EXPERIMENTAL DETERMINATION OF DYNAMIC YOUNG'S MODULUS AND DAMPING OF AN ARAMID-FABRIC/POLYESTER COMPOSITE MATERIAL

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The purpose of these experiments was the direct measurement of dynamic Young's modulus and damping factors for a Kevlar 49* fabric-reinforced polyester composite material. Kevlar fibers have higher stiffness and damping than glass fibers and yet they cost less than graphite fibers. Thus, a composite with Kevlar fibers embedded in a matrix of polyester resin, which is less expensive than epoxy used in aerospace applications, is a likely candidate material for the light-weight automobiles mandated for the 1980's by petroleum scarcity. The dynamic properties measured in the experiments described here are important for successful design of dynamically loaded components made of such a material.

INTRODUCTION

Driven by the stringent fuel-economy requirements mandated by the government for the 1985-model cars, the U.S. automotive industry has begun to mount an extensive research program to incorporate light-weight fiber-reinforced composite materials into future cars, as demonstrated at a recent symposium (1).

Although Kevlar fibers have been developed only rather recently, they are rapidly becoming very popular in such diverse applications as parachute webbing, rocket motor casings, jet-engine containment, aircraft seats, and automobile tires. Their popularity is motivated by their improved stiffness and density properties (2) (see Table 1) relative to glass and their considerably lower cost than boron or even graphite fibers.

Owing to the relatively short time since Kevlar fibers have been introduced, the data available on the dynamic properties for Kevlar-reinforced composites are much more limited than for older composites. This need was the motivation for the work described here.

MATERIAL

The composite material used was reinforced by Kevlar 49 fibers in fabric form. This fabric, classified as a Style 285 plain weave, is now commercially available and was provided to the University of Oklahoma by du Pont. In this style of fabric there is approximately the same number of fiber bundles per unit length in each of the orthogonal fiber directions.

The polyester resin used as the matrix material was a commercially available grade used by boat builders to construct glass-fiber-reinforced plastic boats. Since no data were available on its dynamic proper-

TABLE 1. *Room-temperature properties of Kevlar 49 aramid cloth*/epoxy reported in (2).*

Property	Value
Specific weight	0.048 psi (1.33 g/cm^3)
Tensile strength (dry)	75,000 psi (417 MPa)
Tensile strain to failure	1.7%
Young's modulus, static:	
Tension	4.5×10^6 psi (31,030 MPa)
Compression	4.5×10^6 psi (31,030 MPa)
Damping ratio, p. III-25 of (2)	0.0074 to 0.0084

*Style 181 cloth, 50% by volume.

*Kevlar is a trademark for du Pont's aramid fibers.

ties, separate tests were conducted on beams molded of pure resin.

EXPERIMENTAL PROCEDURE

A wide variety of experimental techniques have been used to determine dynamic stiffness (elastic modulus) and damping of composite materials (3, 4). These include free-vibration decay, rotating-beam deflection, forced vibration, continuous-wave and pulse propagation, and thermal methods.

Forced vibration is the most widely used technique, because it permits direct measurement of both stiffness and damping. Since the specimen geometry is a beam configuration, the resonant frequencies are sufficiently far apart to permit the use of the peak-amplitude method to determine the resonant frequencies (ω_n). Although the material damping for this material is higher than for most structural alloys, it is still relatively small. Thus, it is believed that determination of the damping ratio (ζ) from the half-power frequencies, rather than the more elaborate technique of measuring the hysteresis loss, is adequate. The half-power frequencies are the frequencies, on each side of a given resonance, at which the amplitude is 0.707 times the peak amplitude (5).

Just as in the work of Schultz and Tsai (6), a prismatic, rectangular-cross-section beam specimen was selected. The beam specimens were clamped midway along the length by two hardened steel plates, which in turn were bolted to the moving armature of an LTV Model A 286, 800-lb_f - capacity electrodynamic shaker (Fig. 1). This mounting configuration tended to provide a more symmetric loading on the shaker head. Typical beams were 24.62 in. long, 1.31 in. wide, and 0.31 in. thick.

