AD-A092 194 OKLAHOMA UNIV NORMAN SCHOOL OF AEROSPACE MECHANICAL --ETC F/G 11/4

COMPOSITE MATERIALS: A SURVEY OF THE DAMPING CAPACITY OF FIBER---ETC(U)

AUG 80 C W BERT N00014-78-C-0647

UNCLASSIFIED OU-AMNE-80-17 NL

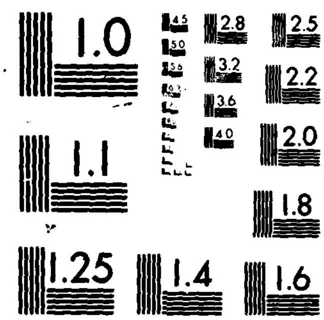
1 of 1

END

DATE FILMED

1 81

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

LEVEL II

(12)

Department of the Navy
OFFICE OF NAVAL RESEARCH
Structural Mechanics Program
Arlington, Virginia 22217

(15) Contract N00014-78-C-0647
Project NR 064-609
(9) Technical Report No. 18

Report OU-AMNE-80-17, TR-18
(14)

(6) COMPOSITE MATERIALS: A SURVEY OF THE DAMPING CAPACITY OF FIBER-REINFORCED COMPOSITES

by

(10) Charles W. Bert

(11) Aug[redacted]980 (12) 14

School of Aerospace, Mechanical and Nuclear Engineering
University of Oklahoma
Norman, Oklahoma 73019

Approved for public release; distribution unlimited

COMPOSITE MATERIALS: A SURVEY OF THE DAMPING CAPACITY OF FIBER-REINFORCED COMPOSITES

Charles W. Bert
School of Aerospace, Mechanical and Nuclear Engineering
University of Oklahoma, Norman, Oklahoma

ABSTRACT

A discussion is given on the importance of damping in fiber-reinforced composites and is followed by concise definitions of the various measures of damping. The current state of the theory of damping in fiber-reinforced composites is reviewed for perfectly-bonded viscoelastic composites, yielding-matrix composites, and those in which slip takes place at the fiber-matrix interface. General trends in stiffness and damping of composites with polymeric matrices are reviewed.

NOMENCLATURE

a_i, a_{i+n}	= response amplitudes at the i-th and (i+n)-th cycles (see Fig. 4)
$\tilde{E}$	= complex elastic modulus
$\tilde{E}_L, \tilde{E}_T$	= complex elastic moduli for L and T directions
E_f, E_m	= elastic moduli of fiber and matrix
E^I, E^R	= loss and storage elastic moduli
$\tilde{G}_{LT}, \tilde{G}_{LZ}, \tilde{G}_{TZ}$	= complex shear moduli for LT, LZ, TZ planes (see Fig. 5)
g	= loss tangent
i	= $\sqrt{-1}$
L	= fiber direction (see Fig. 5)
n	= number of decaying cycles over which δ is measured
Q	= quality factor
T	= inplane direction normal to the fiber (see Fig. 5)
t	= time
U	= maximum strain energy per unit volume
U_d	= energy dissipated in a unit volume per cycle
$V_f, (V_f)_{opt}$	= fiber volume fraction and its optimum for max. damping
Z	= thickness direction (see Fig. 5)
γ	= loss angle (see Fig. 3)
δ	= logarithmic decrement
$\epsilon_{fy}, \epsilon_{my}$	= elastic strain values at initial yielding, fiber and matrix
$\Delta\epsilon_{mp}$	= plastic-strain range in the matrix
ζ	= dimensionless damping ratio
θ	= lamination angle
ν_{12}	= major Poisson's ratio
σ_{my}	= yield strength of matrix

ψ = specific damping capacity
ω_1, ω_2 = half-power-point frequencies (see Fig. 2)
ω_n = specific damping capacity

INTRODUCTION

For composite materials, damping is understood here to mean any phenomenon within the body of the material in which energy is dissipated. This includes, but is not limited to: (1) internal friction or hysteresis within each of the constituent materials and (2) interfacial slip at the fiber-matrix interfaces.

Damping in composites is important for one or more of these reasons:

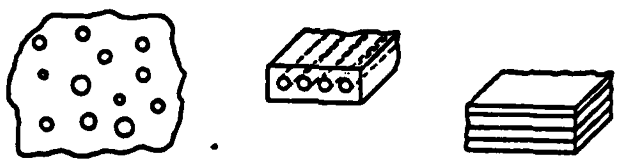
1 In controlling the resonant response of structures and thus in prolonging their service life under repeated-loading environment or impact conditions. In this instance, which is commonly encountered in aircraft structures, for example, it is beneficial to increase the damping capacity of the material.

2 In providing a source of excitation for dynamic instability in gyroscopic systems, such as shaft-disk systems in turbomachinery, energy-storage flywheels, and other rotating machinery. This hysteresis induced whirling was investigated as early as 1928 by Taylor (1)[1]. In this class of application, it was shown by Genin and Maybee (2), for example, that it is beneficial to decrease material damping, provided the operating speed is beyond the first critical speed for lateral whirling. Economic and efficiency requirements dictate that most modern rotating machinery must operate in this regime.

3 Measurement of damping throughout the service use of a structure holds some promise as a means of detecting material failure, cf. (3,4).

The present review is directed primarily at the first reason, for which increased damping (or some combination of increased fatigue strength, increased stiffness, and moderate damping) is desired.

