The effect of natural rubber particle inclusions on the mechanical and damping properties of epoxy-filled glass fibre composites

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Abstract: Vibration damping is proving important for improved vibration and noise control, dynamic stability, fatigue, and impact resistance in advanced engineering systems. In the present work, the effect of natural rubber particle inclusions on the mechanical and damping properties of epoxy-filled glass fibre composites is investigated. Test specimens are fabricated with inclusion of natural rubber particles of different sizes and tested for tensile strength, tensile modulus, flexural strength, and flexural modulus. These mechanical properties are influenced by the size of the rubber particle inclusions. Vibration tests are carried out and damping ratio is calculated. It is observed that damping ratio varies with inclusion of natural rubber particles and that 0.25 mm particle inclusions improve damping better than other selected particle sizes without greatly affecting the stiffness in the case of cantilever beams and fixed free plates.

Keywords: damping, fibre-reinforced composites, natural rubber particles

1 INTRODUCTION

Fibre-reinforced composites are receiving greater importance in the present-day industry because of their low density, high stiffness, high strength, and damping characteristics. Damping is an important feature of the dynamic behaviour of fibre-reinforced composite structures, involving minimization of resonant vibrations. Damping in the structure can be attained by passive or active methods. In active damping, vibration is controlled by an external source of energy and makes use of sensors and actuators for sensing the vibration and activating to suppress the vibrations in real time. The use of sensors and actuators increases the complexity of the system in active damping, whereas in passive damping it is an inherent property to control vibration by dissipating the system energy. The different sources of energy dissipation in fibre-reinforced composites are the viscoelastic nature of the matrix and/or fibre materials, damping due to the interface, damping due to damage, viscoelastic damping, and thermo-elastic damping [**1**]. Because of the reduced system complexity, passive damping is more reliable and cost effective for composite structures than active damping. The enhancement of passive damping is carried out by various researchers through surface attachments and damping treatments, co-cured viscoelastic layers, hybridization at the lamina level, fibre coating techniques, and structural modifications.

Mantena *et al.* [**2**] worked on surface treatments for enhancing the damping in composite structures. Viscoelastic damping tapes were attached to the surface of the base structures after fabrication, and these tapes were sandwiched between the base structure and the constrained layer. The ratio of tape length to beam length and the optimum location of the viscoelastic tape were investigated. Although surface treatments can increase damping significantly, the constrained layer adds undesirable weight to the structure. The drawback of weight addition is avoided by embedded co-cured viscoelastic layers. Rotz and Barrett [**3**] designed composite structures with the required

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damping by using damping hat (selection of damping layers location and stacking sequences). Delamination at the viscoelastic layer is a major drawback with co-cured layers. Both damping and rigidity of composites were improved by hybridization of laminates [**4**, **5**]. These hybrid laminates consist of both polyethylene SPECTRA fibre-reinforced laminae and graphite fibre-reinforced laminae. Experimentally, it was proved that the position of the damping layers is an important factor in influencing the loss factor of the composite structure. Hawng and Gibson [**6**] enhanced the damping of the graphite/epoxy angle ply-laminated composites under extensional vibrations by optimizing the width-to-thickness ratio and the orientation of fibre. They also concluded that the maximum contribution of coupling energy dissipation to the damping is at 30°–45° fibre orientation. Liao *et al.* [**7**] studied the behaviour of unidirectional and symmetric angle-ply carbon fibre-epoxy laminates as well as their interleaved composites with a layer of polyethylene-co-acrylic acid (PEAA) at the mid-plane. Introduction of the PEAA layer significantly improved the damping. The effectiveness of interleaving increases with the flexural modulus of the outer layer. Experimental results revealed that proper selection and placement of interleaving material with appropriate laminate configuration and constituent properties significantly improve the overall damping of the interleaved composite laminate. Pratt *et al.* [**8**] investigated geometric fibre wave patterns in composites as a means of including additional damping due to stress coupling effects by using co-cured viscoelastic layers.

