume (i.e. coating the silica fume with silane prior to using the silica fume) (no. 3, Table 1) and (ii) as an admixture (i.e. adding the silane directly into the cement mix) (no. 4, Table 1). Both methods enhance the workability of silica fume mortar similarly and increase the tensile and compressive strengths of silica fume cement paste similarly. However, the latter method gives silica fume cement paste of lower compressive ductility, lower damping capacity (nos. 3 and 4, Table 1), more drying shrinkage, lower air void content, higher density, higher specific heat and greater thermal conductivity [23]. These differences are mainly due to the network of covalent coupling among the silica fume particles in the latter case.

3. Continuous fiber polymer–matrix composites

Polymer–matrix composites containing continuous fibers are widely used for lightweight structures. (Those containing discontinuous fibers are mainly used for nonstructural applications.) As vibrations are undesirable for most structures, particularly aerospace structures, damping is critically needed. Damping can be enhanced in these materials by the use of interlayers in the interlaminar region and by the choices of matrix and fiber.

3.1. *Use of interlayers*

Viscoelastic polymeric or ionomeric interlayers (i.e. interleaves) incorporated in a composite between the laminae of continuous fibers are used for damping, toughening and impact performance improvement. This method of damping is known as constrained-layer damping [76–78], which has been applied to laminates [79] and filament wound composite cylinders [80]. However, the presence of the interlayer degrades the stiffness of the composite. The use of 0.1-μm diameter carbon filaments (>100 μm long, preferably surface treated) in place of the viscoelastic interlayer alleviates this problem and is particularly attractive when the temperature is high (e.g. 50 °C) [48,81].

The use of a smart constrained layer in the form of a viscoelastic layer sandwiched by two piezoelectric layers [82,83] allows combined active and passive damping [84]. A related technique involves sandwiching a viscoelastic layer with two permanent magnet layers [85]. Electrorheological (ER) fluids can also be used for constrained layer damping [86], due to their viscoelasticity. By control-

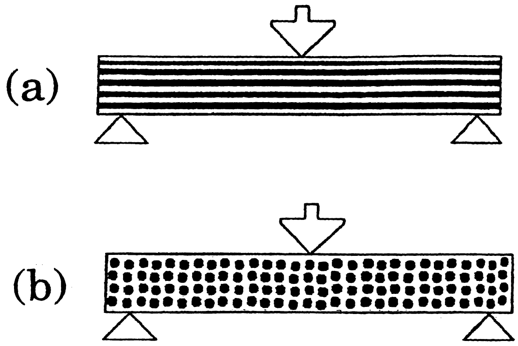

Fig. 1. Geometry for dynamic mechanical testing of unidirectional continuous fiber polymer–matrix composite under three-point bending. (a) Longitudinal configuration, in which the fibers (in the plane of the figure) were bent during flexure. (b) Transverse configuration, in which the fibers (perpendicular to the plane of the figure) were not bent during flexure [80].

ling the electric field, the dynamic properties of ER fluids can vary between those of viscoelastic liquids (at low fields) and those of viscoelastic solids (at high fields). Thus, ER fluids allow an adaptive form of constrained layer damping.

Due to the fact that the continuous fibers in a polymer–matrix structural composite are typically aligned, the composite is highly anisotropic, in contrast to the cement–matrix composites mentioned in the last section. Thus, the flexural testing used to evaluate the damping capacity can be conducted in different configurations. In the longitudinal configuration, the fibers are bent during flexural testing (Fig. 1(a)). In the transverse configuration, the fibers are not bent during flexural testing (Fig. 1(b)). The longitudinal configuration reflects properties that are governed mainly by the fibers; the transverse configuration reflects properties that are governed mainly by the polymer matrix. The properties of a practical structural composite with fibers in multiple directions are mainly governed by the fibers, so the longitudinal configuration is of more practical importance than the transverse configuration.

