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DAMPING EVALUATION OF STRUCTURAL CARBON REINFORCED COMPOSITES

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Abstract: *Carbon Fibre Reinforced Carbon Composites are a class of advanced materials that are being used in the aerospace industry. They are intended to be used as structural materials under varying loading conditions. As a result their dynamic mechanical properties are fundamental characteristics besides strength parameters. The non-destructive character of the dynamic test make it the ideal tool for monitoring the development of mechanical properties during material processing. This work reports vibration experiments conduced on different types of composites made with carbon fibre fabrics. The first was a composite made with a commercial plain weave fabric, in which carbon fibres were heat treated at* 1500^{o}*C. The second composite was made with a twill weave fabric, in which carbon fibres were heat treated at a temperature below* 1000^{o}*C. The fabrics were moulded with phenolic resin, and carbonised. Free vibration testing was conduced in the as-moulded and in the carbonised samples. A decrease in storage modulus was observed for both plain and twill weave fabric composites due to an overall increase in composite porosity. A pronounced decrease in loss modulus and Tan* δ *was observed for the plain weave carbonised composite in relation to the as-moulded composite. This trend was not followed by the twill weave carbonised composite since additional internal friction sites, due to poor fibre/matrix adhesion, were created.*

Key-words: *Composites, Carbon Reinforced Carbon Composites, Vibration Damping, Carbon Fibres.*

1. INTRODUCTION

The fabrication process of Carbon Fibre Reinforced Carbon (CRFC) composites is rather complex, involving carbonisation of a matrix precursor followed by a densification process which results in improved properties of the composite in terms of density, modulus, strength, and adhesion between the carbon fibre and the matrix. These CRFC composites are intended to be utilised as structural material under varying loading conditions. This makes their dynamic mechanical properties the important characteristics besides commonly used parameters (e.g., strength or Young's modulus).

The non-destructive character of the dynamic test and low levels of the applied load allow repeating the tests on the same specimen and thus make the dynamic modulus measurement an ideal tool even for monitoring the development of mechanical properties during material processing (heat treatment, densification, etc.).

Four primary mechanisms have been suggested to contribute to damping in composites (Jang – 1994): (a) viscoelastic response of the constituents, (b) friction at the fibre-matrix interface, (c) thermoelastic damping due to cyclic heat flow, and (d) damage initiation and growth. The damping ratio of a composite is dictated primarily by the viscoelastic or microplastic phenomena in the matrix and relative slipping at the fibre-matrix interface. Other mechanisms are the relative proportions of the matrix and the reinforcement, dimensions of cracks and voids, orientation of the reinforcement with respect to the loading axis, and surface treatments of the reinforcement

Testing parameters and environmental factors such as amplitude, frequency, and temperature will also affect both the dynamic modulus and the damping values of a composite. The resonant frequency has been used as a parameter for detection of localized defects in carbon fibre/epoxy composites and also to evaluate quality of the adhesion between fibre/matrix (Ni – 1984, Wu – 1998)

The anisotropy in bi-directional CFRC composites enables one to measure the elastic properties of specimens cut at various angles to the main fabric axis (warp). It was observed that while the longitudinal Young's modulus depended mainly on the fibres, the shear modulus was governed additionally also by matrix and interface.

In the case of CFRC composites. carbonisation of the matrix precursor is an important stage which has been found to result in changes in the mechanical properties of the base composite. But the information related to resonant frequency and material damping characteristics of this material is rather scarce when considering the type of fabric used in the composite manufacture, fibre volume fractions and final heat treatment temperature.

Thus, the purpose of the present work was to investigate how CRFC composites and their mother material counterparts behaves during vibration damping. The vibration characteristics and parameters obtained from the damping tests showed that for the two composites made with different types of fabrics after carbonisation not necessarily increases damping, i.e., Tan δ, due to effects related to fibre volume fraction and modification of fibre structure.

2. EXPERIMENTAL

2.1 Materials

Two types of composites were prepared by using two types of textile fabrics. The first one was a plain fabric, made with 3000 tow PAN-based carbon fibres. A plain fabric, Figure 1A, is the simplest weave pattern characterised by a frequent exchange of position from top to bottom of made by each yarn. The carbon fibre of the plain fabric has a density of 1,75 g/cm^3, T-300 (Toray Co.), and the areal weight of this fabric was 195 g/m^2. The second fabric was a basket type twill 2x1 woven fabric made also with PAN-based carbon fibres tow. Each two fibre tows from the fill direction crosses over and under one fibre tow from the warp direction, Figure 1B. The carbon fibre of the Twill 2x1 fabric has a density of ~1,55 g/cm^3., and the areal weight of this fabric is 340 g/cm^2. It was measured that Twill 2x1 fabric exhibited a weight loss of ~10% after heat treatment to 1000 ^{o}C, and the carbon fibre increases density for ~1,65 g/cm^3 (Nohara – 1998). The selection of a weave involves manufacturing considerations as well as final mechanical properties.

