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Effect of moisture absorption on damping performance and dynamic stiffness of NY-6/CF commingled yarn composite

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The damping performance of a unidirectional (0°) nylon 6–carbon fibre (NY-6/CF) commingled yarn composite was experimentally studied with special concern for the effect of moisture absorption. Dried specimens were immersed in distilled water for a certain time to allow water to diffuse into the material. The damping measurements were conducted on double-cantilever and cantilever beam specimens using sinusoidal and impact-hammering techniques. The damping loss factor η, flexural dynamic stiffness E' and loss modulus E'' were evaluated as a function of the moisture content up to 8.2 wt%. η and E'' initially increased significantly with increasing moisture content up to 5–6%. Further increase of the moisture content up to 8.2% caused a slight reduction in damping ability. The reverse was true of E' although the variation amplitude was smaller. The moisture content dependency of the damping performance obtained is discussed.

1. Introduction

Continuous fibre-reinforced polymer composites have generally higher specific strengths and stiffnesses than other conventional construction materials. Owing to these advantages they are extensively applied in various engineering fields such as aircraft and aerospace as well as various sporting goods like skis, tennis rackets, golf clubs, etc. The damping performance is an important parameter for structures which are subjected to dynamic loading and vibration during service. A number of analytical and experimental investigations on the damping properties of fibre-reinforced polymer-matrix composites have been reported [1–8]. It has been revealed [1, 2] that the damping in angle-ply and unidirectional off-axis continuous fibre-reinforced composites can be improved by optimizing fibre orientation and laminate geometry. To improve the damping performance of unidirectional (0°) fibre-reinforced composite materials, the use of a highly dissipative polymer matrix is considered an alternative method. A study has indicated that it is feasible to achieve a high loss factor and longitudinal flexural modulus in unidirectional carbon fibre reinforced plastics (CFRP) by employing a highly dissipative epoxy resin as matrix [7]. However, maximum energy was dissipated when the epoxy resin employed was nearly at the glass transition temperature, certainly, other mechanical properties of composites must also be significantly reduced in this case. The use of highly dissipative thermoplastic polymers thus appears more effective and preferable to thermoset resins.

Thermoplastics offer advantages over thermosets as the matrix of composites, but they have not been widely used because of difficulties in the impregnation process which requires high pressure and temperature due to their higher viscosity when melted. This situation has been somewhat improved by the commingled yarn technique [9]. The yarns consist of uniformly distributed thermoplastic polymer fibres and continuous reinforcing fibres. Unidirectional thermoplastic prepregs were produced by winding the yarn on a metal frame followed by hot pressing. A unidirectional composite material was then fabricated from these prepregs by compression moulding. This technique successfully solved the problem of impregnation and allowed the manufacture of thermoplastic composites having greater advantages in productivity and mechanical properties.

This paper reports on the experimental study of damping performance and dynamic stiffness of a unidirectional thermoplastic composite made from nylon 6–carbon fibre (NY-6/CF) commingled yarn. Since polyamides are characterized by considerable moisture absorption and their deformation properties undergo alteration during the moisture diffusion, the main objective of this work was to evaluate the effect of moisture content on the dynamic properties of NY-6/CF composite.

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2. Experimental procedure

2.1. Materials and specimens

The material studied was a compression-moulded NY-6/CF unidirectional (0°) commingled yarn composite with a fibre volume content of 50%. Fig. 1 is a schematic diagram of the composite material utilizing commingled yarns of uniformly distributed continuous reinforcing fibres and thermoplastic fibres. The unidirectional plates of NY-6/CF composite material were fabricated by first winding the yarn on a metal frame. The frame was placed in a hot metal die and after the temperature reached a value approximately 20 °C higher than the melting point of nylon 6 (225 °C) a certain pressure was applied. The moulding pressure and temperature were maintained for the time required for the melted polymer to flow between the fibres, and then the material was cooled under pressure. Optical and scanning electron microscope (SEM) observation showed that the impregnation had been thoroughly done: interfilament areas were properly filled with the matrix material (Fig. 2). It should be noted, however, that slight debonding was observed under SEM at the interface between the fibres and the matrix (Fig. 2b).