In a comparative study [81] involving three-point bending, both configurations in Fig. 1, a thermoplastic (nylon-6) matrix, continuous carbon fibers (7 μm diameter), and three types of interlayer material were used, namely a polymeric viscoelastic sheet (55 μm thick, 4.6 vol.% of composite), the above-mentioned carbon filaments without surface treatment (i.e. as received, 65-μm thick interlayer, 6.3 vol.% of composite), and the above-mentioned carbon filaments with surface treatment (77-μm thick interlayer, 7.1 vol.% of composite). The surface treatment involved surface oxidation by exposure to ozone gas at 160 °C.

Table 2 [81] shows the dynamic mechanical properties at room temperature. The loss tangent for the longitudinal configuration was increased by all three types of interlayer, except that it was essentially not affected by the as-received carbon filament interlayer; the storage modulus for the longitudinal configuration was decreased by any of the three types of interlayer. For the transverse configuration, the loss tangent was increased by the viscoelastic interlayer, but not much affected by either type of filament interlayer; the storage modulus was decreased by the viscoelastic interlayer and the as-received carbon filament interlayer, but was increased slightly by the treated carbon

Table 2
Dynamic flexural properties of continuous carbon fiber nylon-6 matrix composites with and without interlayers, as determined by three-point bending [81]

Interlayer	None	Viscoelastic	As-received carbon filaments	Treated carbon filaments
1. tan δ				
Longitudinal				
0.2 Hz	0.008±0.001	0.43±0.05	0.007±0.001	0.09±0.02
1.0 Hz	<0.0001	0.36±0.05	0.001±0.001	0.001±0.001
Transverse				
0.2 Hz	0.065±0.005	0.24±0.05	0.060±0.005	0.052±0.005
1.0 Hz	0.080±0.005	0.22±0.06	0.090±0.005	0.073±0.005
2. Storage modulus (GPa)				
Longitudinal				
0.2 Hz	127±8	37±4	66±5	115±6
1.0 Hz	132±9	67±5	67±3	97±5
Transverse				
0.2 Hz	9.6±0.2	3.8±0.2	6.1±0.2	10.2±0.3
1.0 Hz	9.9±0.3	4.4±0.2	6.3±0.2	10.8±0.3
3. Loss modulus (GPa)				
Longitudinal				
0.2 Hz	1.0±0.3	16±1	0.35±0.10	9±5
1.0 Hz	<0.013	23.5±1.5	0.067±0.002	<0.097
Transverse				
0.2 Hz	0.62±0.03	0.90±0.20	0.067±0.002	0.60±0.05
1.0 Hz	0.79±0.04	0.94±0.20	0.500±0.003	0.78±0.05

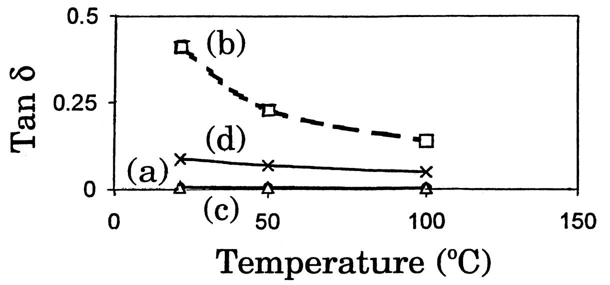

Fig. 2. Effect of temperature on the loss tangent of continuous carbon fiber thermoplastic–matrix composite (longitudinal configuration) at 0.2 Hz. (a) Composite without interlayer. (b) Composite with viscoelastic interlayer. (c) Composite with as-received carbon filament interlayer. (d) Composite with treated carbon filament interlayer [80].

filament interlayer. The loss tangent for both longitudinal and transverse configurations was increased most significantly by the viscoelastic interlayer, while the storage modulus for both configurations was decreased most significantly by the viscoelastic interlayer. For both configurations, the loss modulus was highest for the case of the viscoelastic interlayer. All effects were much larger for the longitudinal configuration than the transverse configuration.

