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Ultrasonic wave propagation in carbon fibre-reinforced plastics

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The attenuation and velocity of the longitudinal and shear waves in unidirectional carbon/epoxy composites have been measured as a function of the fibre volume fraction over the frequency range, 1.84 to 11.9 MHz, using the pulse–echo technique. The decrease of attenuation with fibre volume fraction suggested that the high attenuation in the composites was caused by viscoelastic losses in the epoxy matrix rather than scattering losses by the fibre. The attenuation increased with frequency, while the velocity was found to be independent of frequency.

1. Introduction

Ultrasonic testing is a nondestructive testing method for examining the composite materials in which an ultrasonic stress wave is introduced into a composite and the characteristics are measured after passing through the composite. The most important parameters of stress-wave propagation are the dispersion and attenuation. Dispersion is the dependence of the phase velocity of harmonic waves upon their frequency. Attenuation is a measure of the energy loss of a stress wave as indicated by the decrease in the amplitude as it propagates through the composite. The changes in the material microstructure have an effect on the dispersion and attenuation, hence the measurements of the dispersion and attenuation should be useful in material characterization.

Dispersion in the fibre-reinforced composite materials has been predicted by numerous theories [1–4] and observed in several experimental works [5–7]. The dispersion characteristics in a fibre-reinforced viscoelastic material are attributed to the viscoelastic nature of the medium as well as its structural geometry. The viscoelastic dispersion is characterized by an increase in the phase velocity with an increase in frequency [8], whereas the geometrical dispersion is characterized by a decrease in the phase velocity with increasing frequency for longitudinal waves propagating along and normal to the fibre axis [2, 5]. However, the geometrical dispersion has distinctive characteristics with the wave mode and propagating direction. When both dispersion mechanisms are present in a composite material, either one may dominate the other or they may act in union, depending on the frequency of the wave and the particular composites used [9].

Stress waves in fibrous composites with a viscoelastic matrix are attenuated by various loss mechanisms, such as scattering by fibres and viscoelastic absorption in the matrix. The attenuation due to scattering by fibres has been considered by Bose and Mal [3] and Varadan *et al.* [4] for shear waves propagating normal to fibres and polarized along the fibre axis, but further work is required on various wave modes and propagation directions. Attenuation by viscoelastic losses has been reported in the many experimental observations [8, 10], and the attenuation increase with frequency.

The work presented is concerned with experimental observation of the attenuation and dispersion for ultrasonic waves propagating parallel and normal to the fibre direction in unidirectional carbon fibre composites with various fibre volume fractions. Also, the angular dependence of the attenuation and dispersion with respect to the fibre axis has been measured for the composite with fibre volume fraction $= 0.72$.

2. Experimental procedure

2.1. Materials

Carbon fibre-epoxy resin composites were produced by the leaky-type moulding. The material used was Courtaulds' Grafil XA-S carbon fibre in Ciba-Geigy 1138 epoxy prepreg. The individual filament had a circular cross-section with $7\,\mu m$ nominal diameter. The prepreg sheet was cut to the mould dimension, 130 mm long × 100 mm wide × 14 mm depth, and the prepreg laminae were stacked with filaments in the direction parallel to the mould length.

The loaded mould was placed in a preheated press, the plattens of which were thermostatically controlled at 140° C. After waiting for the chosen dwelling time of about 10 min the mould was closed at a pressure of $50\,kg\,cm^{-2}$, then left to cure for 1 h. The post-curing treatment was carried out by placing the mould in the hot press for 3 h under zero pressure. Then the mould was removed and allowed to cool.

The composites produced covered a range of fibre volume fractions between 0.50 and 0.72. Small samples of the carbon–epoxy composite were cut from the fabricated composite plates and the ends of the sample were polished flat and parallel.

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2.2. Ultrasonic attenuation and velocity measurements

Ultrasonic attenuation and velocity were measured in the frequency ranges 1.84 to 11.9 MHz for longitudinal and shear waves. For simultaneous measurements of attenuation and velocity, the equipment consisted of an r.f. pulsed oscillator and broad-band receiver (Matec Models 6600 and 755), a decade divider and dual delay strobe generator (Matec Model 122B), a continuous wave (cw) signal generator (Matec Model 110), an attenuation recorder (Matec Model 2470), an r.f. impedance matching network (Matec Model 60), a frequency counter, and a wideband oscilloscope.