The three main classes of composite materials are (see Fig. 1): (a) particulate, (b) fiber-reinforced, and (c) laminated. In structural applications, the combination of (b) and (c) is most widely used; i.e., layers of fiber-reinforced material are oriented in various ways and bonded together to form a laminate. In the present review, emphasis is placed upon this combination.



(a) Particulate (b) Fiber-reinforced (c) Laminated

Fig. 1. Types of composite materials.

Although the combinations of different kinds of constituent materials used in composites are limited only by the designer's imagination and the material specialist's fabricational skill, currently the two main categories are polymer-matrix composites and metal-matrix composites. Since polymers generally have higher damping than metallic materials, one would expect polymer-matrix composites to have high damping inherently. However, as will be shown later, this is only true for the damping factors associated with certain orientations and properties (i.e., transverse normal loading and inplane shear loading).

MEASURES OF DAMPING

Before reviewing the theoretical aspects and experimental data for damping in fiber-reinforced composites, it is well to review briefly the most widely used definitions of damping (5). This is done here in the context of a material

1 Underlined numbers in parentheses designate References at end of paper.

which can be modeled by the complex-modulus approach[2].

Energy dissipation under steady-state sinusoidal vibration. This is usually defined in terms of specific damping capacity ψ, which is the ratio of energy dissipated (U_d) in a unit volume per cycle to the maximum strain energy per unit volume (U), i.e., $\psi = U_d/U$.

Bandwidth of half-power points in steady-state sinusoidal excitation. One way of specifying this is in terms of the dimensionless damping ratio ζ, which is defined as the ratio of the actual damping coefficient to the critical one, and can be calculated from

$$\zeta = (\omega_2 - \omega_1)/2\omega_n \tag{1}$$

(see Fig. 2). This measure is the basis for determining damping by the original Kennedy-Pancu system identification method (6). The quality factor

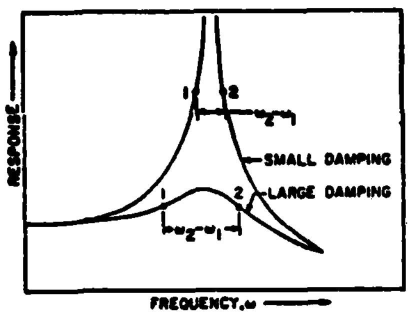


Fig. 2
Effect of damping on half-power frequency separation ($\omega_1 - \omega_2$).

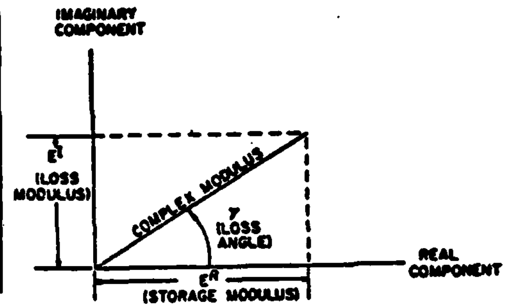


Fig. 3
Concept of complex modulus and loss angle.

(Q) is defined as $1/(2\zeta)$.

Loss tangent under sinusoidal excitation. Applying the complex-stiffness approach to the material stiffness (elastic modulus), we have

$$\bar{E} = E^R + iE^I = E^R(1 + ig) \tag{2}$$

Here $\bar{E}$ is the complex modulus, E^R and E^I are the respective real and imaginary components of E, and g is called the loss factor (see Fig. 3). The quantities E^R and E^I are usually called the storage modulus and the loss modulus, respectively while g is sometimes called the "loss tangent", since $g = \tan\gamma$.

Decay of free vibration (see Fig. 4). The most popular measure of this phenomenon is the logarithmic decrement, defined as follows:

$$\delta \equiv \ln(a_i/a_{i+1}) \tag{3}$$

For most materials, at least at relatively small amplitudes, δ is very small and independent of amplitude. Then a more practical way of calculating δ from experimental data is

[2] It is realized that there are numerous deficiencies in this approach, as has been pointed out in (5). However, in spite of these limitations, the complex-modulus approach is the model most widely used in structural dynamics.

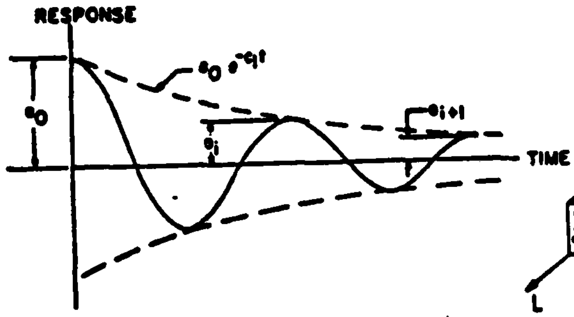


Fig. 4. Exponential decay.

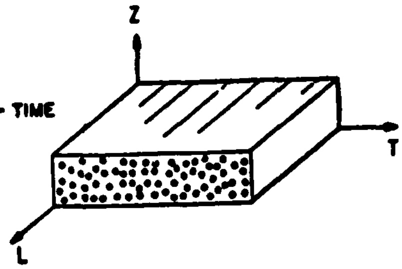


Fig. 5. Definition of axes.

$$\delta = (1/n)\ \ln(a_i/a_{i+n}) \tag{4}$$

where n is any arbitrary integer (often selected to be 10 for convenience).