Figs. 2–4 show the loss tangent, storage modulus and loss modulus, respectively as functions of temperature for the four types of composites in the longitudinal configuration at a loading frequency of 0.2 Hz. The loss tangent was highest for the composite with viscoelastic interlayer (Fig. 2), though the value for this composite decreased substantially with increasing temperature, especially from 20 to 50 °C. The composite with treated carbon filament interlayer gave higher loss tangent than that with as-received filament interlayer. The values for these filament composites dropped only slightly with increasing temperature. The storage modulus decreased with increasing temperature for any of the four types of composites (Fig. 3). The loss modulus also decreased with increasing temperature for any of the four types of composites (Fig. 4); the decrease was most significant for the composite with viscoelastic interlayer, particularly from 20 to 50 °C. At 20 °C, the composite with viscoelastic interlayer exhibited the highest loss modulus; at 50 and 100 °C, the composite with treated filaments exhibited the highest loss modulus. The large amount of interface between the 0.1-μm diameter filaments and the polymer matrix contributed to the damping.

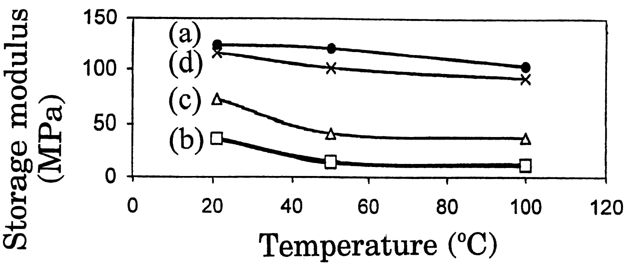

Fig. 3. Effect of temperature on the storage modulus of continuous carbon fiber thermoplastic–matrix composite (longitudinal configuration) at 0.2 Hz. (a) Composite without interlayer. (b) Composite with viscoelastic interlayer. (c) Composite with as-received carbon filament interlayer. (d) Composite with treated carbon filament interlayer [80].

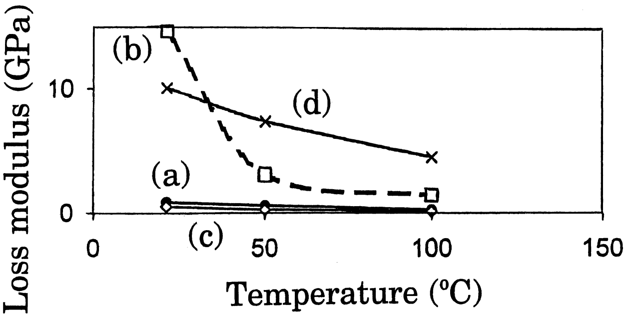

Fig. 4. Effect of temperature on the loss modulus of continuous carbon fiber thermoplastic–matrix composite (longitudinal configuration) at 0.2 Hz. (a) Composite without interlayer. (b) Composite with viscoelastic interlayer. (c) Composite with treated carbon filament interlayer [80].

3.2. Choices of matrix and fiber

Thermosets such as epoxy are the dominant matrix for continuous fiber composites due to the good adhesive ability of epoxy and the long history of service of epoxy–matrix structural composites. However, thermosets tend to be more brittle and less tough than thermoplastics. The loss tangent of epoxy is only 0.04 at 1 Hz [87] (Table 3). Rubber is exceptional in its damping capacity (loss tangent=1.1 at 1 Hz in the case of Neoprene rubber [88]), but its very low storage modulus (7.8 MPa at 1 Hz in the case of Neoprene rubber [88]) makes it unsuitable for structural applications. Polytetrafluoroethylene (PTFE) is a thermoplastic that exhibits moderately high values of both loss tangent (0.22 at 1 Hz) and storage modulus (1.3 GPa at 1 Hz) [87]. Another thermoplastic is poly(methylmethacrylate) (PMMA), which exhibits a lower loss tangent (0.10 at 1 Hz) than PTFE, but a higher storage modulus (3.5 GPa at 1 Hz) than PTFE [87]. Polyamide-66 (Nylon) is a commonly used thermoplastic, but its loss tangent is low (0.08 at 1 Hz) [87]. Thus, PTFE and PMMA are attractive matrices for structural composites that provide damping. Polymer blends and interpenetrating networks are also attractive, due to the interface between the components in the blend or network providing a mechanism for damping [89–91]. However, investigation of the damping performance of composites with these matrices has not been reported.

