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DYNAMIC MECHANICAL PROPERTIS OF WOVEN CARBON FIBRE REINFORCED THERMOPLASTIC COMPOSITE MATERIALS

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ABSTRACT

The aim of this research is to investigate the dynamic mechanical properties of woven carbon fibre reinforced poly ether ether ketone (PEEK) using both experimental and numerical methods. Studies are carried out over a range of temperatures and dynamic strain rates.

A numerical model is developed to predict the response of the composite under mechanical loading. The finite element method is employed to develop a suitable three-dimensional representative volume element (RVE) to predict the Young's modulus and the effective loss factor for the woven composite material. The model allows slip between the bundles of carbon fibre and the polymer; hence the effects of bond strength are studied. The results show that the stiffness increases with friction gradually, and the loss factor increases up to a value of 0.5 for the coefficient of friction. The polymer is modelled using hyperelastic and viscoelastic behaviour which allows analyses to be carried out near the glass transition temperature.

Experimental dynamic mechanical analysis carried out on the composite specimens show that the Young's modulus decreases and the loss factor increases with increasing amplitude. At higher temperatures, an increase in the loss factor, a decrease in the stiffness and greater ductility are observed. In flexural tests an increase in ductility, reduction in modulus and higher resistance to failure are noted with increasing temperature from 25 ℃ to 150 ℃.

The comparisons between numerical and experimental results show similar trends for the modulus and loss factor with temperature.

1 INTRODUCTION

Woven carbon fibre composite materials are receiving more interest in many areas of engineering due to ease of manufacture (even for components with complex shape) and ease of orientation allowing designers to set stiffness and strength in desired directions. For these reasons, woven fibre composites are often cheaper than other types of composites. However, the fibre structure can lead to "unexpected" delaminations, interlaminar stresses and cracks [1, 2].

Several works have been conducted on woven composite materials. Vieille et, al. [3] reinforced poly ether ether ketone (PEEK), PPS and epoxy separately with woven carbon fibre to investigate the effects of the polymer matrix on the failure mechanism under low velocity impact. They found that the matrix has a great effect on the intra-ply damage and delamination with a tougher matrix providing better impact performance. Goertzen et.al [4] have studied the viscoelastic behaviour of woven carbon fibre/epoxy under the effects of temperature and frequency. They indicated that increasing temperature of cure caused increase in the glass transition temperature (T_g) and decrease in loss factor.

Finite element analysis along with the representative volume element (RVE) approach was used to predict the elastic modulus for 3D woven composites with using both the microscopic repeated unit cell (RUC) model for yarn, and mesoscopic-repeated unit cell model for woven composite, and they found good agreement with experimental results [5].

Most researches relating to the strength of woven composite materials are related to impact and interlaminar stresses. However, a few numerical studies using RVEs have been performed to determine the elastic modulus. However, these have not considered the effects of temperature and dynamic strain amplitude for composites of woven carbon fibre.

The aim of this research is to find, experimentally and numerically, the dynamic mechanical properties over a wide range of temperatures, frequencies and amplitudes for woven carbon fibre reinforced thermoplastic polymer.

2 EXPERIMENTAL WORK

2.1 Material and processing

Two kinds of materials used in this paper, plain PEEK and woven composite materials. Both of them prepared in different process.

2.1.1 PEEK material

Test specimens were prepared from granulated PEEK (Victrex type 150p). These were first dried for 120 minutes at 150°C. Melting was carried out at 400°C and a pressure of 550 bar. The material was then injected into a heated mould 200°C and then allowed to cool to ambient temperature for 10 min. to get the solidified specimens.

2.1.2 Woven composite material

The materials studied were laminated sheets of semi-crystalline PEEK reinforced with woven carbon fibre fabric. The material was provided by TenCate, and it is CD0286/PEEK powder coated semi-preg. The laminate is balanced and symmetric in a [(0/90)/(+/-45)] 2s configuration.