The test specimens had the geometry of double-cantilever and cantilever beams with lengths of 250 and 220 mm, respectively. The width and thickness of the specimens were 20 mm and 3.3 ± 0.05 mm, respectively. To determine the loss factor as a function of frequency the specimen length was shortened sequentially to obtain several resonance peaks in a test frequency range of 100 Hz to 1.0 kHz. The influence of moisture content in specimens was determined by initially drying them in a vacuum oven, and then immersing them in distilled water. Immersion was done at room temperature at the first stage (up to 1% moisture content). To increase the moisture content up to 8.2% specimens were immersed in water at 90 °C using a thermobath. Damping measurements were performed at room temperature (22 °C). Specimens were thermostated in a water bath down to room temperature in advance of testing.

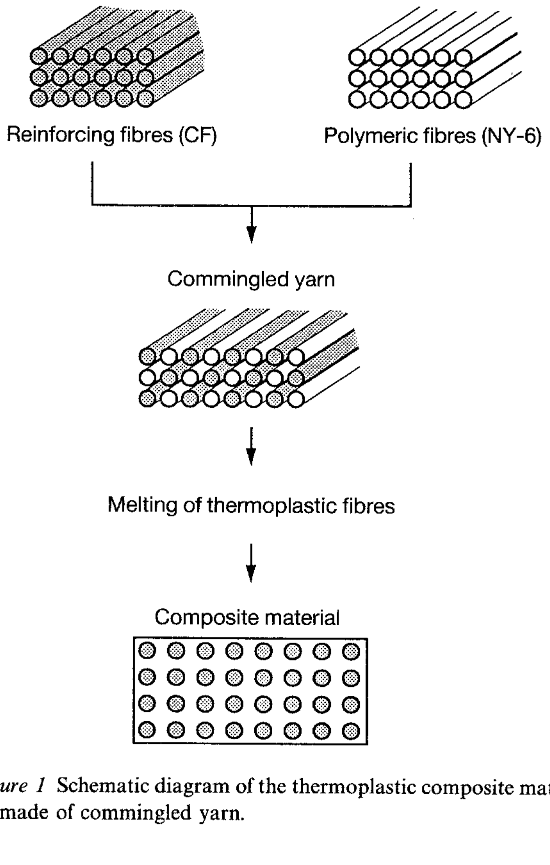

Figure 1 Schematic diagram of the thermoplastic composite material made of commingled yarn.

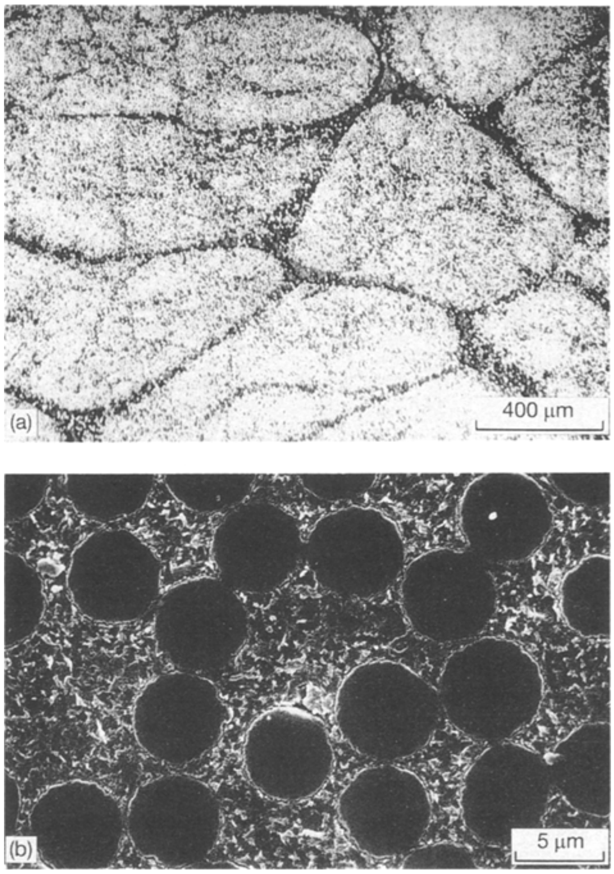

Figure 2 Cross-sections of unidirectional NY-6/CF commingled yarn composite ($V_f = 0.5$): (a) optical microscopy, (b) SEM.