Carbon fibers are dominant among fibers for lightweight structural composites due to their high modulus and low density. However, glass fibers and polymer fibers are more ductile than carbon fibers and may be used along with or in place of carbon fibers for the purpose of enhancing damping.

Table 3
Loss tangent, storage modulus and loss modulus of various polymers

Material	Property	0.2 Hz	1.0 Hz	Ref.
PMMA	Loss tangent	0.093±0.019	0.100±0.038	[87]
	Storage modulus (GPa)	3.63±0.24	3.49±0.7	
	Loss modulus (MPa)	336±70	375±83	
PTFE	Loss tangent	0.1885±0.0005	0.224±0.008	[87]
	Storage modulus (GPa)	1.22±0.05	1.34±0.05	
	Loss modulus (MPa)	229±9	300±15	
PA-66	Loss tangent	0.043±0.009	0.078±0.035	[87]
	Storage modulus (GPa)	4.35±0.05	4.45±0.08	
	Loss modulus (MPa)	187±41	349±161	
Epoxy	Loss tangent	0.030±0.007	0.039±0.015	[87]
	Storage modulus (GPa)	3.20±0.31	3.50±0.07	
	Loss modulus (MPa)	105±24	116±36	
Neoprene rubber	Loss tangent	0.67±0.14	1.12±0.08	[88]
	Storage modulus (MPa)	7.45±0.28	7.83±0.11	
	Loss modulus (MPa)	6.72±1.50	8.23±0.76	

4. Conclusion

The use of composite engineering to tailor structural composite materials for damping results in enhancement of the loss tangent, with negligible, if any, reduction of the storage modulus. In the case of cement–matrix composites, both loss tangent and storage modulus are greatly enhanced by the addition of silica fume. The effect of silica fume is particularly large when sand is present. The addition of fibrous admixtures, whether steel or carbon, ranging from 0.1 to 15 μm in diameter, has only minor effects, if any, on the damping capacity of silica fume cement. In contrast, steel rebars enhance both loss tangent and storage modulus of mortar significantly, whether silica fume is present or not.

The effects mentioned above are further enhanced when the silica fume, carbon filaments or steel rebar has been surface treated. Silane coating is effective for treating silica fume. Sand blasting is effective for treating steel rebars.

In the case of continuous carbon fiber polymer–matrix composites, the use of a viscoelastic interlayer greatly enhances the loss tangent, but greatly diminishes the storage modulus. Both effects are less when 0.1-μm diameter carbon filaments are used as the interlayer. However, the decrease of the modulus with increasing temperature for the viscoelastic interlayer case causes the loss modulus at 50 °C to be higher when the carbon filaments rather than viscoelastic material is used as the interlayer. The choices of fiber and matrix can also be used to enhance damping.