The high shear strain energy stored at interphase plays a major role for damping in fibre-reinforced composites due to a mismatch of the properties. Hence, the fibres are coated with viscoelastic materials to improve the damping in composites. Finegan and Gibson [**9**] proposed and presented the analytical and experimental models to study the influence of fibre coatings on damping. Even though damping is increased through fibre treatments, the stiffness is greatly decreased. Although the vibration damping capacity and fracture toughness are two completely different material properties, both of these involve the process of energy dissipation. Damping capacity is the measure of cyclic dissipation of vibration energy, whereas fracture toughness is the energy dissipated at the crack tip as the crack grows. Kim *et al.* [**10**] improved the fracture toughness of the epoxy composite with the addition of carbon black and micro-clay particles. It was found that reinforcement with micro-particles improved the fracture toughness at room temperature, but decreased the fracture toughness at cryogenic temperatures in spite of their toughening effect. A variety of methods have been used to improve the toughness in polymer matrix composites. Rubber particles were included in polymers to improve the impact strength [**11**]. The mechanisms that dissipate energy in rubber particle-included polymeric composites are crazing, rubber bridging, and the cavitation of rubber particles causing massive shear banding of the matrix around the particles. The rubber particles in polymeric composites act as craze initiators responsible for energy dissipation and improvement in damping. Zhou *et al.* [**12**] fabricated a composite sound absorber using recycled rubber particles with a good attenuation property to dampen the noise.

Suarez *et al.* [**13**] and Suarez and Gibson [**14**] developed the impulse method, in which a test specimen was supported as a flat cantilever beam in a clamping block, and impulse excitation was applied using an electromagnetic hammer. The transverse displacement of the beam was measured over time by means of a non-contact eddy current probe positioned near the tip of the beam, and Fourier transform was performed to obtain the frequency response function (FRF). A curve fitting to Fourier transform was used to yield the complex modulus. Jean and Sefrani [**15**] investigated damping of unidirectional glass and Kevlar fibre composites experimentally using a cantilever beam test specimen and an impulse technique. Damping parameters were derived by fitting the experimental Fourier responses with the analytical motion responses expressed in modal coordinates. Damping ratio evaluation is carried out by four techniques based on both the time domain as well as the frequency domain. The logarithmic decrement method and the Hilbert transform method are based on the time domain, while frequency domain methods include the moving block method and the half-power bandwidth method. Smith and Wereley [**16**] used the logarithmic decrement method, the Hilbert transform method, and the moving block method for the evaluation of the damping ratio of rotor craft fixed beams. It was concluded that these methods could be used for the estimation of low levels of damping (<2 per cent). The evaluation of damping from the logarithmic decrement of free vibrations of cantilever beams was considered by Hadi and Ashton [**17**] using the experimental process developed by Wray *et al.* [**18**]. In this process, the specimen was clamped at one end and an initial displacement was achieved by striking the free end with a controlled striker mechanism. Displacement of the free end with time was detected using a capacitance transducer, and damping was deduced from the logarithmic decrement obtained from the decaying voltage–time signal of the transducer. The damping was evaluated by Crane and Gillespie [**19**] from the loss factor determined by the half-power bandwidth method.

The fracture toughness of polymeric composites is improved with rubber particle inclusions [**10**, **11**]. Many deep-water oil and gas platform operators are replacing their existing PVC water pipes with glass epoxy composites. These pipes require high-impact resistance and damping properties to resist the impact energy of collapsing bubbles due to cavitation and to reduce the noise, vibration transmission, and fatigue damage. The rubber particle-filled glass epoxy composite materials with improved damping capacity could be one method to reduce such problems. Another significant application of rubber particle-filled composites is the reduction of radiated noise from machinery rafts (on which engines are mounted). Both vibration damping and fracture toughness involve the process of energy dissipation, even though studies on vibration damping are few.

In the present work, glass fibre composites are fabricated with natural rubber particles of different sizes as inclusions to enhance the damping. Mechanical properties such as tensile modulus, tensile strength flexural modulus, flexural strength, and their dependence on particle size are measured experimentally. Vibration tests on fabricated composites at each particle size are carried out by the mechanical impedance method at constant fibre orientation and weight fraction. These tests are carried out over a frequency range of 0–3000 Hz for cantilever beams and cantilever plates. The uncertainty in excitation of all modes within the frequency range as in the case of the impact hammer technique is avoided by using an exciter that excites the specimen in all modes within the given frequency range. Damping ratios of the composite beams and plates at each particle size are calculated from the FRF using the half-power bandwidth method.