The following interrelationships among the measures of damping (for materials with small damping) are useful (see (5) for more general ones):

$$g = 2\zeta = 1/Q = \psi/2\pi = \delta/\pi \tag{5}$$

Some additional measures were discussed in (5).

THEORY OF DAMPING IN VISCOELASTIC COMPOSITES REINFORCED WITH PERFECTLY-BONDED CONTINUOUS FIBERS

Here it is assumed that no significant macroscopic yielding or interfacial slip takes place. It is further assumed that the fibers, as well as the matrix, can be characterized by their elastic coefficients and the associated loss coefficients. The pioneering work for this case was the damping micromechanics analysis conducted by Hashin (7). See also (8). Hashin applied the well-known elastic-viscoelastic correspondence principle to relate the effective elastic moduli and creep compliances of the viscoelastic composites. Unfortunately, this method cannot be used in those instances where the elastic moduli cannot be obtained explicitly.

A more generally applicable approach, in which the energy dissipated per cycle in the composite is formulated and used to predict the various loss tangents, was presented by Bert and Chang (9,10). Measured stiffness and damping properties of glass and epoxy as a function of frequency were used to predict these properties for the composite. It is noted that the highest loss tangents were those associated with transverse normal loading and with inplane shear.

It is interesting to note that, to the best of the present investigator's knowledge, no analysis has yet appeared to predict damping in a composite reinforced by anisotropic fibers. In contrast, a number of such micromechanics analyses have been formulated for analyzing stiffness of such composites (11 - 15). It is noted that graphite fibers are known to be highly anisotropic.

THEORY OF DAMPING IN METALLIC-MATRIX COMPOSITES AT HIGH STRAINS

One way to achieve high damping in a metallic-matrix composite is to subject it to sufficiently high loads to cause the matrix to deform plastically. Apparently Baker (16) was the first to investigate this phenomenon. He conducted experiments on aluminum-matrix composites reinforced with either silica or stainless-steel fibers. Based on a simplified model, he obtained an expression to predict the specific damping capacity ψ as a function of the strain. Upon correcting a typographical error in his equation (17), one can express it as follows:

$$\psi = \frac{2\sigma_{my}(1 - V_f)\Delta\epsilon_{mp}}{(E_f V_f/2)[\Delta\epsilon_{mp} + (\sigma_{my}/E_m)]^2 + [2(1 - V_f)\sigma_{my}^2/E_m]} \qquad (6)$$

Here E_f and E_m are the elastic moduli of the fiber and matrix respectively, V_f is the fiber volume fraction, $\Delta\epsilon_{mp}$ is the plastic strain range endured by the matrix, and σ_{my} is the matrix yield strength. The model predicts somewhat higher values than those determined experimentally, yet the trend of ψ versus strain is similar. It is interesting to note the peaking effect in ψ . This optimal-damping condition is due to a balance between two opposing phenomena: the buildup of elastic energy and the loss of energy due to plastic deformation.

Experiments on aluminum-matrix composites with boron fibers were conducted by Varschavsky (17), who also refined Baker's theory. Weiss (18) investigated the effect of prestressing upon the damping of aluminum-matrix composites with high-strength steel fibers. He obtained the following expression for the fiber volume fraction which is predicted to result in the maximum damping capacity

$$(V_f)_{opt} = [1 + (E_f/E_m)(\epsilon_{fy}/\epsilon_{my} - 2)]^{\frac{1}{2}} \qquad (7)$$

Here ϵ_{fy} and ϵ_{my} are the respective fiber and matrix yield strains. The prestressing considered by Weiss took the form of residual stress due to stretching after hot pressing.

THEORY OF DAMPING IN COMPOSITES WITH DISCONTINUOUS FIBERS AND INTERFACIAL SLIP

Apparently the first analysis of damping in composites with discontinuous fibers is due to Pompe and Schultrich (19). They used the well-known shear-lag model of Cox (20) and Rosen (21) modified to include matrix-fiber interfacial slip as approximated by either perfectly-plastic, viscous, or viscoplastic interfacial boundary-layer material. This model predicted peaks to occur in the dependence of damping on both stress amplitude and frequency. They claimed to have correlated the location of these peaks with the shear strength of the fiber-matrix bond. Cox's model was also extended to imperfect adhesion by Yamaki (22), who, however, did not investigate its effect on damping.

The effect of interfacial slip on damping was also investigated experimentally and theoretically by McLean and Read (23), Nelson and Hancock (24), and Plunkett (25). The latter paper was an attempt to quantitatively explain the increase in damping factor with increasing strain in composites previously observed by Schultz and Warwick (3) and Gibson and Plunkett (26), for example, Plunkett (25) found that the damping factor depended upon crack density and strain distribution at maximum previous strain, but was nearly independent of current strain distribution.

Three interesting observations will now be made regarding this topic. First, it is interesting to make an analogy between the damping action of discontinuous-fiber composites, especially when modeled as a shear-lag action, and that of a beam with discontinuous constrained-layer damping. Plunkett and Lee (27) showed that there is an optimal length of damping and it appears that there may be an analogous optimal fiber aspect ratio for damping purposes. It should be interesting to compare this aspect ratio with the one which maximizes the fracture strength of a discontinuous composite. Clearly in each instance we are dealing with an exchange between normal-stress and shear-stress actions.

The second observation has to do with the possible application of continuous damage mechanics (CDM) to predicting damping in composites. The CDM concept was originated by Kachanov (28) to predict creep rupture, but it has been considerably extended by Hult (29), among others. In this approach, one relates material damage to stress level and load-carrying ability to damage.