2.2. Damping measurement

The experimental apparatuses used for damping measurements are schematically shown in Fig. 3. Two kinds of technique were employed. With the sinusoidal technique (Fig. 3a) a double-cantilever beam specimen was horizontally fixed at its midpoint on an electromagnetic shaker using a light aluminium clamping block. The shaker was installed on a massive base to eliminate extraneous energy loss. The base was made of a 300 mm × 300 mm × 90 mm steel plate with a 20 mm thick aluminium plate placed on it. The specimen was excited with controlled sinusoidal forces. The frequency response function was obtained and plotted while the frequency was increased smoothly from 100 Hz to 1.0 kHz. The input force was sensed by a piezoelectric accelerometer. The response signal from the specimen was measured by a non-contacting eddy-current transducer which was attached to an X–Z vernier and positioned close to the specimen's free end. The vernier was installed on the aluminium base plate for the sake of stability and ease of positioning. A thin 19.5 mm × 19.5 mm × 0.08 mm

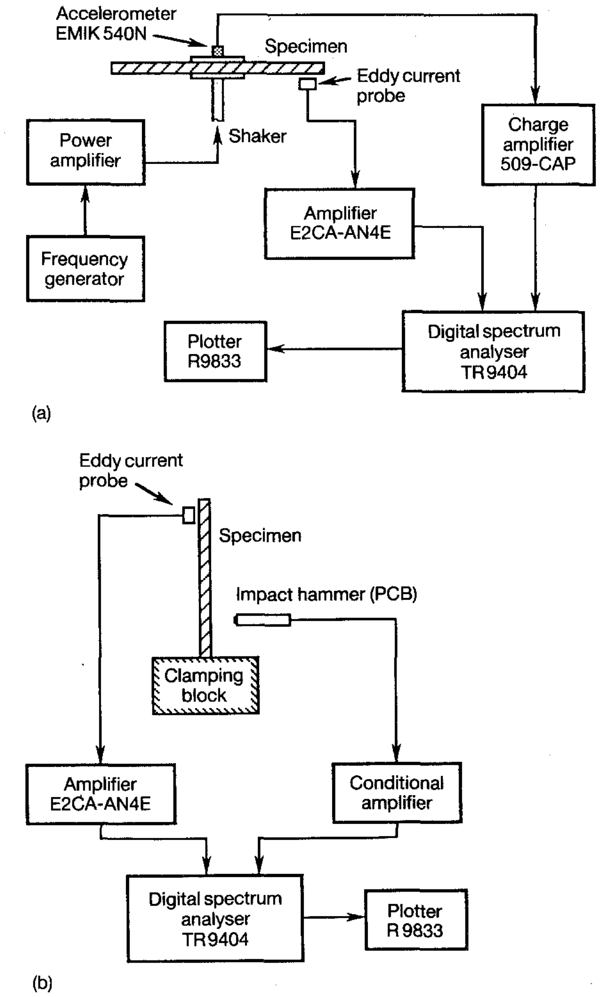

Figure 3 Block diagram of instrumentation for damping measurement: (a) sinusoidal method (double-cantilever beam specimen), (b) impact hammering method (cantilever beam specimen).

piece of steel foil was bonded to each end position of the specimen to provide a conducting surface for the eddy-current sensing. The output signals from the eddy-current probe were preliminarily calibrated using a micrometer calibration fixture so that the output voltage of the transducer was 0.5 V peak to peak at a specimen tip displacement of ± 0.5 mm. To reduce the extraneous losses caused by air damping, the maximum tip displacement was ± 0.2 mm during the tests. Preamplified excitation and response signals were fed into a digital spectrum analyser (TR 9404). The frequency response function was obtained in the sweep mode and was displayed on the screen.

The other method employed was an impulsive excitation technique (Fig. 3b). A cantilever beam specimen was vertically fixed to a massive clamping block and was excited with a modally-tuned instrumented impact hammer which had a built-in force transducer in its head. The specimen response was sensed by the non-contacting eddy current probe. Both excitation and response signals were fed into the spectrum analyser. The transfer function was obtained using the ensemble averaging method and was displayed on the screen.