2 SAMPLE PREPARATION

2.1 Materials

Glass fabric 5 mil plain mat and epoxy resin lapox 12 with hardener K6 are used for the fabrication of the samples. The nominal content of the glass fibre in the composite is set at 40 per cent by weight and the remaining 60 per cent is resin. Natural rubber particles (cross-linked and approximately spherical in shape) are sieved, and four different particle sizes (0.9 mm, 0.45 mm, 0.25 mm, and 0.0975 mm nominal diameter of the pore sizes of the sieves) are segregated. These particles (10 per cent by weight) are added to the 90 per cent glass fibre composite (the glass fibre to resin ratio is 40:60) as inclusions. Rubber particles are manually mixed with epoxy resin at room temperature, followed by mixing with a sonicator for 1 h. The thickness of each composite sample is 4 mm. Details of materials and instruments used in experimentation are presented in Table 1.

Table 1 Experimental details

Material (manufacturer data)
Resin: Lapox 12
Hardener: K6, shear strength: 14 N/mm^2
Glass cloth: plain weave 0.125 mm thick 5 mill fabric glass cloth
Width: 1000 mm, warp: 36, weft: 32
Natural rubber particles: supplied by Ragavendra Rubber Products (India)
Equipment
Exciter: 4809 Bruel and Kjeer made
Force rating: 45 N to 60 N with air cooling
Frequency range: 1–20 kHz
Power amplifier: 2706 Bruel and Kjeer made
Rating power: 75 VA
Sonicator
Maximum power output: 600 W
Operating frequency: 20 kHz
Input: 110VAC at 10 A
Programmable timer: 1 s to 1 h

2.2 Fabrication

The composite sample plates are fabricated in rectangles with the glass fibre fabric mats oriented at 0° and 90° to the length and width directions, respectively. These samples are fabricated by a hand lay-up technique. Samples are fabricated with different sizes of rubber particles as inclusions between the layers, and 16 layers are laid up and cured at room temperature for 24 h. The samples in the form of plates are cut into 300 × 180 mm rectangles and 250 × 25 mm in the form of beams by using a diamond saw. Tensile specimens (250 × 25 × 4 mm) and flexural specimens (94 × 10 × 4 mm) are fabricated as per American Society for Testing and Materials (ASTM) standards [**20**].

3 EXPERIMENTATION

The tensile test is carried out using an INSTRON 1185 testing machine with the test conditions recommended by ASTM D3039. The crosshead speed in the tensile test is set to 1 mm/min. The tensile modulus and tensile strength are determined for composite specimens with and without rubber particle inclusions. The flexural test is carried out as per ASTM D790 standards with INSTRON 1185, and flexural modulus and flexural strength are determined by the three-point bending method. For flexural test, the crosshead speed is set to 2 mm/min. The load and deflection of the specimens are recorded, and the properties are evaluated by the following formulae recommended by ASTM standards

$$\text{Tensile strength} = \frac{P}{bt} \tag{1}$$

$$\text{Tensile modulus} = \frac{\Delta P\ l}{bt\ \Delta l} \tag{2}$$

where P is the maximum load at fracture; t, l, and b are the thickness, gauge length (150 mm), and width of the sample, respectively; ΔP is the load within the elastic limit or up to linearity that appears in the load deflection curve; and Δl is the change in length correspondent to ΔP.

$$\text{Flexural strength} = 1.5\frac{[PL]}{bt^2} \quad (3)$$

$$\text{Flexural modulus} = \left(\frac{L^3}{4bt^3}\right) \times \left(\frac{\Delta P}{\Delta l}\right) \quad (4)$$

where P is the maximum load at fracture; t, L ($L = 15t$), and b are the thickness, span, and width of the sample, respectively. ΔP is the load within the elastic limit or up to linearity that appears in the load deflection curve and Δl is the change in length correspondent to ΔP.

Vibration tests are usually based on measurement of modal frequencies, modal damping factors, and mode shapes of specimens. In the present work, vibration tests are carried out for measuring the damping ratios of composite plates and beams. Vibration tests for cantilever beams and fixed free plates are carried out by the mechanical impedance method in which the specimen is forced to vibrate using an electromechanical exciter while response measurements are collected and model parameters are identified. First the plates of size 300 × 180 × 4 mm are tested for the fixed free condition. Then the beams of size 250 × 25 × 4 mm cut from the same plates are used as test specimens for both tensile and vibration measurements. For non-destructive vibration measurements, five specimens of each particle size are tested, and each specimen is tested three times to establish the uncertainty in the experimentation. The same specimens are used later for the destructive tensile tests. The variations in all the experimental results are within the range of 10 per cent of the average values, and hence the average values are reported. The specimen is excited at the middle of the fixed end and the accelerometer is attached at the free end. Special care has been taken to locate the antinodes for fixing the accelerometer at the free end. The measured analogue response signal from impulse excitation is transformed for analysis in the frequency domain using fast Fourier transform analysis. The peaks in the frequency response spectrum are the locations of natural frequencies. The accelerometer is used to measure the acceleration using a data acquisition card and the response is recorded. The damping ratio is calculated by the half-power bandwidth method [**21**] from the FRF as follows

$$2\xi f = (f_1 - f_2) \quad (5)$$

where ξ is the damping ratio, f is the resonant frequency, and f_1 and f_2 are the frequencies corresponding to the bandwidth at a point $1/\sqrt{2}$ of the maximum amplitude at the resonant frequency.