Attenuation measurements were made by using the pulse–echo method with direct contact between the transducer and sample. A pulse of approximately 2 μsec duration of variable repetition rate is generated by the r.f. pulsed oscillator and impressed on a transducer coupled acoustically to the specimen. The reflected r.f. echoes are received by the same transducer, amplified and displayed on the oscilloscope. The r.f. signals are enveloped to compute the attenuation. Comparing the amplitudes of the first and second enveloped echoes, the attenuation was obtained by the attenuation recorder in decibells.

Wave velocity was calculated from the time delay measurement between the pair of r.f. echoes by the pulse–echo overlap method. Two echoes of interest are chosen by adjusting the dual delays in the dual delay strobe generator and exactly overlapped by adjusting the frequency of the cw oscillator. This frequency, f, is read by the frequency counter and the ultrasonic velocity, v, is computed using the relation $v = 2tf$, where t is the thickness of the specimen. In the present work the first and second echoes were used in the velocity measurements.

Transducers were 2 and 4 MHz X-cut and Y-cut quartz discs, 12.7 mm diameter, for longitudinal and shear wave measurements, respectively. Acoustic bonding was aided by Salol and a metal electrode was placed on the top of the transducer while the bottom was earthed through the specimen. The tests were made using the odd harmonic frequencies as well as the fundamental frequencies of the respective transducers.

In order to facilitate the impedance matching between a high impedance load and a low impedance source, the r.f. impedance matching network was used. At resonance, the maximum voltage will be developed across the transducer and the maximum energy transfer will take place both for the driving pulse and returned echoes to the receiver. The r.f. tuning on the Matec Model 60 was adjusted until the maximum echo response was obtained for the echoes well out into the echo train. Final tuning was achieved by the apparent minimum attenuation. The position of the minimum in attenuation was shifted to a frequency lower than the unbounded resonant frequency of the transducer. The X-cut and Y-cut quartz transducers with fundamental frequencies 2 and 4 MHz had the minimum attenuation at 1.84 and 3.86 MHz, respectively. For the odd harmonic frequencies, the 2 MHz transducers had its minimum attenuations at 5.75 and 8.8 MHz for the third and fourth harmonics, and the 4 MHz transducers at 11.9 MHz for the third harmonics.

3. Results and discussion

The notation X_i/X_j is used to denote a particular wave mode of ultrasonic wave propagating in the X_i direction with the particle motion in the X_j direction. The X_3 direction corresponds to the fibre direction and the X_1 direction is taken as the direction within the specimen along which the moulding pressure has been applied.

3.1. Angular dependence measurements

Angular dependence measurements of attenuation and velocity in the unidirectional carbon fibre–epoxy resin composite of fibre volume fraction 0.72 have been attempted with the longitudinal and shear waves propagating in various directions to the fibre axis. It was observed from the echo trains that the composite did not permit the propagation of coherent pulse for either shear or longitudinal waves propagating in the off-principal directions, especially for shear waves polarized in the plane of the fibre axis and wave propagation direction. A similar observation was reported by Lord and Hay [11] in Ti/Be and Al/W composites. The behaviour is probably due to anisotropic properties of the composite and scattering of the stress waves at the boundaries between fibre and matrix. When the stress wave is propagated in the off-principal directions of the unidirectional composites, the displacement vector of the wave is divided into two components parallel and normal to the fibre axis, i.e. quasi-longitudinal and transverse components [12]. The wave components propagate with different velocities, displaying a series of echoes in a complicated form on the oscilloscope. Thus, the ultrasonic measurement of pure longitudinal and shear wave modes in fibrous composites is difficult in the off-principal directions using the pulse–echo technique with direct contact between transducer and sample.