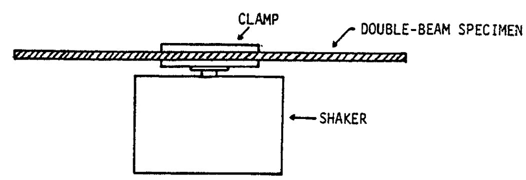

FIGURE 1. Shaker/beam set-up.

The excitation was a sinusoidal displacement monitored by an electronic counter. The beam response was determined by a variable-electric-resistance strain gage, SR-4 Type FAE-25-1256, mounted longitudinally on the top surface of the beam near the clamped end. Of course, the gage was mounted beyond the zone in which the stress-concentrating effect of the clamp was believed to be acting (beyond twice the sum of the cross-sectional dimensions).

The strain-gage voltage output was fed into both an oscilloscope and an rms voltmeter. Thus, peak response values could be determined by either of these instruments.

THEORY AND DATA REDUCTION

The equation governing the small-amplitude motion of a thin beam with Kimball-Lovell material damping (7) is

$$EI\frac{\partial^4 w}{\partial x^4} + \frac{EIg}{\omega}\frac{\partial^5 w}{2x^4\partial t} + \mu\frac{\partial^2 w}{\partial t^2} = 0 \qquad \text{Eq. 1}$$

Here E is the longitudinal Young's modulus, g is the loss tangent for material damping, I is the second moment of the cross-sectional area about the neutral axis, w is the beam deflection, x is the position along the beam, t is time, μ is the beam mass per unit length, and ω is the frequency.

For a base displacement excitation w_o at the clamped end (x = 0) of a clamped-free beam of length L, the boundary conditions are:

$$w(0,t) = w_0 \sin \omega t \quad , \quad \frac{\partial w}{\partial x}(0,t) = 0$$
$$\frac{\partial^2 w}{\partial x^2}(L,t) = 0 \quad , \quad \frac{\partial^3 w}{\partial x^3}(L,t) = 0 \qquad \text{Eq. 2}$$

It can be shown that the solution of Eq. 1 subject to boundary conditions Eq. 2 is a sinusoidal response of frequency ω with a time lag. Furthermore, the peak amplitudes of this response occur at resonant frequencies given by

$$\omega_n = (\beta_n L)^2 (EI/\mu L^4)^{\frac{1}{2}} \qquad \text{Eq. 3}$$

Here $\beta_n L$ denote the dimensionless eigen values which have been tabulated by Young and Felgar (8). For the fundamental (n = 1) and second (n = 2) resonant modes of a clamped-free beam, $\beta_1 L$ = 1.875 and $\beta_2 L$ = 4.694.

Since everything else in Eq. 3 is known except E, measured values of frequency ω_n can be used in Eq. 3 to determine the dynamic Young's modulus E associated with that frequency.

It is important to note that in the present case of Kimball-Lovell material damping, the frequencies at which the peak response occurs are unaffected by the amount of damping present, provided that it does not exceed the critical value. This is in contrast to the more familiar case of a simple system containing damping in the form of a viscous dashpot; for such a system the frequency at the peak decreases as the damping is increased.

The damping ratio ζ is defined as follows

$$\zeta = g/g_{cr} \qquad \text{Eq. 4}$$

where g is the actual loss tangent and g_{cr} is the critical value of g.
It can be shown (5) that

$$\zeta = (\omega_b - \omega_a)/2\omega_n \qquad \text{Eq. 5}$$

where ω_a and ω_b are the half-power frequencies on either side of the resonant frequency ω_n .