4 RESULTS AND DISCUSSION

Morphology studies, in the case of fibre-reinforced composites, revealed the aspects of fibre bonding and adhesion between the fibre and the matrix. Figure 1 shows SEM micrographs of the fractured surface during the tensile test of glass fibre-reinforced epoxy resin composite specimens with rubber particles. Rubber particles are well distributed in the matrix.

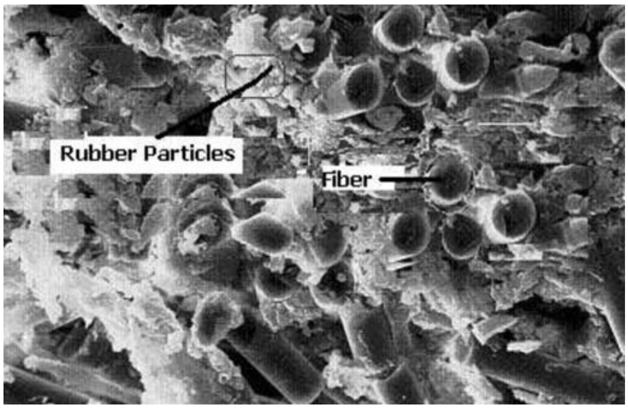

Fig. 1 SEM of the fractured surface during the tensile test of particle-included composite

The tensile and flexural properties are evaluated from the tests and reported in Figs 2 to 5. The error bars denote the standard deviation of the five samples at each particle size. The effect of rubber particle size on tensile strength is presented in Fig. 2. From the results, it is evident that tensile strength is influenced by the size of the rubber particle inclusions. These inclusions increase the tensile strength of rubber particle-filled composites beyond that of a neat composite up to a particle size of 0.45 mm, and decrease it for larger particles. Flexural strength is also influenced by inclusion of rubber particles (Fig. 3). Flexural strength with 0.0954 mm particle size is more than that for the neat composite, but decreases with increasing rubber particle size. The strain energy absorbed by rubber particle inclusions due to rubber bridging may be the reason for this increase in strengths. However, at higher particle sizes, the stress concentration is increased due