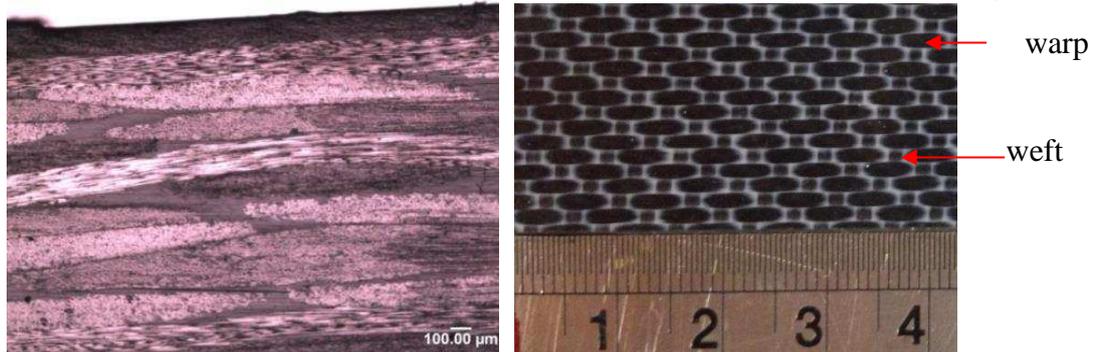The woven composite fabric is of 7 plies of overall thickness about 4.5mm, as shown in (Fig 1).

Figure1: plain weave composite material.

2.2 Scanning Electron Microscope (SEM)

To investigate the effectiveness of the consolidation process for the woven carbon composite material, SEM images were taken for specimens. For that purpose, the surface of the composite material was polished. Then the specimen was coated with gold by using sputter coater Emscope SC500A. After that, the equipment FEI Inspect F. was used to get some SEM images as shown in (Fig. 2).

It is noted that the adhesion of the matrix to individual fibres is relatively good. However, some fibres remain unwetted.
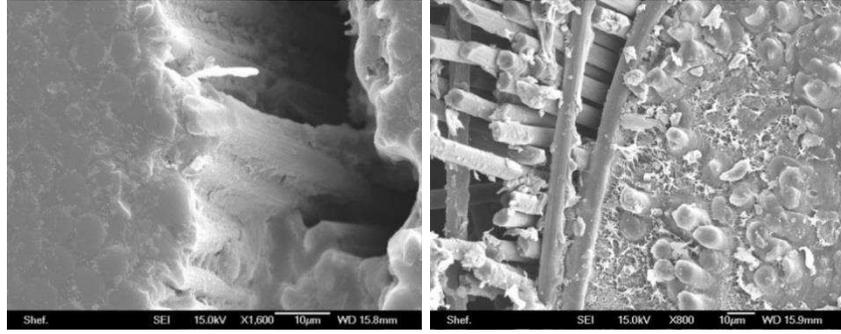
Figure 2: SEM images of woven composite material specimens.

2.3 Flexural Test

Flexural three point bending tests were carried out on the woven composite specimens using a MTS 858 Table Top hydraulic test machine. The specimens were rectangular with dimensions shown in (Table 1). The test was conducted at a steady displacement rate of 1.075mm/min and temperatures of 25 °C and 150°C. Load-deflection curves are presented in (Fig. 3).
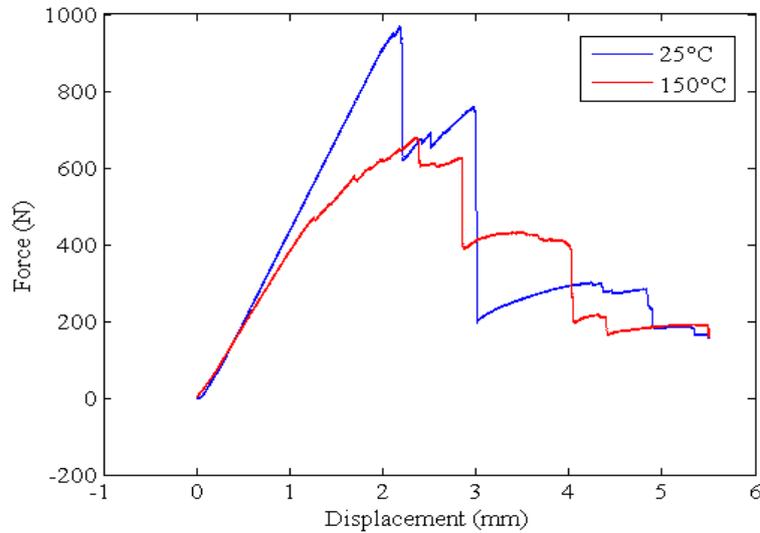

Figure 3: Force-displacement behaviour for woven composite material.

