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Measurement of Damping Capacity of Pultruded Glass Fibre-Reinforced Composite by Forced Vibration Technique

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ABSTRACT

The effect of strain amplitude and frequency on the loss factor of glass fibre-reinforced composite (GFRC) have been investigated by forced vibrations of double cantilever rod specimens. The tests were conducted at room temperature in the frequency range of 70Hz to 320Hz and at atmospheric pressure since the effect of air damping on the rod shape specimens is likely to be small. The measured loss factor is independent of the maximum strain amplitude and increases significantly with frequency. These results indicate that pultruded GFRC has relatively high damping value.

ABSTRAK

Kesan amplitud terikan dan frekuensi keatas faktor kehilangan rencam gentian tetulang kaca (RGTK) telah diselidik dengan mengenakan getaran paksa kepada rod contoh julur dua. Ujian-ujian dijalankan pada suhu bilik dengan julat frekuensi antara 70Hz ke 320Hz dan pada tekanan atmosfera kerana kesan redaman udara keatas rod contoh dijangkakan kecil. Faktor kehilangan yang diperolehi didapati bebas daripada amplitud terikan maksimum dan bertambah secara ketara dengan frekuensi. Keputusan ini menunjukkan RGTK yang dihasilkan secara penarikan mempunyai nilai redaman yang tinggi.

INTRODUCTION

Damping is an energy dissipative process which is manifested during the mechanical vibration of structural elements and systems. The damping of structural elements may be separated into three general types: joint damping arising from friction sliding and slapping of joint interface: air or fluid damping arising from loss of transmission of energy to the surrounding: and material damping, an energy loss arising from complex behaviour of the material itself. However, only material damping arising from inelastic deformation of the material will be analysed in this paper.

When perfectly elastic material is subjected to a single impulse, vibration in the material will impose a cyclic stress on the material as shown in Figure 1, provided that no external friction acting on the system [5]. The maximum amplitude of these vibrations will occur at point σ_o,ϵ_o in Figure 1. The elastic energy stored in the material is equal to the area enclosed by OBA under the curve. The elastic energy will be converted to kinetic energy at point 0 in Figure 1 during the reversible cycle of the stress-strain. Then another peak amplitude will be reached, shown as

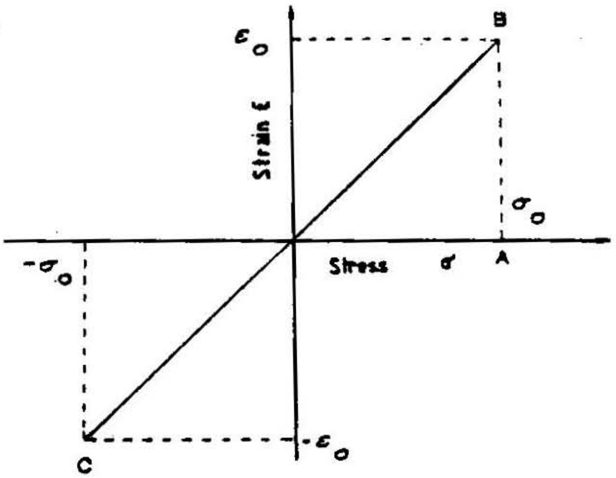

FIGURE 1. Cyclic sress-strain curve for a perfectly elastic material

point C. A futher stress-strain cycle will follow the same locus resulting in the same maximum stress-strain amplitude.

Materials such as metals and composites, and structural assemblies do not behave in a perfectly elastic manner even at low stress. The stress-strain curve for these materials never yield a perfect straight line when subjected to a cyclic loading [5]. The stress-strain curve for these materials generate a hysteresis loop as shown in Figure 2 when experiencing periodic force. The area enclosed by the loop represent the energy dissipated per cycle by the material.