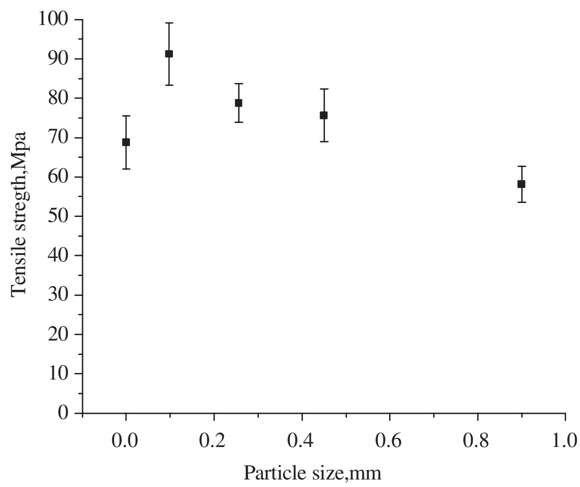

Fig. 2 Effect of particle size on tensile strength

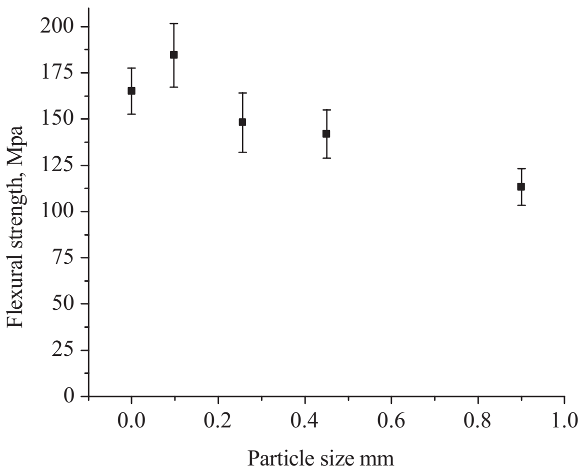

Fig. 3 Effect of particle size on flexural strength

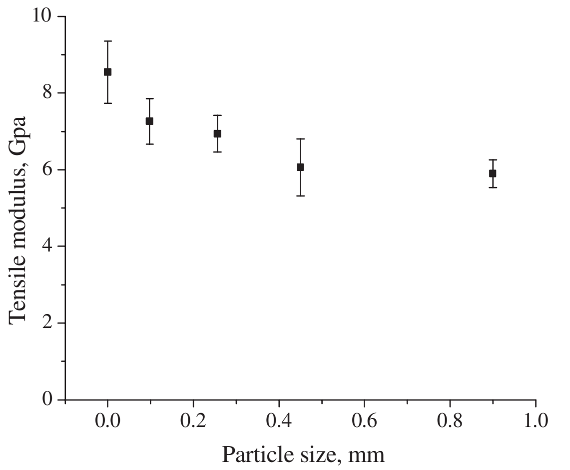

Fig. 4 Effect of particle size on tensile modulus

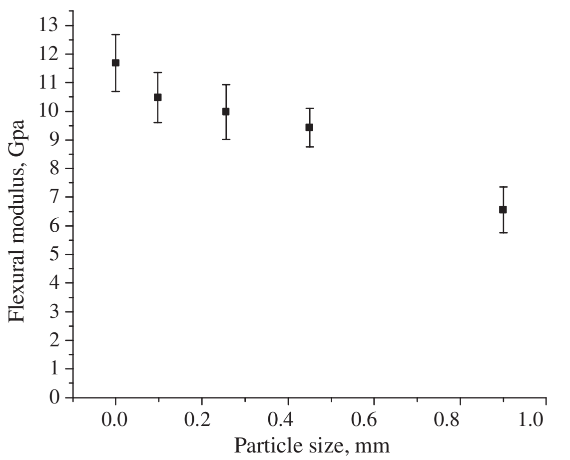

Fig. 5 Effect of particle size on flexural modulus

to abrupt changes in material properties and both the strengths are reduced.

Tensile modulus values evaluated from the tests are presented in Fig. 4. It is observed that the tensile modulus is reduced with increasing rubber particle size. Flexural modulus values evaluated from the tests are shown in Fig. 5. Flexural modulus also reduced with increasing rubber particle size. This may be caused by stick–slip motions between the matrix and the particles at the interface. When the tensile stress is applied to a composite, it starts elongating and the epoxy matrix starts applying shear stress on the rubber particles causing load transfer to rubber particles. Consequently, normal strain appears in the rubber particles and they start elongating. When the applied stress is low, both the rubber particles and the matrix move together and strains are equal during this phase. If the stress is further increased, the shear stress on rubber particles increased and there is a slip between the matrix and the rubber particles, causing a reduction in stiffness. Reduction in flexural modulus is slightly higher than that of tensile modulus at larger particle inclusions. It may be attributed due to the presence of additional shear stress induced due to three-point bending.

The first five resonant frequencies of the beam specimens observed from the experiments are reported in Table 2. The resonant frequencies of rubber-included composite beams are shifted towards higher frequencies than those of the neat composite. The addition of excess mass, the change in stiffness due to viscoelastic rubber particles, and coupling effects (Poisson effects) may be the cause for this shift. The effect of particle size on resonant frequency is not significant. As practical systems are generally operated at lower frequencies and the first five resonant frequencies are obtained up to the range of 2500 Hz, only these five frequencies corresponding to resonant peaks are reported for comparison. As damping plays a major role at resonance frequencies, damping ratios are evaluated at resonant frequencies.