The transfer function was determined in both the above cases as the ratio of the output Fourier spectrum to the input Fourier spectrum as follows:

$$H(f) = Y(f)/X(f) \qquad (1)$$

where f = frequency, $Y(f)$ = Fourier transform of response signal and $X(f)$ = Fourier transform of excitation signal. At the same time, the coherence function was also noted in order to evaluate the relationship between input and output signals. Values of the transfer function at the resonant peak zone were then determined by means of the point-by-point averaging method with the maximum frequency resolution available in the tested frequency range. The averaging repetitions were performed until coherence function values close to 1.0 were obtained. Linear interpolation between digitized points of the transfer function curve was made to determine the frequencies corresponding to the half-power points at the level of 3 dB below the peak value.

The loss factor η was determined by the half-power bandwidth method as follows:

$$\eta = \frac{f_1 - f_2}{f_n} \qquad (2)$$

where f_2, f_1 = frequencies of the half-power points and f_n = resonant frequency. The dynamic storage modulus was calculated from the resonant frequency as follows [10]:

$$E' = \frac{38.24\, \rho\, l^4}{h^2} f_n^2 \qquad (3)$$

where ρ = density of the material, l = (free) length of the specimen and h = thickness.

3. Results and discussion

Fig. 4 shows experimental results for variations in the loss factor with increasing moisture content. The addition of moisture significantly affected the material damping ability; however, the dependency was not as simple as had been expected. The loss factor initially increased with the increase of moisture, the most intensive rise occurring with a moisture content of 5–6% by weight. A slight decrease was then observed with a further increase up to 8.2%. Values of the loss

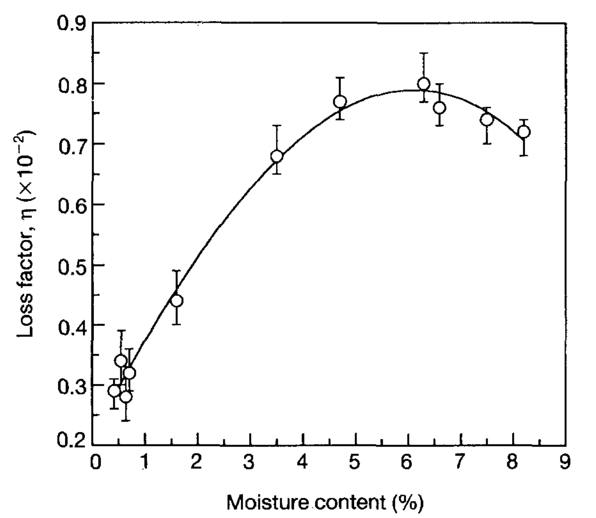

Figure 4 The influence of moisture absorption on damping performance of unidirectional NY-6/CF commingled yarn composite.

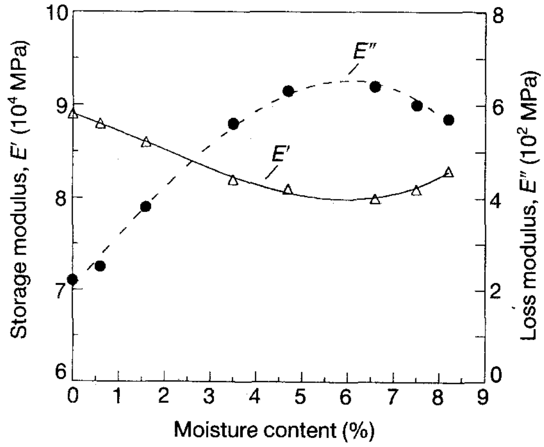

Figure 5 Variation of (△) dynamic storage modulus and (●) loss modulus with the moisture content in water-immersed NY-6/CF composite.

factor for the moisture content of 5–6% were almost three times those obtained in the dried condition.