Lazan [5] defines the following expression to relate damping to the stress amplitude,

$$D = J\,\sigma_a^n \tag{1}$$

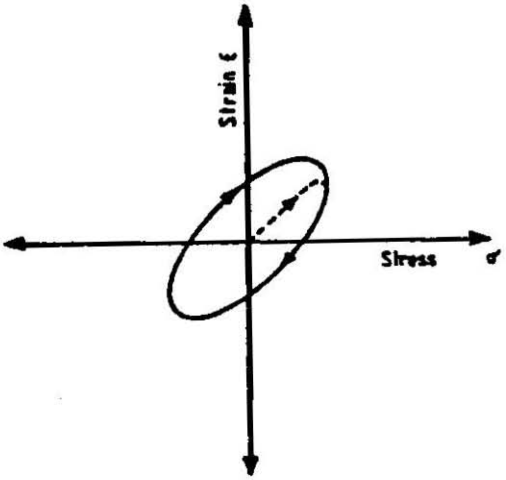

FIGURE 2. Hysteresis loop for a viscoelastic material

For fibre-reinforced composites subjected to low strain amplitude, they can be considered as linear visoelastic materials [5]. The hysteresis loop will form an ellipse with the damping exponent n, equal to 2. This is often recognised as quadratic damping.

It is important to study the damping capacity of a material since material with high damping capacity will have longer life when exposed to dynamic loading. This is due to the fact that the material is capable of dissipating the input energy quickly, and consequently, shortened the time the stress acting on the material.

Recently, pultrusion technique has become an important manufacturing process to produce long and straight fibre-reinforced material with constant cross-sectional area. Many papers have been published by several authors [1, 6, 8, 11, 16] on the damping capacity of GFRC but to the best of author's knowledge no work has been accomplished to analyse the damping capacity of GFRC manufactured by the pultrusion technique. The damping capacity could give insight view how well the resin impregnated the fibre since pultrusion process still facing the problem of not fully wetting all the fibre with the resin.

This paper presents the experimental data on the damping properties of unidirectional and continuous GFRC subjected to transverse vibrations. The effect of strain amplitude on damping (loss factor) was measured. In addition, the dependence of the loss factor on test frequency for the specimen was also measured.

The results obtained were then compared with results acquired by Gibson and Plunkett [3] and Mazzà et al [8]. The comparison was made in order to compare only the variation of the loss factor with the increasing frequency and not with the magnitude of the loss factor. Many variables including the fibre volume fraction, method of production and type of resin determine the magnitude of the loss factor.

Measurements were made by forced transverse vibration method. Double cantilever beam method was employed since this technique has succeessfully yield reliable results as employed by several investigators [1, 4, 8, 9, 10, 13, 16]. For these tests, measurements were conducted at strain amplitude up to $\mp 420\mu\epsilon$ in the frequency range of 70 to 320Hz.

MATERIAL

The material studied was a unidirectional glass fibre-reinforced epoxy resin rod manufactured from pultrusion process. The diameter of the rod was 5.0mm with the longest length of 500mm, and the fibre volume fraction was 74%.

METHOD

A block diagram of the instrumentation and equipment employed in the forced vibration test is shown in Figure 3. The clamping arrangement for the specimen was carefully designed in order to minimize the energy losses at the clamp. The slots in the clamping plates were designed in isosceles triangular shape with 40 degrees base angle to reduce the error due to clamping since the area of rod subjected to clamping force is small, and consequently lessen the deformation of the rod and the energy losses at the clamp arrangement [12].

The effect of any external vibrations were reduced by placing the electrodynamic shaker on a 1016 kg seismic mass. The clamping device was mounted on the vibrator head of an eletrodynamic shaker.

The length of each double cantilever beam were measured precisely to ensure that the specimen was clamped exactly symetric about the base driving point. If both ends of the specimen are not exactly symmetric, one end may vibrate out of phase with the other end, causing a vibratory moment to be transmitted to the support. Frictional energy loss may occur at the specimen-support interface due to this vibratory moment [4].

Excitation of the rod specimen was accomplished by driving the shaker with Frequency Regulator. The frequency of the regulator output was first adjusted to the first modal frequency of the double cantilever beam by varying the frequency until the maximum tip amplitude was obtained. The longitudinal bending strain in the specimen were measured using two strain gauges mounted near the roots of each cantilever. The strain output was amplified by a Flyde strain gauge amplifier, and displayed on a Digital Storage Oscilloscope.