RESULTS AND DISCUSSION

The experimental results obtained are presented in Table 2. It is noted that the Young's moduli at fundamental frequency (4.48 and 4.57 x 10^6 psi) are in very good agreement with the static values reported (2) for Kevlar 49 fabric/epoxy. This would be expected because the elastic modulus of polyester and epoxy are not widely different and do not make a large contribution to the composite modulus.

The Young's moduli decrease with increasing frequency, i.e. in going from the fundamental to the second natural frequency. This same trend has been observed in boron and glass fiber composites with resin matrices (9).

The damping ratio and loss tangent can be related as follows (5): $\zeta = g/2$
Thus, the present results can be compared with those obtained by various other investigators for resin-matrix composites (6, 9). The values obtained here are generally slightly higher than obtained previously by other investigators. For the resin alone, this suggests that polyester has higher damping than epoxy. Since the damping ratios for the composite are lower than for the matrix alone, it appears that the Kevlar 49 fibers exhibit lower damping than the polyester matrix. However, since Kevlar itself is a polymer, it probably exhibits higher damping than glass or boron.

The difference between the 0° and the 90° fabric specimens was less than 2%, which is certainly within the bounds of experimental error for these experiments.

It should be mentioned that only the first two resonant modes were investigated in order to keep the vibratory wave length sufficiently long that the Bernoulli-Euler beam theory used in the data reduction is adequate. For higher frequencies and the consequent lower wave lengths, especially in composite materials, which have much lower ratios of transverse shear modulus to longitudinal Young's modulus than do homogeneous materials, it would be necessary to use Timoshenko beam theory, which includes transverse-shear flexibility and rotatory inertia (10).

CONCLUSIONS

The results show that a Kevlar-49 cloth/polyester resin composite will provide the automotive industry with a low-cost com-

TABLE 2. *Young's modulus and damping ratio for Kevlar 49 cloth*/polyester and for plain polyester.*

Material	Orientation	Mode	Frequency, Hz	Young's modulus, psi	Damping ratio
Kevlar/polyester	0°	1	67.3	4.48×10^6	0.027
		2	367	3.38×10^6	0.046
Kevlar/polyester	90°	1	68.0	4.57×10^6	0.035
		2	not	measured	
Polyester	—	1	60.5	0.95×10^6	0.057
		2	283	0.53×10^6	0.048

*Style 285, 35% by volume.

posite with good strength and stiffness, and damping properties that are better than Kevlar-49 cloth/epoxy resin composite.

REFERENCES

1. S. V. KULKARNI, et al., eds., *Composite Materials in the Automobile Industry,* Am. Soc. Mech. Engrs., New York, N.Y., 1978.
2. KEVLAR 49 DATA MANUAL, E. I. du Pont de Nemours & Co., Inc., Wilmington, DL, revised Dec. 1974, Section IV.
3. C. W. BERT and R. R. CLARY, *Composite Materials: Testing and Design (3rd Conference),* Amer. Soc. for Testing & Matls., Philadelphia, PA, Spec. Tech. Publication 546, 1974, pp. 250-265.
4. Y. F. CHENG, Fibre Sci. Technol. 10: 23-35 (1977).
5. C. W. BERT, J. Sound Vibration 29: 129-153 (1973).
6. A. B. SCHULTZ and S. W. TSAI, J. Composite Materials 2: 368-379 (1968).
7. K. N. TONG, *The Mathematical Theory of Mechanical Vibration,* John Wiley & Sons, Inc., New York, NY, 1960.
8. D. YOUNG and R. P. FELGAR, "Tables of Characteristic Functions Representing Normal Modes of Vibration of a Beam", University of Texas, Austin, TX, Publication 4913, July 1949.
9. S. CHANG and C. W. BERT, *Composite Materials in Engineering Design,* Proc. 6th St. Louis Symp., May 1972, B. R. NOTON, ed., Amer. Soc. for Metals, Metals Park, OH, 1973, pp. 51-62.
10. S. P. TIMOSHENKO, Phil. Mag. [6] 41: 742-746 (1921).