The last observation is concerned with the different behavior, of composites with interfacial slip, when they are unloaded. Amirbayat and Hearle (30) showed that in this case, fiber buckling often occurs. It is clear that this should affect the hysteresis loop very drastically, and that it may be quite different under compressive rather than tensile loading (31).

EXPERIMENTAL METHODS FOR DETERMINING COMPLEX MODULI OF FIBER-REINFORCED COMPOSITES

It is not the purpose of the present work to discuss the experimental details of the numerous methods which have been used for determining the complex moduli of fiber-reinforced composites. For this purpose, the reader is referred to the survey papers of Bert and Clary (32) and Bert (33) and the book by Read and Dean (34). However, it goes without saying that the macroscopic anisotropic nature of fiber-reinforced composites with respect to damping as well as to stiffness makes the determination of these properties considerably more complicated than for homogeneous, isotropic materials or even for isotropic composites (i.e., particulate composites).

As in the case of homogeneous, isotropic materials, the main kinds of tests are (32):

1 Resonance method
2 Non-resonant forced vibration
3 Free vibration
4 Pulse propagation
5 Continuous-wave propagation
6 Thermal methods

Obviously, the type of motion, specimen configuration and fiber orientation determine the kind of complex moduli determined. Thus, axial motion of a slender bar with the fibers oriented along the axis can be used to determine the complex modulus in the fiber direction, $\bar{E}_L$. A similar specimen undergoing the same motion but with the fibers oriented transversely can be used to obtain $\bar{E}_T$, normal to the fiber direction. However, if the fibers are oriented at an acute angle θ to the axis of the bar, shear-normal coupling considerably complicates the motion and the interpretation of test results in terms of complex moduli.

It is well-known that torsion of a bar can be used to measure the complex shear modulus of a homogeneous, isotropic material. However, in the case of a fiber-reinforced bar, there may be three different principal orthotropic, complex shear moduli ($\bar{G}_{LT}$, $\bar{G}_{LZ}$, and $\bar{G}_{TZ}$). Here L denotes the fiber direction, and T and Z denote two directions orthogonal to L (see Fig. 5). If there are numerous small-diameter fibers (as in the case of glass or carbon fibers), the material is usually considered to be statistically transversely isotropic, with the plane of isotropy being the cross-sectional plane (TZ). In this case, $\bar{G}_{LZ}=\bar{G}_{LT}$ and this is the modulus determined by motion of a torsion bar with the fibers oriented along the bar axis (not $\bar{G}_{TZ}$ as sometimes incorrectly assumed). See Lekhnitskii's anisotropic elasticity book (35), pages 197-203.

If the composite contains large-diameter fibers (such as boron fibers) and the manufacturing process is such that the fiber spacing in the cross-sectional plane is different in the T and Z directions, then $\bar{G}_{LZ}\neq\bar{G}_{LT}$. In this case one cannot determine either $\bar{G}_{LT}$ or $\bar{G}_{LZ}$ without additional measurements, since the complex torsional rigidity depends upon both $\bar{G}_{LT}$ and $\bar{G}_{LZ}$, see (35), page 201.

If one twists a torsion bar with the fibers oriented at an acute angle to the bar axis, there is a coupling with flexural action which complicates the data analysis even more; see (35), page 180.

Although it is conceptually possible to determine all of the complex moduli of a cube-shaped specimen, this is extremely difficult experimentally so that this approach is relatively unexploited to date.

TRENDS IN MEASURED COMPLEX MODULI OF FIBER-REINFORCED, POLYMER-MATRIX COMPOSITES

Due to the facts that even a transversely isotropic material has five independent stiffnesses and an equal number of associated damping factors, as well as the strong dependency of these properties upon temperature and frequency, it is an extremely monumental effort to even approach a complete characterization of the complex moduli for a single composite material. (This increases the importance of the theoretical predictive methods described above.) However, an extremely large number of investigators have obtained limited dynamic stiffness and damping (DS&D) data for glass-fiber/polymer-matrix composites. A smaller number of researchers have studied carbon/polymer and boron/polymer composites. Beyond these composites, data are extremely sparse. Furthermore, detailed DS&D data depend on the method of measurement and upon air damping (damping values measured under high vacuum are lower than those measured at standard atmospheric pressure).

Due to all of the above factors, it would be a monumental task to attempt any significant correlation among the myriads of information existing. Thus, instead, the general trends for the effects of various parameters on DS&D of polymer-matrix composites are discussed and data sources referenced so that the reader may study the original data. Since adequate data are not yet available for other material combinations, the trends discussed are applicable only to composites with either epoxy or polyester matrices and glass, carbon, or boron fibers. These composites are denoted by GFRP, CFRP, and BFRP, respectively.

Effect of Temperature. This depends upon both the kind of fiber and orientation (36). For example, the storage modulus (E^R) of CFRP (36) is virtually independent of temperature regardless of orientation, while its associated logarithmic decrement (δ_E) for 0° orientation decreases slightly as temperature is lowered. For other orientations such as ± 45° and 90°, the effect of the matrix comes into play and produces a damping peak at about 0°C. The damping data for BFRP (36) and GFRP (37) have similar trends. In (37), it was concluded that the damping of GFRP at cryogenic temperatures is essentially the same as metals, even though GFRP has an order of magnitude more damping at room temperature.