Additionally, even though the measurements are carried out in the principal directions, the other problem encountered on the velocity measurement by the pulse–echo overlap method is high attenuation of the stress waves in the composites. Because the wave form of the second echo was greatly deformed in comparison with the first echo by attenuation, it was impossible to match up cycle for cycle in overlapping two echoes to measure the time delay. Eventually, the pulse–echo technique may lead to measurement errors of travelling times in unidirectional carbon–epoxy composites.

3.2. Attenuation of longitudinal and shear waves

Attenuation of longitudinal waves in the X_3/X_3 and X_1/X_1 directions as a function of fibre volume fraction, V_f, at various frequencies are shown in Figs 1 and 2, respectively. Similar results for shear waves in X_3/X_2, X_1/X_3, and X_1/X_2 directions at 1.84 MHz are presented in Fig. 3. The general tendencies of the attenu-

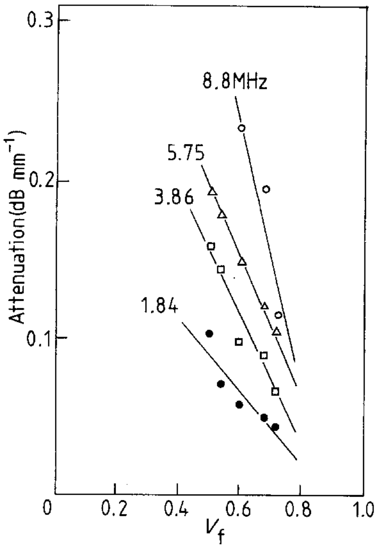

Figure 1 Attenuation of longitudinal waves propagating along the fibre direction as a function of fibre volume fractions at various frequencies.

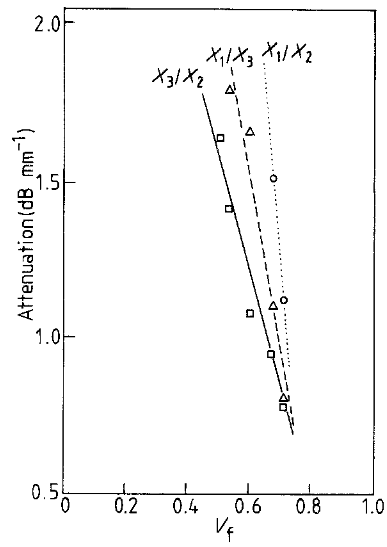

Figure 3 Attenuation of shear waves as a function of fibre volume fractions at frequency 1.84 MHz.

ation for longitudinal and shear waves propagating parallel and normal to the fibre direction are similar; i.e. the attenuation decreases with the fibre volume fraction over the frequency and fibre volume fraction ranges used. The rate of the decrement is greater for higher frequencies in shear waves rather than in longitudinal waves and in the propagation direction normal rather than parallel to the fibre direction.

For frequencies higher than 1.84 MHz, the shear wave attenuation was so large that the measurements could be only made with one or two specimens at 3.86 MHz, the attenuation values were 1.64 and 1.73 dB mm^{-1} for fibre volume fraction 0.72 and 0.68 in X_3/X_2 mode, respectively, and 2.18 dB mm^{-1} for fibre volume fraction 0.72 in X_1/X_3 mode.

Attenuation of ultrasonic wave in a fibrous composite material with a viscoelastic matrix results from the scattering by fibres, the absorption in the fibre material, and the viscoelastic loss in the epoxy matrix. The attenuation coefficient, α, for the fibrous com-

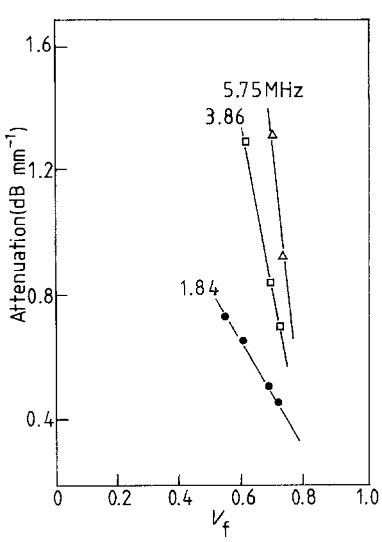

Figure 2 Attenuation of longitudinal waves propagating normal to the fibre direction as a function of fibre volume fractions at various frequencies.