To find the Young's modulus and the maximum stress from the force-displacement test the following formulas were used:

$$\sigma_f = \frac{3FL}{2bd^2} \tag{1}$$

$$E_f \frac{mL^3}{4bd^3} \tag{2}$$

where, σ_f is stress in outer fibres at midpoint, E_f is flexural modulus of elasticity, F is load at a given point on the load deflection curve, L is the support span, b is widthand d is depth of tested beam, D is maximum deflection of the centre of the beam, m is the gradient (i.e. slope) of the initial straight-line portion of the load deflection curve.

Temperature	Thickness (t)	Width (w)	Length (L)	Young's modulus (E)	Maximum stress
°C	mm	mm	mm	GPa	MPa
25	2.48	12.7	40	30.2	798
150	2.48	12.7	40	25.5	564

Table 1: woven composite specimen properties used in flexural tests.

The test results show that the material at temperature 25°C is stiffer than when it is at 150°C, and possesses higher resistance to failure. However, is more brittle.

2.4 Dynamic mechanical analysis test (DMA)

Testing was carried out on the woven composite materials to investigate their stiffness and damping at different temperatures and dynamic strains. For that purpose, the Metravib Viscoanalyser VA2000 system was used for conducting two types of tests: temperature sweep test and strain sweep test. The specimens for DMA tests are of dimensions as in (Table 2).

No.	Test name	Length (mm)	Width (mm)	Thickness (mm)
1	Temperature sweep test	45	4.06	2.39
2	Strain sweep test at 25°C	45	3.25	2.38
3	Strain sweep test at 160°C	45	3.85	2.4

Table 2: DMA specimen dimensions.

2.4.1 Temperature sweep test

Temperature sweep testing was carried out on the woven composite material specimens that shown in Table. The stiffness of the material meant that the specimens could not be tested in tension-compression mode on this machine. Instead, the specimens were tested by three point bending under a load conditions of dynamic strain of 0.001, frequency of 1Hz and temperature environment range from 25°C to 230°C with a step of 3°C. The test results are shown in (Fig. 4) and (Fig.5). As the temperature rises, it can be seen that the modulus decreases. The damping rises and falls, reaching a maximum around150 °C near the glass transition temperature.
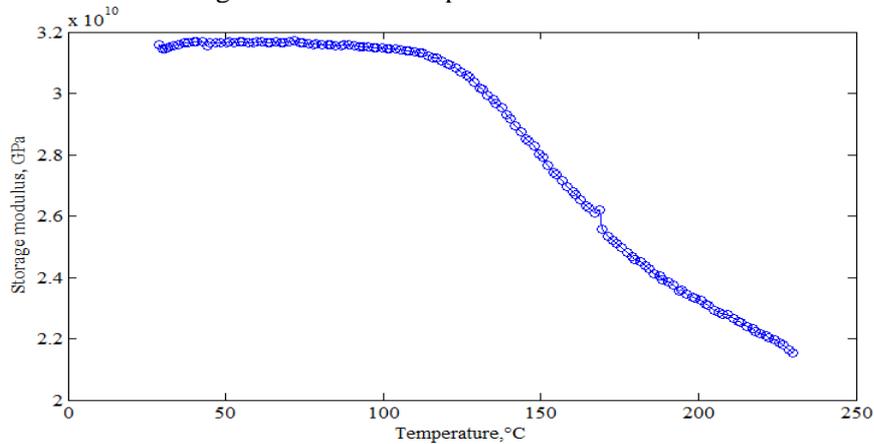

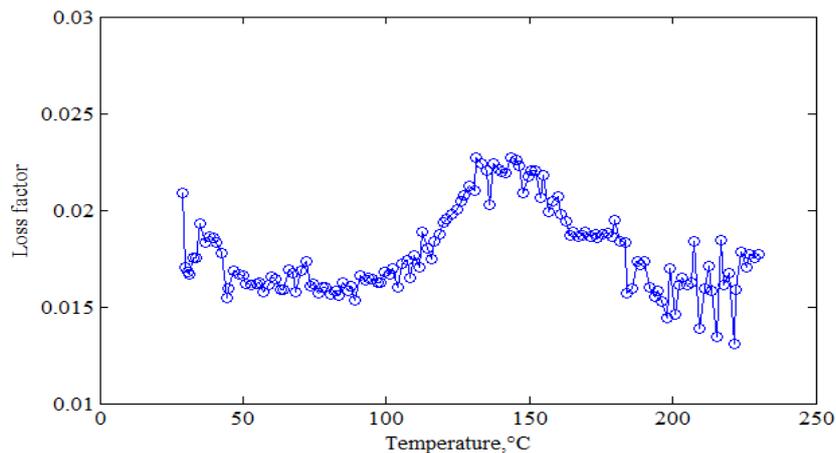Figure 4: Effects of temperature on flexural modulus for woven composite material.