The variations in the damping ratio of the cantilever composite beam with rubber particle inclusions ξ_p and the damping ratio of the neat composite ξ as a function of frequency are reported in Fig. 6. It is observed that damping decreases when the resonant frequency is increased for all specimens. The ratio r denoting the improvement in damping $[\xi_p/\xi]$ at each resonant peak for a selected particle size is reported in Fig. 7. Damping ratio is increased by inclusion of rubber particles at all modes due to the viscoelastic nature of the rubber particles. However, the size of the

Table 2 Resonant frequencies of a cantilever beam

Particle size	No. of particles	0.09 mm	0.254 mm	0.45 mm	0.9 mm
Resonant peak 1 Hz	150	165	175	175	175
Resonant peak 2 Hz	425	490	575	550	525
Resonant peak 3 Hz	800	1050	1050	1025	1000
Resonant peak 4 Hz	1325	2075	1675	1550	1230
Resonant peak 5 Hz	1875	2950	2425	2125	2200

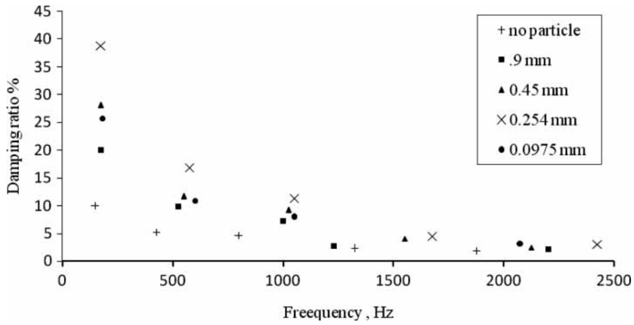

Fig. 6 Influence of natural rubber particles on damping ratios of cantilever beams

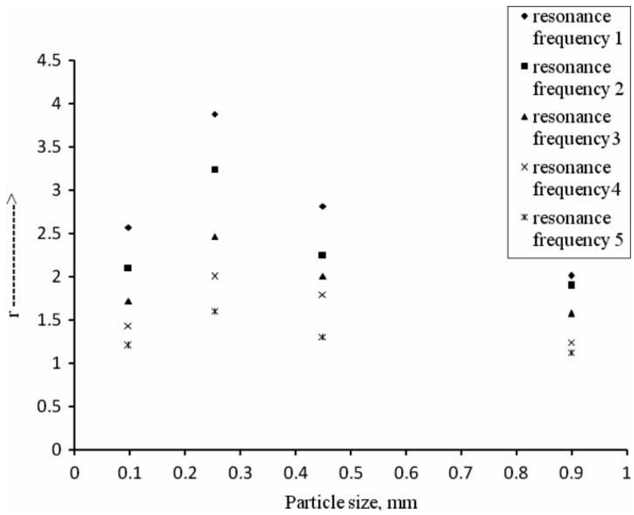

Fig. 7 Particle size versus improvement of damping at each resonant peak of cantilever beams

rubber particle and the resonant frequency are significant in damping ratio improvement. Improvement in damping ratio is greater at the lower frequencies. The effect of the size of the inclusions on damping ratio improvement is reduced from the first resonant peak to the fifth resonant peak gradually as the frequency increases. The effect of the size of inclusion on damping is increased up to particle size 0.254 mm and then decreases with increasing particle size. The particle size of 0.254 mm exhibited better performance in improving the damping ratio among the selected particle sizes at all resonant peaks. At the first resonant peak, it is almost four times than that of the neat composite. The reason for exhibiting lower damping ratio at particle size 0.0954 mm compared to 0.254 mm may be due to the fact that fine particles may not exist in the interphase layer of the fibre and the matrix, which is of the order of 50 nm [**22**]. Similarly, at higher particle size, the energy dissipation due to microshear yield mode of deformation is suppressed [**23**] and decreases the damping. Hence, 0.254 mm rubber particle inclusions improved damping of the composite to a greater extent than other particle sizes. It is observed that at higher particle size and at higher resonant frequencies, the effect of inclusions is less significant. The damping ratio of rubber particle-reinforced composites with larger particles at higher modes is slightly higher than the composite with no inclusions. This is probably due to the fact that at high resonant frequencies the particles may not have sufficient time to dissipate strain energy.

Fixed free plates are scanned for 3000 Hz and the responses are noted in $m/s^2/N$. The first five resonant frequencies of the fixed free plate specimens observed from the experiments are reported in Table 3. The damping ratio is calculated by the half-power bandwidth method for the first five resonant peaks and is presented in Fig. 8 as a function of the resonant frequencies. The damping decreased with increasing frequency for all the composite specimens. The ratio

Table 3 Resonant frequencies of a fixed free plate

Particle size	No. of particles	0.0975 mm	0.254 mm	0.45 mm	0.9 mm
Resonant peak 1 Hz	130	112.5	120	125	128
Resonant peak 2 Hz	300	275	280	252	265
Resonant peak 3 Hz	512.5	350	425	437.5	362.5
Resonant peak 4 Hz	775	437	462.5	625	512.5
Resonant peak 5 Hz	1050	612.5	637.5	930	750