posites may be written as

$$\begin{aligned}\alpha &= \alpha_s + \alpha_f V_f + \alpha_m(1 - V_f)\\ &= \alpha_s + \alpha_m - (\alpha_m - \alpha_f)V_f \qquad (1)\end{aligned}$$

where α_s, α_f, and α_m are the contributions arising from the above three mechanisms, respectively, and α_s is the function of fibre volume fraction, frequency and wave mode, α_f and α_m are the function of frequency and wave mode. The attenuation term from the fibre material is expected to be very small compared with the other two mechanisms because the material is regarded as elastic in general. Then Equation 1 can be rewritten as

$$\begin{aligned}\alpha &= \alpha_s + \alpha_m - \alpha_m V_f\\ &= a - bV_f \qquad (2)\end{aligned}$$

where $a = \alpha_s + \alpha_m$ and $b = \alpha_m$.

In the case of low fibre volume fractions and frequency, the attenuation due to scattering by fibres is a linear function of fibre volume fraction because the fibres behave like single scatterers independent of each other [13]. However, multiple scattering will occur for the composites with high fibre volume fraction and the effect of correlation between fibres must be taken into account. The ultrasonic attenuation caused by multiple scattering of time–harmonic plane shear waves in the X_1/X_3 direction was considered by Bose and Mal [3] and Varadan *et al.* [4]. For an aluminium matrix reinforced by boron fibres they showed that the attenuation increased with the volume fraction of fibres in the Rayleigh limit, the rate of increment being greater for higher fibre volume fractions. Thus coefficient a in Equation 2 is an increasing function of fibre volume fraction and b is a constant, independent of fibre volume fraction at a given frequency and wave mode. Therefore, the results shown in Figs 1 to 3 indicate that the coefficient b dominantly contributes to the total attenuation, and the high attenuation in the composites is caused by viscoelastic losses in the epoxy matrix rather than scattering losses by fibres.

The frequency dependence of attenuation for X_3/X_3

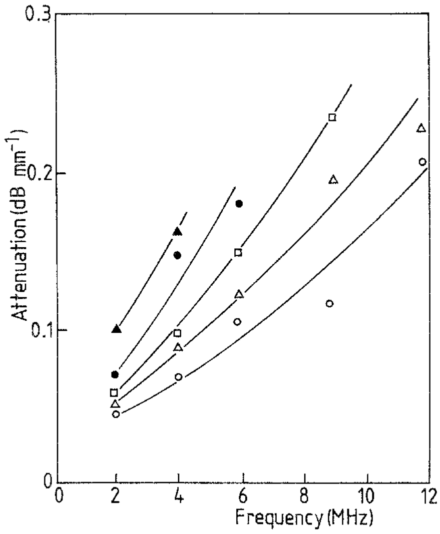

Figure 4 Frequency dependence of attenuation of longitudinal waves propagating along the fibre direction at various volume fractions of fibres. V_f = (○) 0.72, (△) 0.68, (□) 0.60, (●) 0.53, (▲) 0.50.

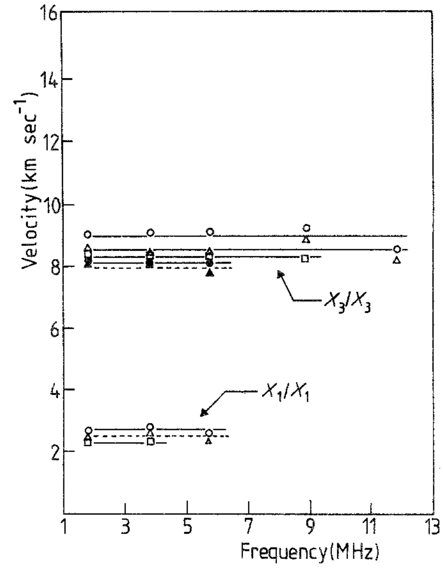

Figure 6 Frequency dependence of velocity of longitudinal waves propagating along and normal to the fibre direction at various volume fractions of fibres. V_f = (○) 0.72, (△) 0.68, (□) 0.60, (●) 0.53, (▲) 0.50.