References

[1] D.D.L. Chung, J. Mater. Sci. 36 (24) (2001) 5733.
[2] Z. Maekawa, H. Hiroyuki, A. Goto, Nippon Kikai Gakkai Ronbunshu C Hen. 60 (571) (1994) 831.
[3] I.C. Finegan, R.F. Gibson, Compos. Struct. 44 (2) (1999) 89.
[4] M.R. Maheri, R.D. Adams, JSME Int. J. Ser. A—Solid Mech. Mater. Eng. 42 (3) (1999) 307.
[5] J.J. Hollkamp, R.W. Gordon, Smart Mater. Struct. 5 (5) (1996) 715.
[6] Y.K. Kang, H.C. Park, J. Kim, S.-B. Seung, Mater. Design 23 (3) (2002) 277.
[7] S. Raja, G. Prathap, P.K. Sinha, Smart Mater. Struct. 11 (1) (2002) 63.
[8] M. Hori, T. Aoki, Y. Ohira, S. Yano, Composites—Part A: Appl. Sci. Manufact. 32 (2) (2001) 287.
[9] M. Arafa, A. Baz, Compos. Sci. Tech. 60 (15) (2000) 2759.
[10] M. Arafa, A. Baz, Compos.—Part B: Eng. 31 (4) (2000) 255.
[11] I.G. Ritchie, Z.-L. Pan, Metall. Trans. A—Phys. Metall. Mater. Sci. 22A (3) (1991) 607.
[12] K. Fujisawa, M. Taniuchi, T. Kogishi, Y. Sasaki, A. Kobayashi, K. Iwai, R&D 44 (3) (1994) 12.
[13] J.N. Wei, H.F. Cheng, Y.F. Zhang, F.S. Han, Z.C. Zhou, J.P. Shui, Mater. Sci. Eng. 325 (1–2) (2002) 444.
[14] S. Thomas, A. George, Eur. Polym. J. 28 (11) (1992) 1451.
[15] D.A. Greenhill, D.J. Hourston, in: Proceedings of the ACS Division of Polymeric Materials Science and Engineering, Dallas, 1989 (ACS, Books & Journals Division, Washington, DC, 1989) Vol. 60, p. 644.
[16] S. Nazarenko, D. Haderski, A. Hiltner, E. Baer, Polym. Eng. Sci. 35 (21) (1995) 1682.
[17] S.N. Ganeriwala, in: Proceedings of SPIE—The International Society for Optical Engineering, Smart Structures and Materials, 1995: Passive Damping, San Diego, 1995, (Society of Photo-Optical Instrumentation Engineers, Bellingham, 1995) Vol. 2445, p. 200.
[18] J.N. Das, N.G. Nair, N. Subramanian, Plastics Rubber Compos. Process. Appl. 20 (4) (1993) 249.
[19] R. Schaller, G. Fantozzi, Mater. Sci. Forum 366–368 (2001) 615.
[20] R. De Batist, J. Phys. (Paris) Colloq. C9 44 (12) (1983) 39.
[21] Y.P. Lu, H.C. Neilson, A.J. Roscoe, J. Compos. Mater. 27 (16) (1993) 1598.
[22] L. Yan, C.H. Jenkins, R.L. Pendleton, Cem. Concr. Res. 30 (3) (2000) 391.
[23] Y. Xu, D.D.L. Chung, Cem. Concr. Res. 30 (8) (2000) 1305.
[24] X. Fu, X. Li, D.D.L. Chung, J. Mater. Sci. 33 (1998) 3601.
[25] R. Chandra, S.P. Singh, K. Gupta, Compos. Struct. 46 (1) (1999) 41.
[26] J. Lu, D.C. Van Aken, Metallurgical and Materials Transactions A—Physical Metallurgy and Materials Science 27A (9) (1996) 2565.
[27] H. Furuya, N. Kogiso, S. Mantunaga, K. Senda, Mater. Sci. Forum 350 (2000) 341.