The longitudinal modulus was not affected by moisture as much as the damping ability. As shown in Fig. 5, a slight decrease was observed for the dynamic storage modulus E' with increase in moisture content; the maximum decrease of about 10% occurred at a content of 6.6%. With further moisture absorption the storage modulus increased again and at 8.2% had regained approximately 93% of the initial value. It is of interest that the maximum decrease was observed for the flexural stiffness of NY-6/CF at a moisture content not at, but close to saturation, consistent with the result for Kevlar–epoxy laminates reported by Allred [11].

From these results, it is supposed that there are at least three factors which contribute to increase the material damping. Firstly, the change in observed dynamic behaviour of NY-6/CF seems to be primarily related to a structural change in the polymeric matrix which, when exposed to moisture, exhibits plasticization and swelling. This may, in turn, affect the interphase reaction between fibres and the matrix. The plasticization certainly causes a gradual softening of the matrix which proceeds from the outer to the inner layers of the composite, as a result of moisture diffusion. This process slightly affected the dynamic storage modulus, since the longitudinal stiffness of unidirectionally reinforced composites is predominantly associated with the modulus of fibres. At the same time, the plasticization may significantly affect the energy dissipation under flexural dynamic loading because the deformation properties under flexure are very sensitive to the stiffness of outer layers. The outer layers would have been moistened very promptly. Secondly, there is likely to be another factor which increases energy dissipation in the material exposed to moisture. This is an enhanced frictional loss at the fibre–matrix interface due to absorbed water. Water may penetrate into the free area between fibres and matrix (e.g. interphase debonding) and tend to make the debonded area slide. Thirdly, because stress variation arises in the thickness direction due to differences in deformation characteristics between the outer and inner layers, it probably also contributes to the energy dissipation at low and intermediate moisture content.

The loss modulus E'', which is proportional to the energy dissipated in the material at a specific strain, increased intensively with the increase in moisture content because of the different effects of moisture on the damping loss factor and dynamic stiffness. As a result, the optimum values of E'' were obtained at a moisture content of 4.7 to 6.6%. It is noted that the loss factor of the NY-6/CF composite at an intermediate moisture content is roughly threefold greater than that for the unidirectional epoxy–carbon composite reported by Grane and Gillespie [6].

The decrease of the loss factor in the range of moisture content 6.6–8.2%, which is close to saturation, suggests that some different situation occurred at the fibre–matrix interface. This situation may be associated with substantial swelling of the matrix which would have enhanced the contact force at the interface. Support for this supposition is given by the fact that in the same range of moisture content a slight increase took place in the dynamic storage modulus, as shown in Fig. 5.

The experimental data illustrating the variation of loss factor with frequency in the range 100 Hz–1.0 kHz are presented in Fig. 6 for dry and water-immersed NY-6/CF composites. The specimen geometry and corresponding frequency response and damping characteristics are listed in Tables I and II. Values of the loss factor were obtained for a dry specimen using the sinusoidal and impact hammering methods. The advantages and drawbacks of both experimental damping measurement methods are discussed in detail elsewhere [12, 13]. The impact hammering technique is widely used due to the ease and rapidity of *in situ* damping characterization of engineering structures and consumer products. On the other hand, the sinusoidal technique allows one to obtain the frequency response function of materials more accurately. The latter is important in studying factors which affect material damping. We applied

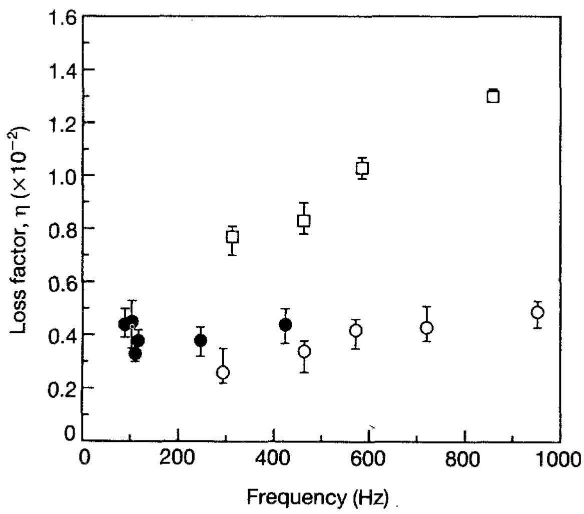

Figure 6 Loss factor as a function of frequency in dried and water-immersed (moisture content 4.5%) NY-6/CF composites. Sinusoidal method: (○) dry material, (□) water-immersed. Impact hammering method: (●) dry material.