The base-acceleration amplitude was measured using B&K accelero meter. The accelerometer signal was amplified by a B&K accelerometer charge amplifier before being displayed on a B&K High Resolution Signal Analyser. The magnitude of the acceleration was determined directly from the captured signal, and the frequency of the accelerometer could then be acquired directly from the frequency spectrum displayed by B&K FFT Signal Analyser.

The forced vibration provided a voltage time plot of the accelerometer output, longitudinal bending strain in the specimen and the experimental resonance frequency.

DETERMINATION OF THE LOSS FACTOR

Using the data obtained from the tests, voltage time plot of the accelerometer output, longitudinal bending strain and the resonance frequency, and the characteristic functions of the beam-deflection curve [2] as well as the eigenvalue of the first mode of vibration [2], the loss factor is determined by an expression similar to equation employed by Gibson and Plunkett [4]:

$$\eta_S = \frac{-\lambda_r \phi_r'''(0) \phi_r''(X_0) dV_0}{2L\omega^2 \epsilon(x)} \tag{2}$$

The maximum bending strain in the cantilever specimen occurs at the root of the beam, and is related to the measured longitudinal bending strain by the following expression [4]:

$$\epsilon_{max} = \epsilon(0) = \frac{\epsilon(X_0)\phi_r''(0)}{\phi_r''(x_0)} \tag{3}$$