Figure 5: Effects of temperature on loss factor for woven composite material.

2.4.2 Strain sweep test

The modulus and damping behaviour at different amplitudes for woven composite material specimens were found by strain sweep tests. Three point bending tests were carried out to the specimens that shown in (Table 2). The tests were conducted under loading conditions of frequency 1Hz and at two temperatures room temperature of 25 ºC and glass transition temperature of 160ºC. The effects of dynamic strain amplitude on the modulus and loss factor are shown in (Fig. 6) and (Fig.7).
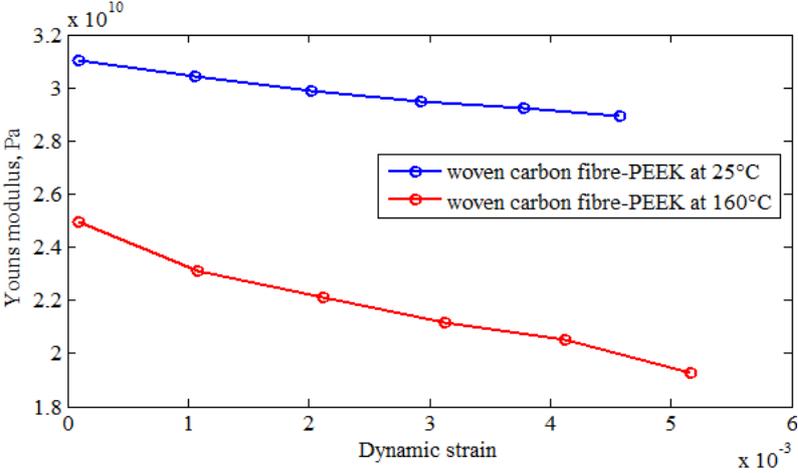

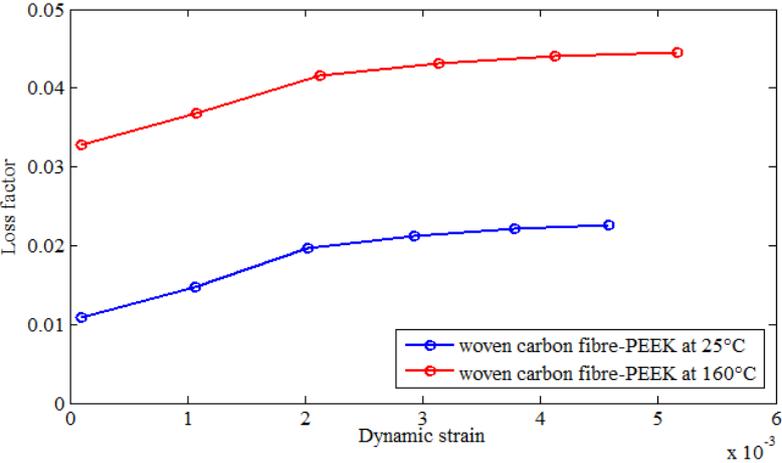Figure 6: Strain sweep modulus results for woven composite material.

Figure 7: Strain sweep loss factor results for woven composite material.

It can be observed that the modulus decreases somewhat with dynamic strain while the loss factor rises. It can also be observed that the modulus at 160°C is much lower than at 25°C but the loss factor is higher.