[28] X. Hou, H. Li, C. Wang, Z. Zhu, J. Shen, Carbon 38 (15) (2000) 2095.
[29] C. Wang, Z. Zhu, X. Hou, H. Li, Carbon 38 (13) (2000) 1821.
[30] A. Wolfenden, K.J. Spann, M.G. Hebsur, J. Adv. Mater. 32 (4) (2000) 66.
[31] A. Wolfenden, J.E. Gill, K.K. Chawla, R.U. Vaidya, R. Venkatesh, J. Test. Evaluat. 22 (6) (1994) 571.
[32] H. Sueyoshi, K. Tagami, N.T. Rochman, Mater. Trans. 42 (6) (2001) 965.
[33] W.-H. Liu, J.-S. Zhu, Gongneng Cailiao/J. Funct. Mater. 32 (4) (2001) 440.
[34] A. Wolfenden, C.M. Miller, M.G. Hebsur, J. Mater. Sci. Lett. 17 (21) (1998) 1861.
[35] S.K. Srivastava, B.K. Mishra, S.C. Jain, J. Reinforced Plastics Compos. 20 (1) (2001) 37.
[36] S. Sastry, M. Krishna, J. Uchil, J. Alloys Comp. 314 (1–2) (2001) 268.
[37] D. Rouby, Mater. Sci. Forum 366–368 (2001) 581.
[38] J. Vantomme, J. De Visscher, H. Sol, W.P. De Wilde, Revue M. Mecan. 40 (4) (1995) 203.
[39] M.D. Rao, R. Echempati, S. Nadella, Compos.—Part B: Eng. 28 (5–6) (1997) 547.
[40] J.M. Biggerstaff, J.B. Kosmatka, J. Compos. Mater. 33 (15) (1999) 1457.
[41] R.F. Gibson, H. Zhao, American Society of Mechanical Engineers Noise Control and Acoustics Division (Publication) 26 (1999) 333.
[42] J. Oborn, H. Bertilsson, M. Rigdahl, J. Appl. Polym. Sci. 80 (14) (2001) 2865.
[43] N. Nugay, B. Erman, J. Appl. Polym. Sci. 79 (2) (2001) 366.
[44] I.C. Finegan, R.F. Gibson, Compos. Sci. Tech. 60 (7) (2000) 1077.
[45] I.C. Finegan, R.F. Gibson, J. Vibr. Acoust.—Trans. ASME 120 (2) (1998) 623.
[46] I.C. Finegan, R.F. Gibson, in: Proceedings of the 1997 ASME International Mechanical Engineering Congress and Exposition, Dallas, 1997, (ASME, Fairfield, NJ, 1997) Vol. 24, p. 127.
[47] S.W. Hudnut, D.D.L. Chung, Plastics Rubber Compos. Process. Appl. 25 (2) (1996) 77.
[48] S.W. Hudnut, D.D.L. Chung, Carbon 33 (11) (1995) 1627.
[49] J.M. Biggerstaff, J.B. Kosmatka, in: Proceedings of SPIE—The Int. Soc. for Optical Engineering, Newport Beach, CA, (Society of Photo-Optical Instrumentation Engineers, 2000) Vol. 3989, p. 531.
[50] T. Tanimoto, Acta Mater. 46 (7) (1998) 2455.
[51] G. Rohrauer, S.V. Hoa, in: Proceedings of 31st National SAMPE Symposium and Exhibition, Los Angeles, CA, (SAMPE, Azusa, CA, 1986) p. 1038.
[52] L. Balis Crema, A. Castellani, U. Drago, Composites 20 (6) (1989) 593.
[53] R.C.L. Dutra, B.G. Soares, E.A. Compos, J.D.G. De Melo, J.L.G. Silva, J. Appl. Polym. Sci. 73 (1) (1999) 69–73.
[54] M.A. Lopez-Manchado, M. Arroyo, Polymer 41 (21) (2000) 7761.
[55] R.C.L. Dutra, B.G. Soares, E.A. Compos, J.L.G. Silva, Polymer 41 (10) (2000) 3841.
[56] G.A. Lesieutre, S. Yarlagadda, D. Christiansen, W. Whatley, AIAA J. 31 (4) (1993) 746.
[57] A. Djumaev, K. Takahashi, J. Mater. Sci. 29 (18) (1994) 4736.
[58] P.R. Mantena, R.F. Gibson, in: 22nd International SAMPE Technical Conference, Advanced Materials: Looking Ahead to the 21st Century, Boston, MA, (SAMPE, Covina, CA, 1990) Vol. 22, p. 370.
[59] D.-Y. Ju, A. Shimamoto, J. Intell. Mater. Sys. Struct. 10 (7) (2000) 514.
[60] C. Boller, P. Konstanzer, Y. Matsuzaki, T. Ikeda, in: Proceedings of SPIE—The Int. Soc. for Optical Engineering, Newport Beach, CA, (Society of Photo-Optical Instrumentation Engineers, 2001) Vol. 4332, p. 471.