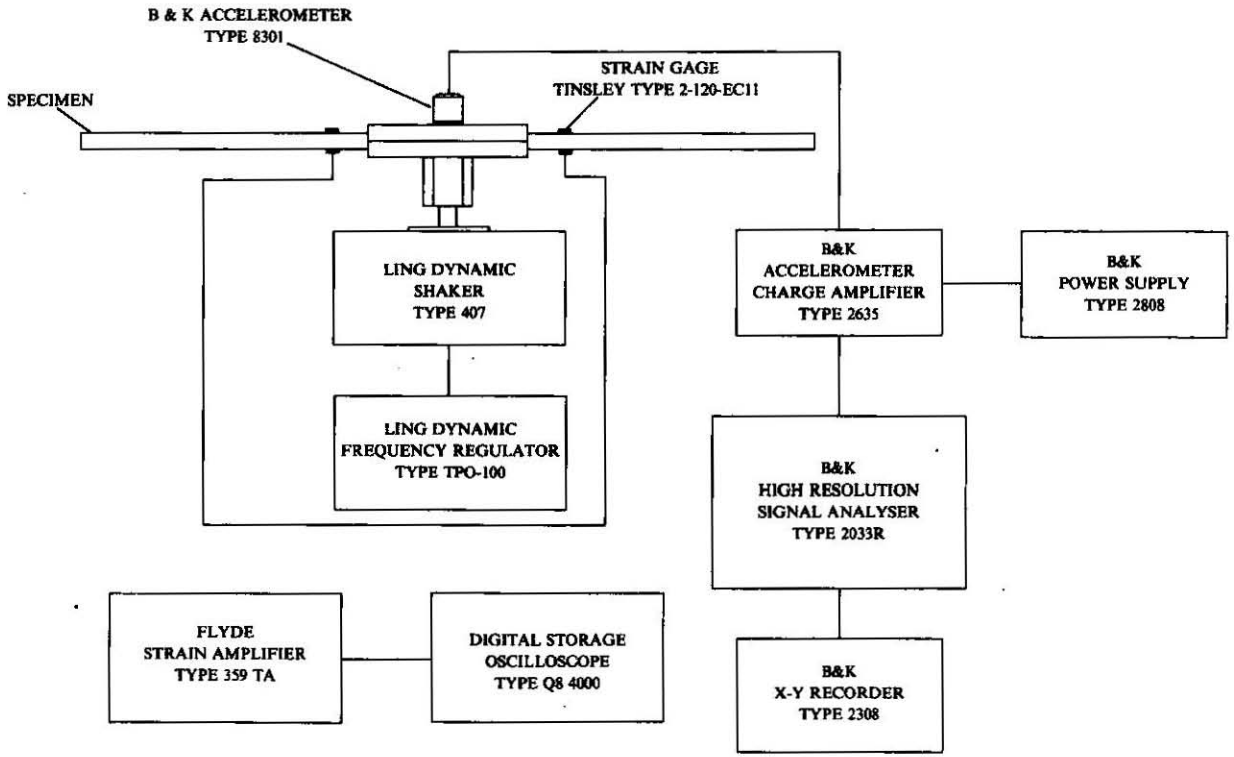

FIGURE 3. Block diagram of forced vibration apparatus

RESULTS AND DISCUSSION

Figure 4 shows the effect of the maximum strain amplitude ocurring at the root of the cantilever beam on the loss factor of the GFRC. The loss factor is independent of amplitude ranging from 120 to 420$\mu\epsilon$. These results were obtained by increasing the amplitude of vibration at constant frequency, and the loss factor for each measurement of strain was calculated applying equation 2.

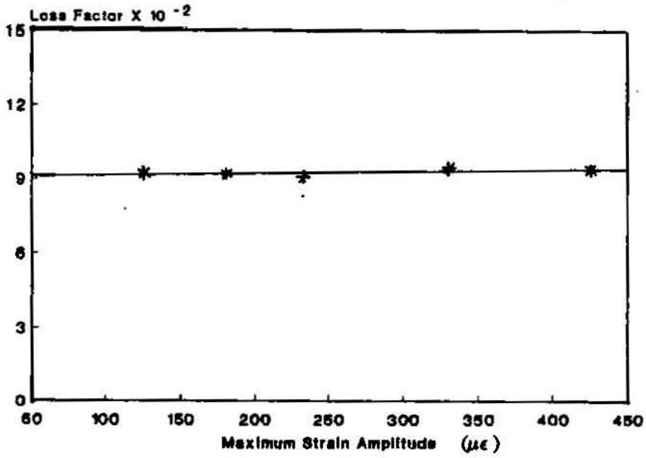

FIGURE 4. Dependence of loss factor on average strain amplitude

Stepanenko et al [14] who have investigated unidirectional laminates of continuous glass fibre-reinforced epoxy also indicated that the loss factor is independent of strain amplitude in the range of 250 to 3000$\mu\epsilon$. A similar result has also been obtained by Gibson and Plunkett [3] who studied the damping behaviour of E-glass fibre-reinforced epoxy resin for maximum strain amplitude up to 1000$\mu\epsilon$. It is important to study the effect of strain amplitude on the loss factor since the loss factor calculated using the decay method is only applicable if the loss factor is independent of the strain amplitude as indicated by Wright [16].

Figure 5 shows the variation of the loss factor with frequency in the range of 70Hz to 330Hz. It is obvious that the loss factor increases significantly as the frequency increases. The loss factor was found to increase by 160.98% in the frequency range indicated above.

The results in figure 5 has been fitted to an equation of the form,

$$\eta_s = A + Bf \qquad (4)$$

The coefficient B, which is the gradient ($\partial\eta_s/\partial f$), indicates the degree that the loss factor varies with the frequencies. The coefficient A and B are determined to be equal to 4.86E-3 and 4.92E-5Hz^{-1} respectively. Therefore, the loss factor of GFRC is related to the frequecy by the following equation,

$$\eta_s = 4.86E\text{-}3 + 4.92E\text{-}5Hz^{-1}f \qquad (5)$$

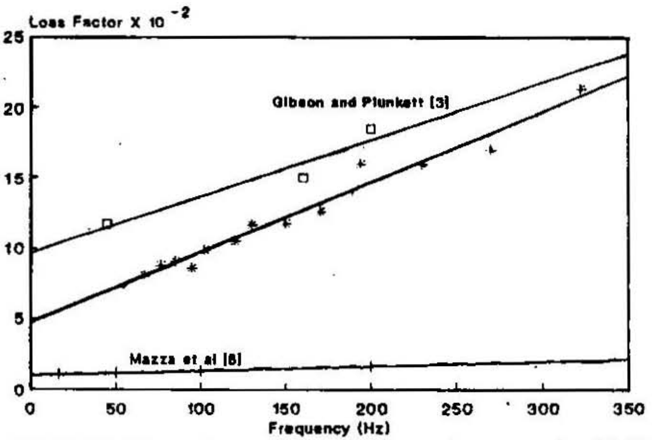

FIGURE 5. Dependence of loss factor on frequency for GFRC

The correlation coefficient of equation 5 is equal to 0.9667 which indicates that there is reasonable agreement with equation 4.