Each composites was moulded using a resole phenolic resin Resafen 8121 as a carbon matrix precursor and using 8 fabric plies. Cure of the phenolic resin was done by multistage heating cycle up to 180^{o}C final cure temperature. The as-moulded composites were designated as ***CFRP-Plain*** and ***CFRP-Twill***. After curing the composites were trimmed in appropriate prismatic shaped specimens (250 mm long, 15 mm wide) for dynamic vibration testing. One batch of these specimens was submitted to carbonisation up to 1000^{o}C in inert atmosphere (nitrogen) and were designated as **CFRC-Plain** and **CFRC-Twill**. After carbonisation all composites experiment a ~20% weight loss. Twill weave composites were tested in warp direction. Table 1 shows weight fractions and volume fractions for both as-moulded and carbonised composites.

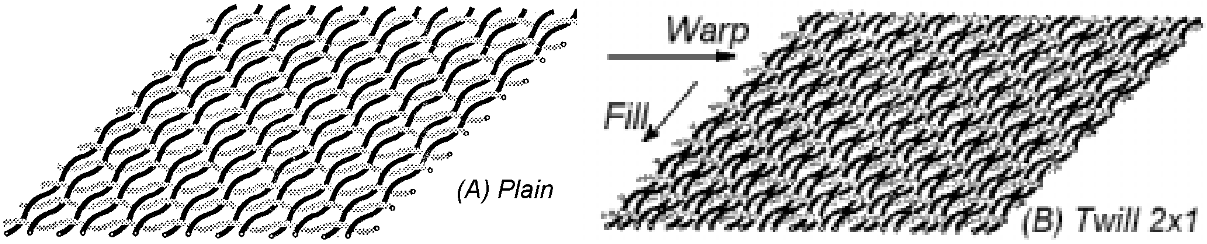

Figure 1 – Weave patterns of fabrics used in this work for composites.

Table 1. Results for fibre and matrix volume fraction for moulded and carbonised composites.

	Plain		Twill 2X1	
Composite ⇒	*CFRP*	CRFC	*CFRP*	CRFC
Fabric areal weight (g/m^2)	195	195	340	306
Composite density (g/m^3)	1,40	1,10	1,26	1,19
Fibre weight fraction(%)	56,4	67,0	75,0	83,0
Resin weight fraction (%)	42,5	-	25,0	-
Fibre volume fraction (%)	45,0	42,0	60,0	58,0
Resin volume fraction (%)	47,6	-	23,0	-
Carbon matrix volume fraction (%)	-	29,0	-	13,5
Void Volume fraction (%)	7,4	29	13,0	28,5

2.2 Testing set-up

A dynamic test involves quantitative measure of the effect of a vibratory force on a structure. Measurement of the exciting force, and the resulting motion in the resonant frequency, provides useful information regarding damping behaviour of the material. Damping is often expressed in terms of quantities conveniently obtained with the type of instrument used. In this work it was used the free vibration technique. In this test one of the ends is clamped and in the other an accelerometer is attached and is submitted to a free vibration, as shown schematically in Figure 1. The decay function is found by tapping the specimen with a small metal bar.

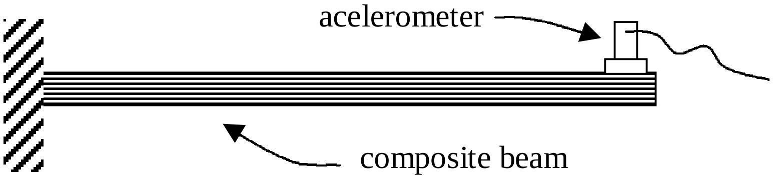

Figure 1 – Experimental set-up for flexural vibration of composite beam.

The succesive amplitudes Xi decrease, as shown in Figure 2, because of the gradual dissipation of the elastic energy into heat. The resonance frequency is dependent on the specimen dimensions, density variation and the frequency resolution of the analyser.