Effect of Fiber Orientation[3]. In the case of GFRP (38), BFRP (36,39), and CFRP (36), damping is minimum and stiffness is maximum at 0°, i.e., in the fiber direction. This is very reasonable, since the fibers play a dominant role at 0°, and all three of these fibers exhibit less damping and much higher stiffness than the matrix material. As the orientation angle is increased, the general trends are for the damping to increase (up to a peak) and the stiffness to decrease. For these composites, the maximum damping occurs at different angles. For GFRP, maximum damping probably occurs at 45° (38), but for BFRP, it occurs anywhere from 10° (39, 2nd mode) to 90° (39, 3rd mode)(36 reported 67°). For CFRP, (36) reported maximum damping at 67°. For the three composites discussed, E^R was a maximum at 90°; however, it is theoretically possible (40) to have a composite in which E is not maximum at 0° and not minimum at 90°.

Effect of Lamination. Relatively few lamination schemes have been investigated. However, Mazza et al. (41) showed that cross-ply GFRP has considerably more damping than 0° unidirectional. Using beam specimens of BFRP, (41) and also Paxson (42) found that ± 45° angle-ply laminates exhibited even higher damping than did unidirectional material at 90°. (Unfortunately, he did not investigate unidirectional material at 45°, so it is not known how much of the improvement is due to orientation and how much is due to lamination.)

Probably the most extensive investigation of DS&D of laminates was the CFRP beam investigation carried out by Adams and Bacon (43). They investigated the effect of cross-ply ratio (ratio of total thickness of 0° layers to total thickness of 90° layers) and found good agreement with predictions. (Dynamic modulus increased considerably with increasing cross-ply ratio, while damping

[3] The effect of random fiber orientation, as in SMC (sheet molding compound) and DMC (dough molding compound), is discussed later under Effect of Short Fiber Length.

decreased slightly.) They also investigated the effect of lamination angle (θ) on $\pm\theta$ angle-ply laminates and obtained maximum damping at $\theta=45°$ in every instance. They also investigated a rather complicated laminate[*] $(0°/0°/30°/30°/45°/45°)_s$. As a result of their extensive investigation, Adams and Bacon concluded that shear stresses (and sometimes transverse normal stresses) are the predominant factors in a lamination geometry that result in high damping.

Schultz and Tsai (44) investigated two GFRP laminates: (a)$(0/-60°/+60°)_s$ and (b)$(0/90°/45°/-45°)_s$. These laminates were designed to be quasi-isotropic, i.e., isotropic with respect to inplane (stretching) stiffness. However, they were not isotropic with respect to flexural stiffness and the associated flexural damping. Thus, both the predicted and measured values of E^R and damping ratio displayed an angular dependence. The stiffnesses were predicted quite accurately by use of single-layer properties (38) and classical anisotropic-elastic-property transformations. The measured damping values followed the same trend as predicted from single-ply data, but the measured values were 25% to 100% higher than predicted except at 0°, where agreement was good. Apparently some interply shear deformation was taking place and resulted in an increase in damping.

Effect of Number of Loading Cycles. Information on this effect shows the most inconsistency and thus is the most controversial. The general trend (3, 4,45-47) is for the damping to increase with number of loading cycles. However, (45,46) concluded that damping was not sufficiently sensitive to be useful as a practical indicator of incipient failure. In contrast to this general trend, (48) found a rapid decrease in damping in the first few cycles, followed by a gradual decrease after that. The investigators in (48) attributed the rapid initial decrease on the basis of residual strain caused by the mismatch between the fiber and matrix thermal-expansion coefficients.

Effect of Short Fiber Length. As predicted by various analyses previously mentioned, the storage elastic moduli of composites with short, unidirectionally aligned fibers are usually lower than those of ones having the same fiber volume fraction of continuous, unidirectional fibers (24,49). Likewise the damping of short-fiber composites is usually greater. However, the trend is not as pronounced for the case of shear stiffness and damping. In (50), it was reported that the storage moduli in shear (G^R) for a short-fiber composite (SFC) were lower than for a continuous-fiber composite (CFC), but the decrease in G^R with temperature was considerably less. Thus, at temperatures above approximately 75°C, G^R is actually higher for SFC. Similarly, the peak in the curve of shear loss modulus (G^I) versus temperature for SFC, although smaller in value, occurs at a higher temperature than that for CFC. Thus, G_I for SFC is higher than that for CFC only at temperatures above approximately 108°C.

In high-production, short-fiber composites, the fibers are usually more or less randomly oriented. In England such composites are called DMC (dough molding compound), while in the U.S. they are referred to as SMC (sheet molding compound). These composites lend themselves readily to high production rates because they can be matched-die and injection molded.

In (50) it was reported that DMC has G^R values only slightly less than unidirectional SFC and G^I values somewhat higher. In an investigation (51) of SMC (25% and 65% E-glass fibers by weight) and XMC (hybrid with 25 wt % random E-glass fibers, 50 wt % continuous E-glass fibers), it was found that the measured E^R values fell between the estimated bounds obtained by using Paul's elastic-modulus bounds (52) in conjunction with the elastic-viscoelastic correspondence principle.

CONCLUDING REMARKS

It is concluded that existing prediction techniques are adequate for composites with well-bonded continuous fibers. However, for short-fiber composites, with or without fiber slippage, and for continuous-fiber composites having fiber slippage, more extensive analysis and analysis-experiment corre-

[*] The notation $(0°/0°/30°/30°/45°/45°)_s$ means a symmetric laminate having layers at 0°, 0°, 30°, 30°, 45°, and 45°.

lation needs to be carried out.