[61] D.D. Olcott, C.A. Rotz, P.F. Eastman, in: Proceedings of the 1993 38th Int. SAMPE Symp. and Exhib., Advanced Materials: Performance through Technology Insertion, Anaheim, CA, (SAMPE, Covina, CA, 1993) Vol. 38, no. 2, p. 1357.
[62] W.F. Pratt, M.S. Allen, S.D. Sommerfeldt, Intern. SAMPE Symp. Exhibition (Proceedings) 46 (2001) 216.
[63] W.F. Pratt, M.S. Allen, C.G. Jensen, Intern. SAMPE Symp. Exhibition (Proceedings) 46 (2001) 203.
[64] K.A. Steurer, D.W. Jensen, Collection of Technical Papers—AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 1(II) (2000) 1039.
[65] J.D. Marshal, D.W. Jensen, in: Proceedings of SPIE—The Int. Soc. for Optical Engineering, Newport Beach, CA, (Society of Photo-Optical Instrumentation Engineers, 2000) Vol. 3989, p. 344.
[66] N. Moiseev, in: C.G. Gordon (Editor), Proc. SPIE—The Int. Soc. for Optical Engineering, Vol. 1619 (Vibration Control in Microelectronics, Optics, and Metrology), published by Int. Soc. for Optical Engineering, Bellingham, WA, 1992, pp. 192–202.
[67] X. Fu, D.D.L. Chung, Cem. Concr. Res. 26 (1994) 69.
[68] X. Fu, D.D.L. Chung, ACI Mater. J. 96 (4) (1999) 455.
[69] Y. Xu, D.D.L. Chung, Cem. Concr. Res. 29 (7) (1999) 1107.
[70] Y. Wang, D.D.L. Chung, Cem. Concr. Res. 28 (10) (1998) 1353.
[71] Y. Xu, D.D.L. Chung, ACI Mater. J. 97 (3) (2000) 333.
[72] D.D.L. Chung, Composites: Part B 31 (6–7) (2000) 511.
[73] S. Wen, D.D.L. Chung, Cem. Concr. Res. 30 (2) (2000) 327.
[74] J. Cao, D.D.L. Chung, unpublished result.
[75] S. Wen, D.D.L. Chung, unpublished result.
[76] R.F. Gibson, Y. Chen, H. Zhao, J. Eng. Mater. Tech.—Trans. ASME 123 (3) (2001) 309.
[77] Y.P. Lu, J.M. Bai, C.T. Sun, Key Eng. Mater. 141–143 (Pt 2) (1998) 623.
[78] A. Akimoto, G.O. Shonaike, Y. Usui, Y. Aoki, A. Murakami, S. Matsuda, M. Hojo, S. Ochiai, J. Thermoplastic Compos. Mater. 13 (4) (2000) 314.
[79] Y. Ohta, Y. Narita, in: Proceedings of the 1995 Joint ASME/JSME Pressure Vessels and Piping Conference, Honolulu, HI, (ASME, New York, NY, 1995), Vol. 301, p. 175.
[80] J.F. Wlodarski, A.R. Johnson, B.K. Taleghani, R.N. Evans, R.S. Garner, R.S. Pappa, Collection of Technical Papers – AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, 1 (1996) 409.
[81] M. Segiet, D.D.L. Chung, Compos. Interfaces 7 (4) (2000) 257.
[82] I.Y. Shen, Smart Mater. Struct. 3 (1) (1994) 59.
[83] A. Baz, J. Ro, Smart. Mater. Struct. 10 (1) (2001) 112.
[84] J. Gao, Y. Shen, Appl. Math. Mech. (English Edition) 20 (10) (1999) 1075.
[85] J. Oh, M. Ruzzene, A. Baz, Int. J. Appl. Electromagn. Mater. 11 (2) (2000) 95.
[86] S.O. Oyadiji, J. Intelligent Mater. Sys. Struct. 7 (5) (1996) 541.
[87] W. Fu, D.D.L. Chung, Polym. Polym. Compos. 9 (6) (2001) 423.
[88] X. Luo, D.D.L. Chung, Carbon 38 (10) (2000) 1510.
[89] R.P. Chartoff, J.M. Butler, R.S. Venkatachalam, D.E. Miller, in: Proceedings of the 41st Annual Technical Conference—Society of Plastics Engineers, 1983, (Society of Plastics Engineers, Brookfield Center, 1983) p. 360.
[90] K. Sasaki, T. Okumoto, J. Koizumi, SAE Technical Paper Series (1990).
[91] C.-J. Tung, T.-C.J. Hsu, J. Appl. Polym. Sci. 46 (10) (1992) 1759.