The results obtained in this work are compared with the results presented by Gibson and Plunkett [3] and Mazza et al [8]. The significant feature of this figure is that the loss factor for this test is 69.27% and 8.91% lower than the results acquired by Gibson and Plunkett [3] as the frequency increases from 70Hz to 320Hz respectively. Also, the loss factor presented by Mazza et al [8] is much lower than the loss factor found in this work. Specifically, the loss factor is 452.27% and 1022.83% higher than the results by Mazza et al [8] as the frequency changes from 70Hz to 230Hz respectively. The loss factor of Mazza et al [8] depends slightly on the frequency and does not increases as rapidly as the loss factor found in this work.

The specimens used by Gibson and Plunkett [3] were prepared from 51 unidirectional plies, each ply having a nominal thickness of 0.25mm. Mazza et al [8] used specimens prepared from single unidirectional ply having thickness of 3.175mm. The difference in the loss factor between these tests is most probably due to the fact that the materials were prepared by different manufacturing processes. The damping of the glass fibre-reinforced epoxy is not only caused by the viscoelastic behaviour of the resin but also caused by the sliding occuring at the fibre-matrix interface. Since the different manufacturing methods produced GFRC materials with dissimiliar fibre-matrix adhesion and interface, the local hysteresis loop produced are unlikely to be the same, and hence the variability of the loss factor.

Futhermore, the pultrusion technique used for manufacturing the GFRC rod is known to have a problem of not fully wetting all the fibres with epoxy resin. The existence of the unwetted fibres in the specimen introduces another internal friction damping between the fibres themselves. This friction along with the sliding at the fibre-matrix interface is likely to give greater damping in the rod specimen. This internal friction increases as the vibrational frequency increases.

A laminated structure is likely to contain more voids than a specimen prepared by the pultrusion technique and a single ply specimen, and consequently will have higher damping capacity because of the existence of the voids. Also the disparity among the loss factors might be attributed to the variation of the fibre volume fraction in each specimen. Unfortunately, Gibson and Plunkett [3] and Mazza et al [8] did not specify the percentage fibre volume content in their specimens. However, the fibre content does not play as significant a role as the structure of the specimens in determining the loss factor provided that the fibre volume fraction is larger than 40% [16].

Wright [16] has shown that the loss factor of glass fibre-reinforced polyester resin decreased by about 10% when the fibre volume fraction is increased from 40% to 70%. It is expected that the loss factor of glass fibre-reinforced epoxy resin will decrease by less than 10% since the loss factor of the polyester resin is larger than the epoxy resin [15]. For example, at a frequency of 60Hz, Lubin [7] reported that the loss factor of polyester resin is equal to 0.013 compared 0.012 for the epoxy resin. As the frequency increases to 300Hz, the loss factor of polyester and epoxy resin increases to 0.0212 and 0.0178 respectively [7]. The loss factor of GFRC manufactured from pultrusion process has relatively high damping although the fibre content in the composite is quite high, 74%.

CONCLUSION

The loss factor for the unidirectional pultruded gfrc is independent of the strain amplitude up to $420\mu\epsilon$. On the other hand, the loss factor increases significantly with the frequency as shown by the forced vibration tests. The loss factor increases from 0.075 to 0.214 as the frequency increases from 70 to 320Hz. The significant increases of the loss factor is due to the sliding at the fibre matrix interface and the internal frictional damping between the unwetted fibres. These results show that the unidirectional GFRC manufactured by the pultrusion technique has relatively high damping capacity eventhough the fibre volume fraction is relatively high.