Although the trends described here may be quite useful to designers, what is sorely needed at this time is a design synthesis procedure to achieve the combination of fiber and matrix materials, volume fractions, orientations, and lamination arrangements to result in minimum dynamic response to either sinusoidal or random excitations, as appropriate in the application.

ACKNOWLEDGMENTS

This work was financially supported by the Structural Mechanics Program, Office of Naval Research.

REFERENCES

1 Kimball, A.L., "Internal Friction as a Cause of Shaft Whirling," Philosophical Magazine, Ser. 7, Vol. 16, 1925, pp. 724-727.

2 Genin, J. and Maybee, J.S., "The Role of Material Damping in the Stability of Rotating Systems," Journal of Sound and Vibration, Vol. 21, No. 4, 1972, pp. 399-404.

3 Schultz, A.B. and Warwick, D.N., "Vibration Response: A Non-Destructive Test for Fatigue Crack Damage in Filament-Reinforced Composites," Journal of Composite Materials, Vol. 5, No. 3, 1971, pp. 394-404.

4 DiBenedetto, A.T., Gauchel, J.V., Thomas, R.L., and Barlow, J.B., "Nondestructive Determination of Fatigue Crack Damage in Composites using Vibration Tests," Journal of Materials, Vol. 7, No. 2, 1972, pp. 211-215.

5 Bert, C.W., "Material Damping: An Introductory Review of Mathematical Models, Measures and Experimental Techniques," Journal of Sound and Vibration, Vol. 39, No. 2, 1973, pp. 129-153.

6 Kennedy, C.C. and Pancu, C.D.P., "Use of Vectors in Vibration Measurement and Analysis," Journal of the Aeronautical Sciences, Vol. 14, 1947, pp. 603-625.

7 Hashin, Z., "Complex Moduli of Viscoelastic Composites - II. Fiber Reinforced Materials," International Journal of Solids and Structures, Vol. 6, No. 6, 1970, pp. 797-807.

8 Hashin, Z., "Damping Characteristics of Fiber Composites," Technion-Israel Institute of Technology, Haifa, Israel, Report AFOSR-TR-72-2327 (NTIS Document AD-753699), July 1972.

9 Bert, C.W. and Chang, S., "In-Plane, Flexural, Twisting and Thickness-Shear Coefficients for Stiffness and Damping of a Monolayer Filamentary Composite," University of Oklahoma, Norman, OK, NASA CR-112141 (NTIS Document N72-29889), Mar. 1972.

10 Chang, S. and Bert, C.W., "Analysis of Damping for Filamentary Composite Materials," Composite Materials in Engineering Design (Proc., 6th St. Louis Symposium, May 1972), American Society for Metals, Metals Park, Ohio, 1973, pp. 51-62.

11 Whitney, J.M., "Elastic Moduli of Unidirectional Composites with Anisotropic Filaments," Journal of Composite Materials, Vol. 1, No. 2, 1967, pp. 188-193.

12 Bloom, J.M. and Adams, D.F., "Axial Loading of Unidirectional Composites - Anisotropic Filaments," Journal of Composite Materials, Vol. 3, No. 1, 1969, pp. 186-188.

13 Heaton, M.D., "A Calculation of the Elastic Constants of a Unidirectional Composite Containing Transversely Isotropic Fibres," Journal of Physics, Ser. 2, Vol. 30, 1970, pp. 672-676.

14 Chen, C.H., "Rectangular or Square Array Fibrous Composite with Anisotropic or Isotropic Filament," ASME Journal of Applied Mechanics, Vol. 38, No. 3, 1971, pp. 710-712.

15 Behrens, E., "Elastic Constants of Fiber-Reinforced Composites with Transversely Isotropic Constituents," ASME Journal of Applied Mechanics, Vol. 38, No. 4, 1971, pp. 1062-1065.

16 Baker, A.A., "The Fatigue of Fibre-Reinforced Aluminum," Journal of Materials Science, Vol. 3, No. 4, 1968, pp. 412-423.

17 Varschavsky, A., "The Matrix Fatigue Behaviour of Fibre Composites Subjected to Repeated Tensile Loads," Journal of Materials Science, Vol. 7, No. 2, 1972, pp. 159-167.

18 Weiss, H.-J., "The Effect of Axial Residual Stress on the Mechanical Behaviour of Composites," Journal of Materials Science, Vol. 12, No. 4, 1977, pp. 797-809.

19 Pompe, W. and Schultrich, B., "Zur Grenzschichtdämpfung von Verbundwerkstoffen mit kurzfasrigen Einlagerungen," Annalen der Physik, Vol. 31, No. 2, 1974, pp. 101-119.

20 Cox, H.L., "The Elasticity and Strength of Paper and Other Fibrous Materials," British Journal of Applied Physics, Vol. 3, 1952, pp. 72-79.

21 Rosen, B.W., "Mechanics of Composite Strengthening," Fiber Composite Materials, American Society for Metals, Metals Park, Ohio, 1965, pp. 38-58.

22 Yamaki, J.-I., "Tensile Strength of Discontinuous Fibre Composites - the Effect of Fibre/Matrix Interface Strength," Journal of Physics, Ser. 2, Vol. 9D, No. 1, 1976, pp. 115-131.

23 McLean, D. and Read, B.W., "Storage and Loss Moduli in Discontinuous Composites," Journal of Materials Science, Vol. 10, No. 3, 1975, pp. 481-492.