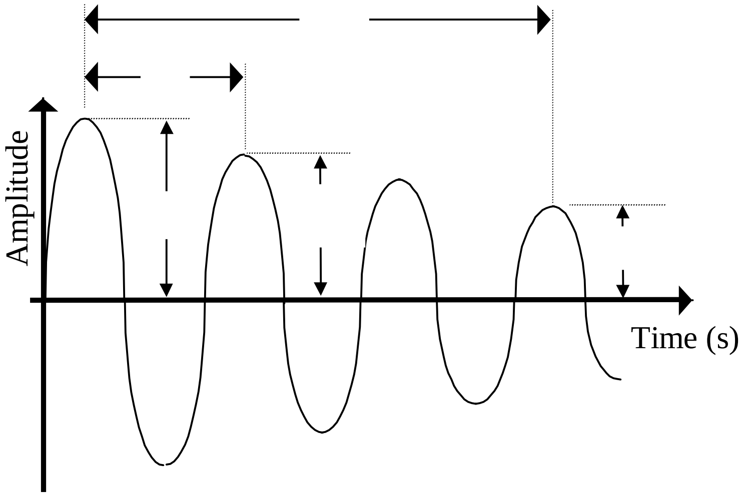

Figure 2 - Typical damping oscillation curve.

The logarithmic decay is defined by:

$$\Delta = \ln \frac{X_1}{} = \ln \frac{X_2}{} = \frac{1}{} \ln \frac{X_1}{} \tag{1}$$

At low damping (Δ <1) it is related to the dissipation factor approximately by (Hertzberg , 1976):

$$\Lambda \simeq \pi \frac{E''}{} \tag{2}$$

where E” is the loss modulus and E’ is the storage modulus.

In this work a Brüel Kjaer Vibration Analyser type 2515 was used where a Brüel

Kjaer accelerometer type 4375 was attached. The modulus was determined from the formula:

$$E' = \frac{4.\pi^2.f^2}{3.I}\left[M + \frac{33}{140}.m\right].L^3.\left[1 + \frac{\Delta^2}{4.\pi^2}\right] \tag{3}$$

where:

f = natural frequency, I = inertia moment of the beam ($I=b.h^3/12$), M = mass of the beam under vibration, m = mass of accelerometer , L = length of the beam specimen, Δ = logarithm decay

The loss coefficient can be calculated by:

$$\eta = \tan\delta = \Delta/\pi = E''/E' = 2\zeta \tag{4}$$

The damping factor is expressed by:

$$\zeta = \frac{\Delta}{\sqrt{(\Delta^2 + 4\pi^2)}} \tag{5}$$

The points of the decay curve where fitted to the following equation using Microcal Origin 5.0 software:

$$y = Ae^{-x/t_o}\ \mathrm{sen}\left(\pi\frac{x - x_c}{w}\right) \tag{6}$$

3. Results and Discussion

The results for resonant frequencies, damping ratio, storage and loss modulus and Tan δ are shown in Table 2.

Table 2. Results for free vibration damping of composites made with plain and twill weave fabrics

Fabrics ⇒	Plain		Twill 2x1	
Composite⇒	***CFRP***	**CFRC**	***CFRP***	**CRFC**
ρ (g/cm^3)	1,40	1,15	1,26	1,19
Beam dimension (mm)	150x15x1,8	150x14,8x2,3	217x20x3	212x15x4
Resonance Frequency (Hz)	40	43,2	29,6	36,8
Period (10^{-3} s)	24,4	23,2	34	28,1
Δ	0,1780	0,0502	0,07084	0,03764
E’ (GPa)	35,0	19,2	17,5	13,5
E’’ (GPa)	1,95	0,3069	0,39	0,32
η (Tan δ)	0,0566	0,01598	0,0225	0,0240
ζ	0,0283	0,00799	0,01127	0,012

Both plain and twill fabrics have maximum kinks in the fibre bundles, i.e., the density of cross over kinks in these fabrics is much higher than any other fabric used for structural composites (Manocha & Bahl , 1988). During moulding the impregnated matrix usually gets deposited in the space between the two parallel tows Resin matrix entrapped between the sharp cross over bundles from both fabrics can as consequence give rise to a lot of porosity of closed nature. The amount of porosity generated after carbonisation depends not only on fibre kinks but also on many other parameters, such as fibre/matrix adhesion, curing cycle, etc. For the composite made with the Twill weave fabric there is also a weight loss related to the fibre which is another factor influencing the increase in porosity.

The main parameters that influences the damping characteristics of these composites are type of carbon fibre used, fibre volume fraction and fibre/matrix interactions and type of fabric weave. The fibre used in the plain composites is a standard commercial carbon fibre which have a higher strength and modulus than the fibre used in the twill weave fabric. As a consequence the *CFRP-Plain* composite have a higher storage modulus (E'), Table 2, than the CFRP-Twill composite. However the higher volume fraction of fibres in the CFRP-Twill composite resulted in a lower loss modulus, which in turn resulted in a lower Tan δ, compared to the *CFRP-Plain* composite.