2.5 Master curve for PEEK

Dynamic mechanical analysis was carried out on plain PEEK specimen of bar of length L=33.7mm, width w=6 mm and thickness t=3.04 mm. The test was conducted under condition of dynamic strain rates of 0.001, environment temperature from 25°C to 280 °C in 5°C steps and frequencies from 1 to 31.6 Hz in 7 logarithmic steps. From this test Young's modulus and loss factor were found. Also, viscoelastic master curve was obtained as shown in (Fig. 8). From the master curve modulus and loss factor at any temperature and frequencies could be found.
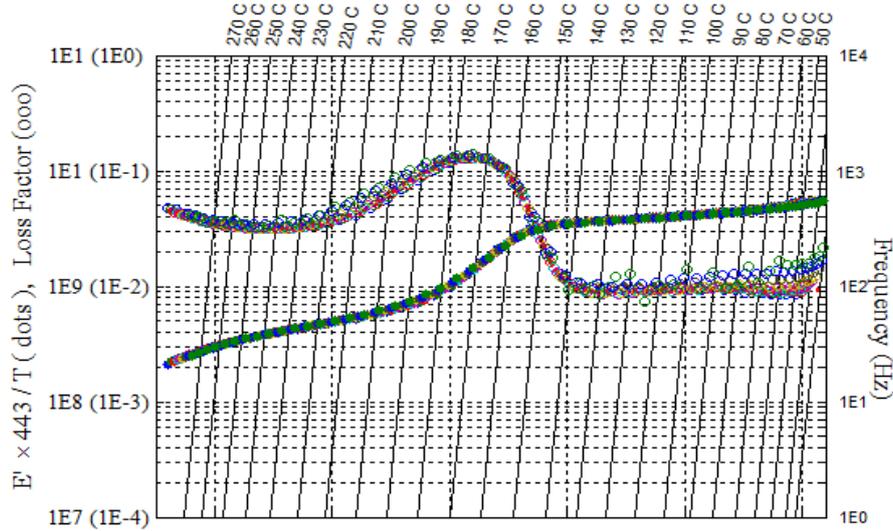
Figure 8: master curves for neat PEEK.

3 NUMERICAL STUDY OF WOVEN COMPOSITE MATERIALS

The Representative Volume Element (RVE) approach was used to predict the mechanical properties of composite material of woven carbon fibre reinforced PEEK.

3.1 Elastic analysis

The RVE is the smallest model of material that can be used to find the effective properties for the homogenized macroscopic model, and it should be large enough to contain the information about that model [6]. The generation of the RVE depends on the microstructure of the heterogeneous material. The RVE approach was developed in this work for woven composite material with considering the principles of material periodicity for the fibres and boundary condition periodicity for the unit cell, as in the following equations:

$$u_1\left(x, \frac{y}{2}, z\right) = 0 \quad , u_1\left(x, \frac{-y}{2}, z\right) = 0 \tag{3}$$

$$u_2\left(\frac{x}{2}, y, z\right) = 0 \quad , u_2\left(\frac{-x}{2}, y, z\right) = 0 \tag{4}$$

$$u_3\left(x, y, \frac{z}{2}\right) = 0 \quad , u_3\left(x, y, \frac{-z}{2}\right) = \Delta L \tag{5}$$

where, u is displacement in the unit cell.

The woven composite unit cells involved representing each bundle of carbon fibres forming warp and weft strands as a single geometry entity within a matrix of PEEK. Four different sizes of unit cells were chosen with six different types of each size. For each size, the woven bundle fibre distribution in the unit cell is different, as shown in Figures 9-12. All the unit cells are of the same volume fractions and bundle carbon fibre dimensions.
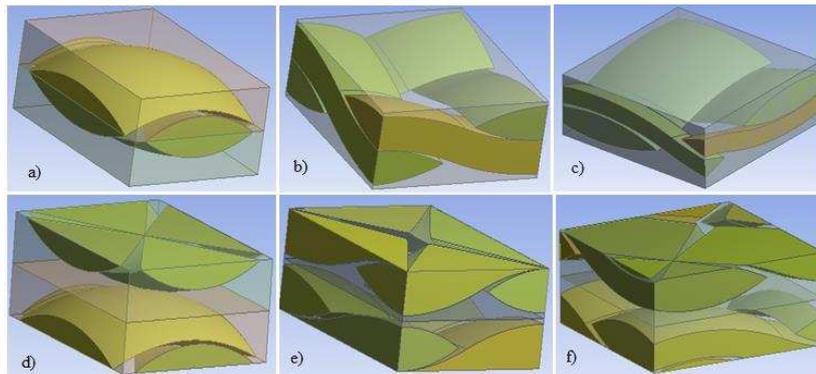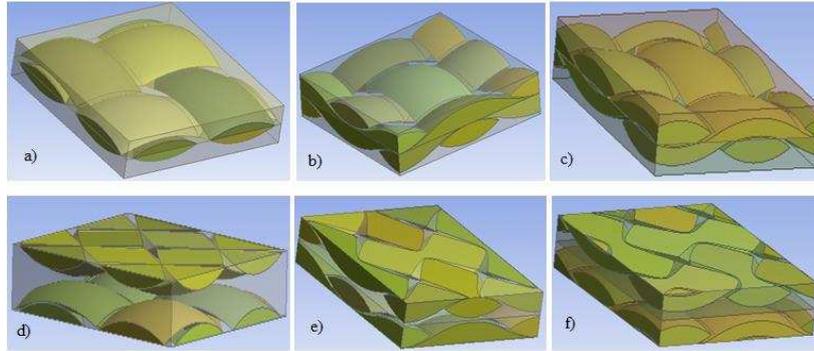