24 Nelson, D.J. and Hancock, J.W., "Interfacial Slip and Damping in Fibre Reinforced Composites," Journal of Materials Science, Vol. 13, No. 11, 1978, pp. 2429-2440.

25 Plunkett, R., "Damping in Fiber Reinforced Laminated Composites at High Strain," University of Minnesota, Dept. of Aeronaut. Eng'g. and Mechanics, Report AEM-RP-79-2, Jan. 1980.

26 Gibson, R.F. and Plunkett, R., "Dynamic Mechanical Behavior of Fiber-Reinforced Composites: Measurement and Analysis," Journal of Composite Materials, Vol. 10, No. 4, 1976, pp. 325-341.

27 Plunkett, R. and Lee, C.T., "Length Optimization for Constrained Viscoelastic Layer Damping," Journal of the Acoustical Society of America, Vol. 48, 1970, pp. 150-161.

28 Kachanov, L.M., "Time of the Rupture Process under Creep Conditions," Izvestiya Akademiya Nauk SSSR, Otdelenie Tekh. Nauk, 1958, No. 8, pp. 26-31.

29 Hult, J., "CDM - Capabilities, Limitations and Promises," Mechanisms of Deformation and Fracture (Proc. of a conference held at University of Lulea, Lulea, Sweden, Sept. 20-22, 1978), K.E. Easterling, ed., Pergamon, Oxford, 1979, pp. 233-247.

30 Amirbayat, J. and Hearle, J.W.S., "Properties of Unit Composites as Determined by the Properties of the Interface. Part I: Mechanism of Matrix-Fibre Load Transfer," Fibre Science and Technology, Vol. 2, No. 2, 1969, pp. 123-141.

31 Bert, C.W., Micromechanics of the Different Elastic Behavior of Filamentary Composites in Tension and Compression," Mechanics of Bimodulus Materials, AMD Vol. 33, ASME, New York, 1979, pp. 17-28.

32 Bert, C.W. and Clary, R.R., "Evaluation of Experimental Methods for Determining Dynamic Stiffness and Damping of Composite Materials," Composite Materials: Testing and Design (3rd Conference), ASTM STP 546, 1974, pp. 250-265.

33 Bert, C.W., "Experimental Characterization of Composites," Composite Materials, Vol. 8: Structural Design and Analysis Part II, Chamis, C.C., ed., Academic Press, New York, 1975, Ch. 9, pp. 114-133.

34 Read, B.E. and Dean, G.D., The Determination of Dynamic Properties of Polymers and Composites, Wiley, New York, 1978.

35 Lekhnitskii, S.G., Theory of Elasticity of an Anisotropic Elastic Body, Holden-Day, San Francisco, 1963.

36 Georgi, H., "Dynamic Damping Investigations on Composites," Damping Effects in Aerospace Structures, NATO-AGARD-CP-277, Apr. 1979, Paper No. 9.

37 Yakovlev, A.P. and Bykovskii, A.I., "Study of the Damping Properties of Certain Types of Glass Textolites at Various Temperatures," Strength of Materials, Vol. 4, No. 6, 1972, pp. 681-685.

38 Schultz, A.B. and Tsai, S.W., "Dynamic Moduli and Damping Ratios in Fiber-Reinforced Composites," Journal of Composite Materials, Vol. 2, No. 3, 1968, pp. 368-379.

39 Clary, R.R., "Vibration Characteristics of Unidirectional Filamentary Composite Material Panels," Composite Materials: Testing and Design (2nd

Conference), ASTM STP 497, 1972, pp. 415-438.
40 Jones, R.M., Mechanics of Composite Materials, McGraw-Hill, New York, 1975, p. 57.
41 Mazza, L.T., Paxson, E.B., and Rodgers, R.L., "Measurement of Damping Coefficients and Dynamic Modulus of Fiber Composites," U.S. Army Aviation Materiel Laboratories, Ft. Eustis, VA, USAAVLABS-TN-2 (NTIS Document AD-869025), Feb. 1970.
42 Paxson Jr., E.B., "Real and Imaginary Parts of the Complex Viscoelastic Modulus for Boron Fiber Reinforced Plastics (BFRP)," Journal of the Acoustical Society of America, Vol. 57, No. 4, 1975, pp. 891-898.
43 Adams, R.D. and Bacon, D.G.C., "Effect of Fibre Orientation and Laminate Geometry on the Dynamic Properties of CFRP," Journal of Composite Materials, Vol. 7, No. 4, 1973, pp. 402-428.
44 Schultz, A.B. and Tsai, S.W., "Measurements of Complex Dynamic Moduli for Laminated Fiber-Reinforced Composites," Journal of Composite Materials, Vol. 3, No. 3, 1969, pp. 434-443.
45 Sutton, S.A., "Cyclically Induced Mechanical Hysteresis of a Glass Fiber-Reinforced Plastic," University of Illinois at Urbana-Champaign, Dept. of Theoretical and Applied Mechanics, T&AM Report No. 362 (NTIS Document AD-753823), Oct. 1972.
46 Ulitchney, M.G. and Lucas, J.J., "Evaluation of Graphite Composite Materials for Bearingless Helicopter Rotor Application," Sikorsky Aircraft, Div. of United Aircraft Corp., Stratford, CT, NASA CR-132414 (NTIS Document N74-21656), Jan. 1974.
47 Harris, B., Guild, F.J., and Brown, C.R., "Accumulation of Damage in GRP Laminates," Journal of Physics, Ser. 2, Vol. 12D, 1979, pp. 1385-1407.
48 Kim, H.C. and Matthews, F.L., "Hysteresis Behaviour in CFRP," Journal of Physics, Ser. 2, Vol. 6D, No. 15, 1973, pp. 1755-1761.
49 Nelson, D.J., "Dynamic Testing of Discontinuous Fibre Reinforced Composite Materials," Journal of Sound and Vibration, Vol. 64, No. 3, 1979, pp. 403-419.
50 Cawthorne, D. and Harris, B., "Dynamic Elastic Moduli and Toughness of Dough Moulding Compounds," Composites, Vol. 6, No. 1, 1975, pp. 25-29.
51 Gibson, R.F. and Yau, A., "Complex Moduli of Chopped Fiber and Continuous Fiber Composites: Comparison of Measurements with Estimated Bounds," Journal of Composite Materials, Vol. 14, No. 2, 1980, pp. 155-167.
52 Paul, B., "Prediction of Elastic Constants of Multiphase Materials," Transactions of the Metallurgical Society of AIME, Vol. 218, 1960, pp. 36-41.