During pyrolysis and carbonisation of carbon phenolic composites, inevitable resin shrinkage and composite thermal expansion mismatch lead to microstructural defects, such as microcracking and porosity. These defects are in fact energy absorbing sites which certainly influences the damping parameters.

Figure 3 shows decay curves for Plain and Twill weave composites. In general carbonised composites have lower damping amplitudes and higher resonant frequencies, and as consequence, a lower storage modulus than their as-moulded counterparts, see Table 2. Note that fibre volume fraction for both as-moulded and carbonised Plain composites (~40%/volume) are virtually the same, and as so for Twill composites (~60%/volume). Surprisingly, for the CFRC-Twill composite higher amplitudes in the decay curve are observed in relation to the as moulded one, *CFRP-Twill*. The most probable explanation for this is that after carbonisation not only a large number of porosity is created due to resin pyrolysis, similarly to the CFRC-Plain composite, but also other energy dissipating mechanisms are formed, mainly in between fibre/matrix interface. The fact that loss modulus (E") and Tan δ from both *CFRP-Twill* and CFRC-Twill have almost the same value corroborates with the idea of a more pronounced effect of internal friction related to fibre/matrix interface. Results from flexural tests for CFRC-Twill showed flexural modulus in the same magnitude of the one found by damping test (Pina – 1996).

Table 3 shows the parameters of the equation (6) for the composites studied. The χ^2 test for the data found are in good agreement between observed and expected results.

Table 3. Parameters fitted for equation (6)

Fabric ⇒	Plain		Twill	
Composite ⇒	*CFRP*	CFRC	*CFRP*	CFRC
x_c	100	101,5	-60	114
w	12	11,5	17	14
t_o	80,5	500	636,5	806,5
A	1515,5	-124,5	116,5	77,5

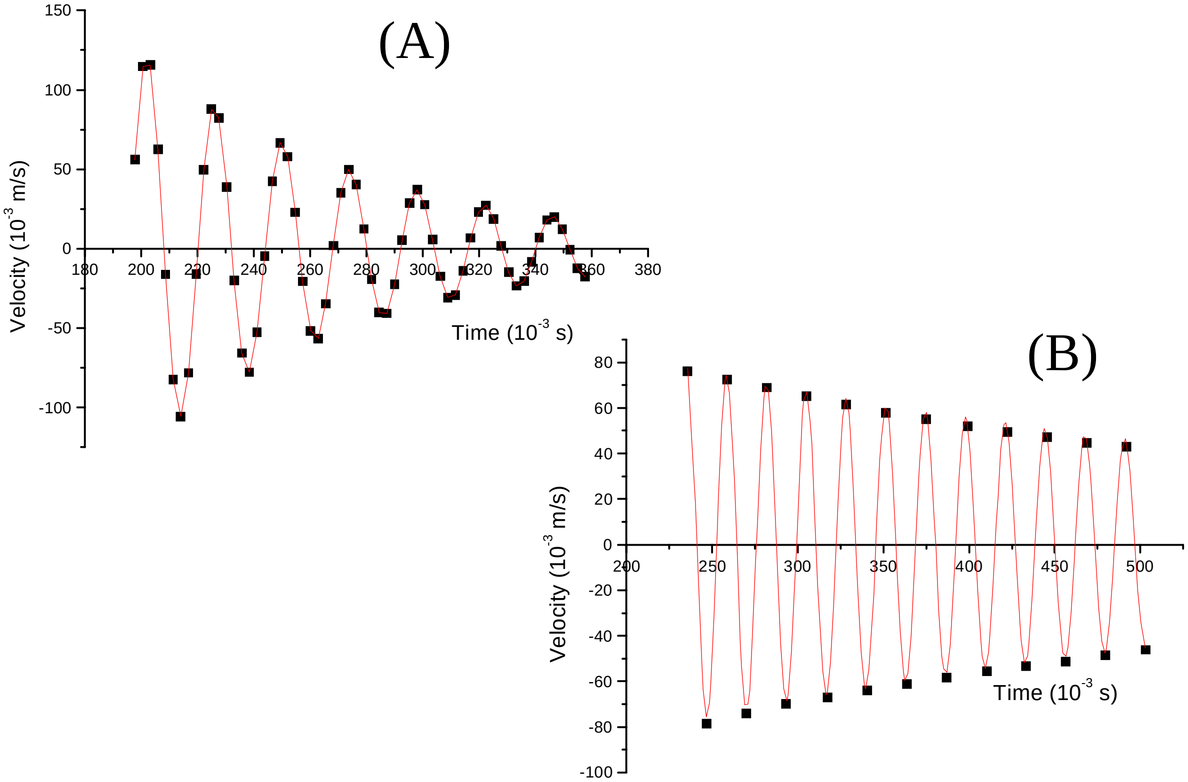

Figure 3 – Damping curves for Plain weave fabric composites.
(A) Moulded (*CFRP*), (B) Carbonised (CFRC).