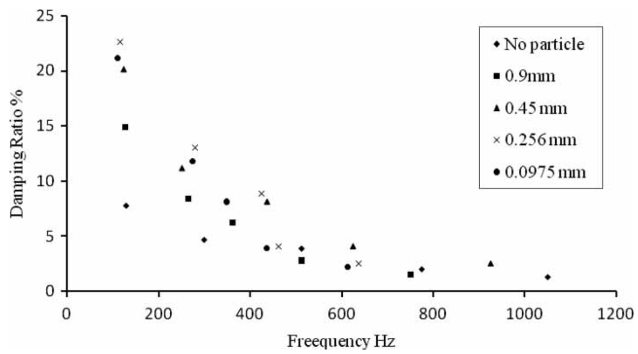

Fig. 8 Influence of natural rubber particles on damping ratios of fixed free plates

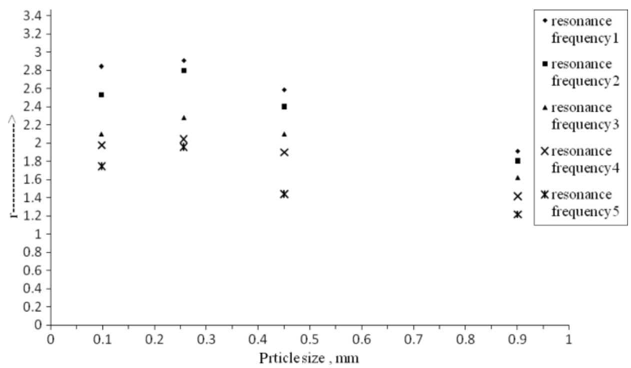

Fig. 9 Particle size versus improvement of damping at each mode of fixed free plates

r at each resonant frequency for fixed free plates is reported in Fig. 9. It is observed (Fig. 9) that the damping is greatest at the first resonant peak and decreases gradually up to the fifth resonant peak for all plate specimens. The damping effect of inclusions is increased with rubber particle reinforcement in all the modes. However, 0.254 mm particle-reinforced composites exhibited the highest damping ratio compared to other particle sizes. The damping ratio is increased approximately three times relative to that of the neat composite at the resonant peak for the same reasons as in the case of cantilever beams. The effect of rubber particles on damping ratio decreases with increasing frequency as less time is available for dissipation of the strain energy.

5 CONCLUSIONS

Mechanical and damping properties of woven glass fabric plain mill epoxy composites with natural rubber particle inclusions have been tested experimentally. The following conclusions are drawn from the experimental data.

1. Tensile strength and flexural strength are influenced by the size of the rubber particle inclusions. At smaller particle sizes, tensile strength and flexural strength increased compared to the neat composite and then decreased with increasing particle size.
2. Tensile modulus and flexural modulus are reduced slightly up to 0.254 mm particle size; thereafter, the reduction in these properties is significant. The influence of the size of the rubber particles is greater in flexural modulus than in tensile modulus.
3. Due to particle rubber inclusions, there is a frequency shift towards higher resonant frequencies in the case of composite beams and towards lower frequencies in the case of fixed free plates than that of neat composites.
4. Particle size is insignificant in the shift of natural frequencies.
5. Damping is decreased with increasing resonant frequency in all the test conditions and is influenced by the rubber particle size. Variation in damping ratios is greater at the first mode with rubber particle inclusions, decreasing gradually up to the fifth mode.

Improvement in damping increased up to 0.254 mm particle inclusions and then decreased. Among the selected particle sizes, 0.254 mm particle inclusions improved damping compared to other particle sizes without significantly affecting the stiffness in the case of cantilever beams and fixed free plates.