PREVIOUS REPORTS ON THIS CONTRACT

Project Rept. No.	OU-AMNE Rept. No.	Title of Report	Author(s)
1	79-7	Mathematical Modeling and Micromechanics of Fiber-Reinforced Bimodulus Composite Material	C.W. Bert
2	79-8	Analyses of Plates Constructed of Fiber-Reinforced Bimodulus Materials	J.N. Reddy and C.W. Bert
3	79-9	Finite-Element Analyses of Laminated Composite-Material Plates	J.N. Reddy
4A	79-10A	Analyses of Laminated Bimodulus Composite-Material Plates	C.W. Bert
5	79-11	Recent Research in Composite and Sandwich Plate Dynamics	C.W. Bert
6	79-14	A Penalty Plate-Bending Element for the Analysis of Laminated Anisotropic Composite Plates	J.N. Reddy
7	79-18	Finite-Element Analysis of Laminated Bimodulus Composite-Material Plates	J.N. Reddy and W.C. Chao
8	79-19	A Comparison of Closed-Form and Finite-Element Solutions of Thick Laminated Anisotropic Rectangular Plates (With a Study of the Effect of Reduced Integration on the Accuracy)	J.N. Reddy
9	79-20	Effects of Shear Deformation and Anisotropy on the Thermal Bending of Layered Composite Plates	J.N. Reddy and Y.S. Hsu
10	80-1	Analyses of Cross-Ply Rectangular Plates of Bimodulus Composite Material	V.S. Reddy and C.W. Bert
11	80-2	Analysis of Thick Rectangular Plates Laminated of Bimodulus Composite Materials	C.W. Bert, J.N. Reddy, V.S. Reddy, and W.C. Chao
12	80-3	Cylindrical Shells of Bimodulus Composite Material	C.W. Bert and V.S. Reddy
13	80-6	Vibration of Composite Structures	C.W. Bert
14	80-7	Large Deflection and Large-Amplitude Free Vibrations of Laminated Composite-Material Plates	J.N. Reddy and W.C. Chao
15	80-8	Vibration of Thick Rectangular Plates of Bimodulus Composite Material	C.W. Bert, J.N. Reddy, W.C. Chao, and V.S. Reddy
16	80-9	Thermal Bending of Thick Rectangular Plates of Bimodulus Material	J.N. Reddy, C.W. Bert, Y.S. Hsu, and V.S. Reddy
17	80-14	Thermoelasticity of Circular Cylindrical Shells Laminated of Bimodulus Composite Materials	Y.S. Hsu, J.N. Reddy, and C.W. Bert

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: OU-AMNE-80-17 / 2. GOVT ACCESSION NO.: AD-A092 194	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): COMPOSITE MATERIALS: A SURVEY OF THE DAMPING CAPACITY OF FIBER-REINFORCED COMPOSITES	5. TYPE OF REPORT & PERIOD COVERED: Technical Report No. 18
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): C.W. Bert	8. CONTRACT OR GRANT NUMBER(s): N00014-78-C-0647
9. PERFORMING ORGANIZATION NAME AND ADDRESS: School of Aerospace, Mechanical and Nuclear Engineering, University of Oklahoma, Norman, OK 73019	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 064-609
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of the Navy, Office of Naval Research, Structural Mechanics Program (Code 474), Arlington, Virginia 22217	12. REPORT DATE: August 1980
	13. NUMBER OF PAGES: 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This is an invited paper to be presented at the Symposium on Damping Applications for Vibration Control, sponsored by the Applied Mechanics Division, ASME Winter Annual Meeting, Chicago, IL, November, 1980.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Complex moduli, composite materials, damping, dynamic response, dynamic stiffness, fiber-reinforced materials, interfacial slip, laminates, material damping, material behavior, materials testing, viscoelasticity.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A discussion is given on the importance of damping in fiber-reinforced composites and is followed by concise definitions of the various measures of damping. The current state of the theory of damping in fiber-reinforced composites is reviewed for perfectly-bonded viscoelastic composites, yielding-matrix composites, and those in which slip takes place at the fiber-matrix interface. General trends in stiffness and damping of composites with polymeric matrices are reviewed.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

80 11 25 003

END

DATE FILMED

81

DTIC