TABLE I Frequency response and damping characteristics of NY-6/CF composite (dry) obtained with sinusoidal and impact hammering techniques

Specimen length (mm)	Resonant frequency (Hz)	Transfer function peak value (dB)	Loss factor, $\eta(\times 10^{-3})$
Sinusoidal method (double-cantilever beam)			
248	295.0	22.8	2.6
200	465.0	18.1	3.4
180	572.5	13.0	4.2
160	720.0	12.0	4.3
140	952.5	10.7	4.9
Impact hammering method (cantilever beam)			
207	89.5	45.2	4.4
192	103.5	51.0	4.5
186	111.0	52.3	3.3
183	117.0	42.4	3.8
120	247.5	30.9	3.8
90	425.0	20.5	4.4

TABLE II Frequency response and damping characteristics of water-immersed NY-6/CF composite (moisture content 4.5%)

Specimen length (mm)	Resonant frequency (Hz)	Transfer function peak value (dB)	Loss factor, $\eta(\times 10^{-3})$
240	313.8	15.4	7.7
200	463.8	10.2	8.3
180	586.3	4.9	10.3
150	858.7	2.7	13.0

both methods in the present damping measurements in order to evaluate the consistency of the loss factors obtained by the two techniques.

The experimental results in Fig. 6 show that the loss factor values determined by the impact hammering method are approximately 30% higher than those found by the sinusoidal method. One possible reason for this may be that a higher level of excitation force was used for specimens in the case of impact hammering due to difficulties involved in controlling the input force by hand. In addition, when a cantilever beam specimen is excited with an impact hammer the loading point may also slightly vary on the beam surface from time to time in the averaging tests, and if the excitation was not made exactly at the centre of the beam width, a slight torsion may occur in the beam resulting in additional energy dissipation.

Support for this explanation is found in the fact that the loss factor measured by the impact hammering method at frequencies below 100 Hz exhibited a tendency to increase with decreasing frequency for longer specimens (Fig. 6). Still, the correspondence between the two kinds of experimental data is acceptable. We can see the overlap between the two sets of data in the frequency range 250 to 500 Hz. It is seen in Fig. 6 that the loss factor increased linearly with frequency in the range tested for both dry and water-immersed NY-6/CF composite specimens. This is consistent with results of other studies [6, 8] reported on the frequency dependency of the loss factor for unidirectional (0°) CFRP laminates with an epoxy matrix. It is recognized at the same time that the addition of moisture magnifies significantly the frequency sensitivity of the loss factor for NY-6/CF composites (data in Fig. 6 are for the composite with a moisture content of 4.5%, which corresponds to an equilibrium moisture content in nylon 6 at 20 °C and 65% RH). Thus, the viscoelastic response of the polymer matrix as well as the interface interaction is believed to contribute greatly to the damping performance of continuous fibre-reinforced polymeric composites, particularly in a higher frequency range.

4. Conclusions

Material damping performance was experimentally determined under flexural vibration in the frequency range 100 Hz–1.0 kHz for a unidirectional (0°) NY-6/CF composite made from commingled yarn. Attention was focused on the effect of moisture absorption on the damping loss factor and dynamic stiffness for specimens immersed in distilled water. The conclusions are as follows:

1. The loss factor initially increased significantly with increasing moisture content up to 5–6%. Further increase of the moisture content up to 8.2% resulted in a slight reduction in loss factor.
2. The effect on the flexural dynamic stiffness was not significant. A slight decrease of the dynamic storage modulus (about 10%) was observed with an increase in moisture content up to 6.6%. However, the modulus increased again with higher moisture content, recovering to about 93% of its initial value.
3. The loss modulus E'' significantly increased with moisture content and the maximum value was obtained at between 4.7 and 6.6%.
4. The loss factor increased linearly with frequency in a range from 100 Hz to 1.0 kHz. Addition of moisture thus significantly magnifies the frequency sensitivity of the loss factor.
5. The loss factor values determined by the impact hammering method were approximately 30% higher than those by the sinusoidal method.

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