NOTATION

A	Coefficient in best fit equation
B	Coefficient in best fit equation
D	Damping energy
J	Damping energy dissipated at unit stress amplitude
L	Specimen length
V_o	Voltage
d	Specimen diameter
f	Frequency
x	Distance along beam from fixed end
x_o	Distance along beam from fixed end to the centre of strain gauge
ϵ	Strain
η	Loss factor
λ_r	Eigenvalue of rth mode
σ	Stress

ϕ_r	Characteristic function describing beam-deflection curve
ω	Angular frequency

SUPERSCRIPTS

n	Damping exponent
''	Second derivation
'''	Third derivation

SUBSCRIPTS

a	amplitude
r	rth mode of vibration
s	Property refers to specimen

REFERENCES

1. Adams R.D., Fox M.A.O, Flood R.J.L, Friend R.J. & Heritt R.L. 1969. The Dynamic Properties of Unidirectional Carbon and Glass Fibre Reinforced Plastics in Torsion and and Flexure. *J. Comp. Mats.* **3**: 594 – 603.
2. Bishop R.E.D. & Johnson D.C. 1960. *The Mechanics of Vibration.* Cambridge: Cambridge University Press.
3. Gibson R.F. & Plunkett R. 1976. Dynamic Mechanical Behaviour of Fibre-Reinforced Composites: Mechanical and Analysis. *J. Comp. Mats.* **10**: 325–51.
4. —————— . 1978. Forced Vibration Technique for Measurement of Material Damping. *Exp. Mech.* **17**: 297–302.
5. Lazan B.J. 1978. *Damping of Material and Members in Structural Mechanic.* London. Pergamon Press.
6. Lin D.X., Ni R.G., & Adams R.O. 1984. Prediction and Measurement of Vibrational Damping Parameters of Carbon and Glass Fibre-Reinforced Plastics Plates. *J. Comps. Mats.* **18**: 132 – 152.
7. Lubin G. 1982. *Handbook of Composites.* London: Van Nostrand Reinhold Co.
8. Mazza I.T., Paxson Jr E.B. & Rodgers R.L. 1970. Measurement of Damping Coeffients and Dynamic Modulus of Fibre Composites, USAAVLABS Technical Note2, U.S. Army Aviation Material Laboratories, Ford Eustics, Virginia, February.
9. Nelson D.J. & Hancock J.W. 1978. Interfacial Slip and Damping in Fibre Reinforced Composites. *J. Mat. Sci.* **13**: 2429 – 2440.
10. Paxson Jr E.B. 1975. Real and Imaginary Parts of the Complex Viscoelastic Modulus for Boron Fibre Reinforced Plastics. *J.Acous. Soc. Am.*, **57**: 891 – 899.
11. Pulgrano D.J. & Miner L.H. 1983. Effects of Fibre and Resin on the Vibration Damping of Composites Reinforced with Fibreglass, Graphite and Aramid. 28th National SAMPE Symposium. 56 – 64.
12. Read B.E. & Dean G.D. 1983. *The Determination of Dynamic Properties of Polymers and Composites.* Bristol: Adam Higler Ltd.
13. Schultz A.B. & Tsai S.W. 1968. Dynamic Modulus and Damping Ratios in Fibre-Reinforced Composites. *J.Comp.Mats.* **2**: 368 – 379.
14. Stepanenko N.D., Kovenshnikov B.N., Gunyaev G.M. & Gumyantsev A.F. 1982. Anisotropy of the Damping Properties of Composite Materials. *Problemy Prochnosti.* 154 (in Russian).

15. Wallace M.M. & Bert C.W. 1979. Experimental Determination of Dynamic Young's Modulus and Damping of an Aramid-Fabric/Polyester Composite Materials, Proceedings of Oklahoma Academy of Science. **59**: 98–101.
16. Wright G C. 1972. The Dynamic Properties of Glass and Carbon Fibre Reinforced Plastics Beam, *J. S. and Vib.* **21**: 205 – 212.

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