and X_1/X_1 modes are shown in Figs 4 and 5. The attenuation in both cases increased with frequency for fibre volume fractions tested. This may have resulted from the coupling of two dissipative mechanisms of scattering losses and viscoelastic losses. The attenuation due to scattering by fibres increases with frequency in the Rayleigh limit. This was observed in tungsten fibre–aluminium matrix composites by Sutherland and Lingle [5] for X_1/X_1 mode and shown by Bose and Mal [3] and Varadan *et al.* [4] for X_1/X_3 mode. The absorption in the viscoelastic matrix increases with frequency as observed by Hartmann and Jarzynski [10]. However, it is impossible to differentiate the contributions from the scattering and matrix because the attenuation in the epoxy matrix has not been measured at the present.

3.3. Velocity of longitudinal waves

Velocity of longitudinal waves in X_3/X_3 and X_1/X_1 directions plotted against frequency is shown in Fig. 6 for various fibre volume fractions. The maximum frequency which could be investigated for a particular specimen was restricted by the attenuation of signals at higher frequencies. The attenuation in composites with the lower fibre volume fraction increased so rapidly that the velocity could only be measured for the lower frequency regions. The results in Fig. 6 show no dispersion over the indicated range of frequencies and fibre volume fractions. The scattering dispersion for the X_1/X_1 mode in fibrous composites has been treated by Hlavacek [2] and the dispersion in X_3/X_3 mode has been observed by Sutherland and Lingle [5]. The scattering dispersion for X_1/X_1 and X_3/X_3 modes is characterized by decreasing phase velocity with frequency. On the other hand, the viscoelastic dispersion is characterized by increasing phase velocity as shown by Sutherland and Lingle [8]. Therefore, the absence of dispersion may result from coupling of the effects of the increasing velocity with frequency due to viscoelastic dispersion by the epoxy matrix and decreasing velocity due to scattering dispersion by fibres.

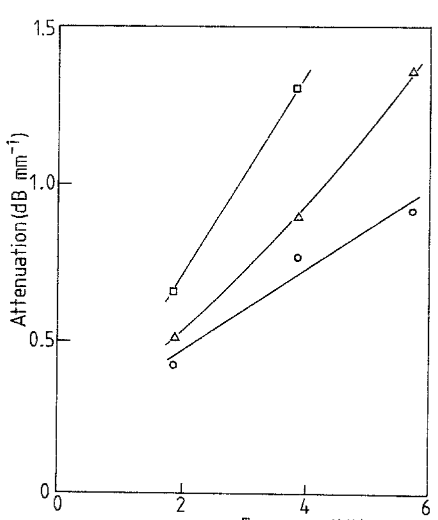

Figure 5 Frequency dependence of attenuation of longitudinal waves propagating normal to the fibre direction at various volume fractions of fibres. V_f = (○) 0.72, (△) 0.68, (□) 0.60.

4. Conclusions

The angular dependence measurements of attenuation and velocity with respect to the fibre direction showed that the composite did not permit coherent pulse propagation for either shear or longitudinal waves propagating in the off-principal directions due to the anisotropic properties and scattering.

Attenuation decreased with increasing fibre volume fraction for both longitudinal and shear waves in the frequency range tested, and the rate of the decreament was greater for higher frequencies in the shear waves rather than longitudinal waves and in the propagation direction normal rather than parallel to the fibre direction. The results indicate that the high attenuation in the composites is caused by viscoelastic losses in the epoxy matrix rather than scattering losses by fibres. The attenuation was smallest for the longitudinal wave propagating parallel to the fibre direction and largest for the shear wave propagating and polarized normal to the fibre axis. The attenuation of longitudinal waves increased with frequency for all fibre volume fractions examined. This is considered to be a result of the coupling of two dissipative mechanisms, scattering losses and viscoelastic losses.

Ultrasonic velocity of longitudinal waves was found to be independent of frequency for the range measured. The absence of the dispersion may result from a coupling of the effects of the increasing velocity with frequency due to viscoelastic dispersion by the epoxy matrix and decreasing velocity due to scattering dispersion by fibres.

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