REFERENCES

1 **Chandra, R., Singh, S. P.,** and **Gupta, K.** Damping studies in fibre-reinforced composites – a review. *Compos. Struct.*, 1999, **46**, 41–51.
2 **Mantena, P. R., Gibson, R. F.,** and **Hawng, S. J.** Optimal constraint viscoelastic tape lengths for maximizing damping in laminated composites. *AIAA J.*, 1991, **29**, 1678–1685.
3 **Rotz, C. A.** and **Barrett, D. J.** Co-cured damping layers in composite structures. In Proceedings of the 23rd International SAMPE Technical Conference, 1991, pp. 352–363 (Society for the Advancement of Materials and Process Engineering, Covina, CA).
4 **Adams, D. F.** and **Zimmerman, R. S.** Static and impact performance of polyethylene/graphite fibre hybrid composite. In Proceedings of the 31st International SAMPE Symposium, 1986, pp. 1456–1468 (Society for the Advancement of Materials and Process Engineering, Covina, CA).
5 **Mantena, P. R.** and **Gibson, R. F.** Dynamic mechanical properties of hybrid composites polyethylene/graphite composites. In Proceedings of the 22nd International SAMPE Technical Conference, 1990, pp. 370–382 (Society for the advancement of materials and Process Engineering, Covina, CA).
6 **Hawng, S. J.** and **Gibson, R. F.** The use of strain energy based finite element techniques in the analysis of various aspects of damping of composite materials and structures. *J. Compos. Mater.*, 1992, **26**, 2585–2605.
7 **Liao, F. S., Su, A. C.,** and **Hsu, T. C.** Vibration damping of interleaved carbon fibre-epoxy composite beams. *J. Compos. Mater.*, 1994, **28**(18), 1840–1854.
8 **Pratt, W. F., Rotz, C. A.,** and **Jensen, C. G.** Improved damping and stiffness in composite structures using geometric fibre wave patterns. In Proceedings of the ASME Noise Control and Acoustics Division (2), Advanced Materials for Vibroaccoustic Applications, 1996, pp. 37–43 (ASME, New York).
9 **Finegan, I. C.** and **Gibson, R. F.** Analytical and experimental characterization of damping and stiffness in polymer composites having coated fibers as reinforcement. In Proceedings of the ASME Noise Control and Acoustics Division, NCA, 1997, vol. 24, pp. I27–138 (American Society for Mechanical Engineers, New York).
10 **Kim, B.-C., Park S. W.,** and **Lee, D. G.** Fracture toughness of the nano-particle reinforced epoxy composites. *Compos. Struct.*, 2008, **86**, 69–77.
11 **Collyer, A. A.** *Rubber toughened engineering plastics*, 1st edition, 1994 (Chapman and Hall, London, UK).
12 **Zhou, H., Li, B., Huang, G.,** and **He, J.** A novel composite sound absorber with recyclic rubber particles. *J. Sound Vibr.*, 2007, **304**, 400–406.
13 **Suarez, S. A., Gibson, R. F.,** and **Deobald, L. R.** Random and impulse techniques for measurement of damping in composite materials. *Exp. Tech.*, 1984, **8**(10), 19–24.
14 **Suarez, S. A.** and **Gibson, R. F.** Computer-aided dynamic testing of composite materials. In Proceedings of the SEM Conference on *Experimental mechanics*, Milwaukee, WI, USA, 1984, pp. 118–123.
15 **Berthelot, J.-M.** and **Sefrani, Y.** Damping analysis of unidirectional glass and Kevlar fibre composites. *Compos. Sci. Technol.*, 2004, **64**, 1261–1278.

16 **Smith, C. B.** and **Wereley, N. M.** Composite rotorcraft flexes beams with viscoelastic damping layers for aeromechanical stability augmentation ASTM STP 1304. In *Mechanics and mechanisms of material damping*, 1997, pp. 66–67 (ASTM, Virginia).
17 **Hadi, A. S.** and **Ashton, J. N.** Measurement and theoretical modeling of the damping properties of a uni-directional glass/epoxy composite. *Compos. Struct.*, 1996, **34**, 381–5.
18 **Wray, S., Ashton, J. N.,** and **El-Sobky, H.** An investigation of the influence of anisotropy and frequency on damping in short fibre reinforced polypropylene. *Compos. Struct.*, 1990, **15**, 43–60.
19 **Crane, R. M.** and **Gillespie, J. W.** Characterization of the vibration damping loss factor of glass and graphite fibre composites. *Compos. Sci. Technol.*, 1991, **40**, 355–375.
20 ASTM. *ASTM volume 08.01, 08.02*, June 2008 (ASTM International).
21 **Rao, S. S.** *Mechanical vibrations*, 4th edition, 2004 (Pearson Education, New Delhi).
22 **Wu, S.** Impact fracture mechanisms in polymer blends: rubber-toughened nylon. *J. Polym. Sci.: Polym. Phys. Ed.*, 1983, **21**(5), 699–716.
23 **Charles, B.** *Arends, polymer toughening*, 1996, p. 277 (Marcel Dekker Inc., New York, USA).