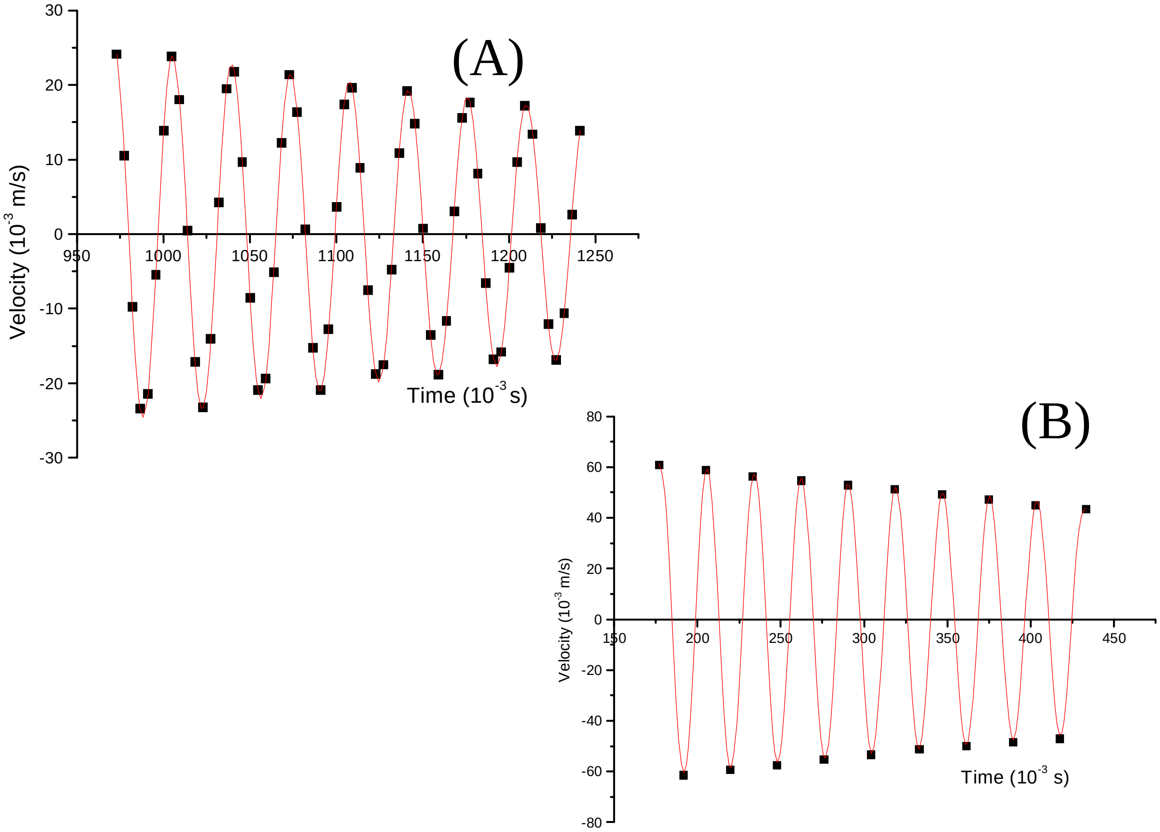

Figure 4 – Damping curves for Twill weave fabric composites.
(A) Moulded (CFRC), (B) Carbonised (CFRC).

4. Conclusion

Vibration damping technique gives a very good assessment of mechanical properties of composites. Basic properties of the fibre and matrix influence the ultimate properties of carbon fibre phenolic composites and carbon fibre reinforced carbon composites. In general, for composites using commercial carbon fibres (heat treated at ~1500 ^{o}C) there is a decrease in storage modulus, loss modulus and Tan δ due to an increase in porosity after carbonisation. For composites having low strength carbon fibres (heat treatment lower than 1000 ^{o}C) there is also a decrease in storage modulus after carbonisation due to an increase in the overall porosity of the composite, but this was not sufficient to decrease the loss modulus and Tan δ due to addition weight loss of the carbon fibre which in turn causes a higher magnitude of internal friction. The establishment of damping characteristic of carbon fibre reinforced carbon composites would help design structures for high temperature applications with desired levels of damping, and where mechanical properties are not the sole criteria in design.

Acknowledgements

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