Figure 9: Unit cells of size 1.
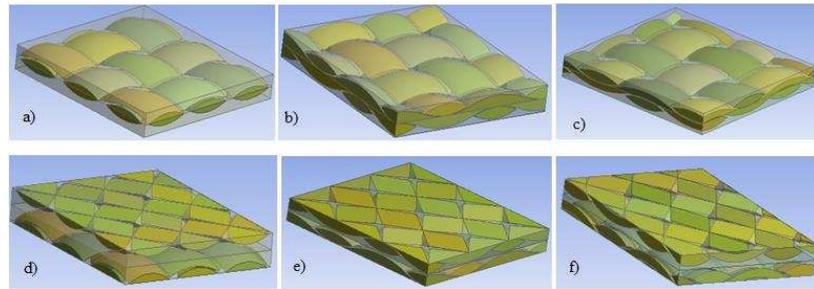
Figure 10: Unit cells of size 2.
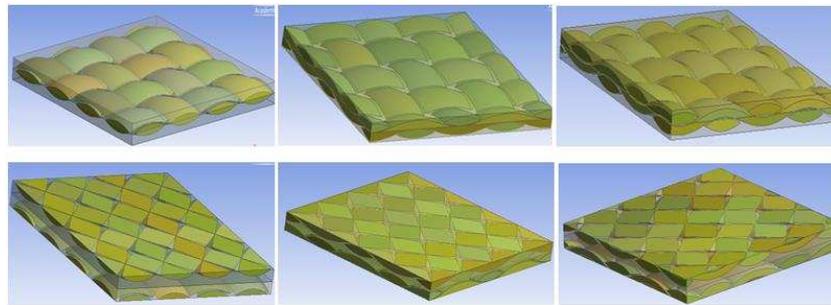

Figure 11: Unit cells of size 3.

Figure 12: Unit cells of size 4.

The geometry, dimensions and volume fraction for the fibres were estimated from microscope images. The dimensions for the unit cells are shown in (Table 3). The dimensions for the carbon fibre bundles are as in Fig.13 with L=1mm, V=0.2mm, R=1.3mm, We=1mm, SWe=1.2mm, SWa=1.2mm and Wa=1mm. Also, the carbon fibre volume fraction was fixed to the ratio of 48% for all unit cells.

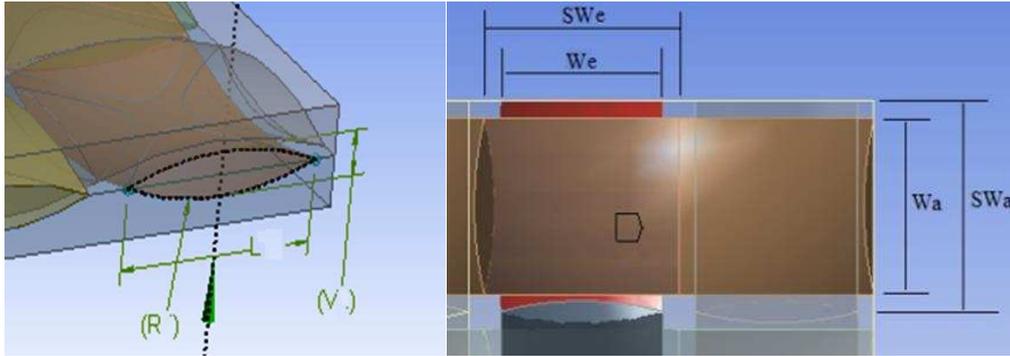| Unit cell size	Length (mm)	Width (mm)	Thickness (mm)
Size 1	1.2	1.2	0.45
Size 2	2.4	2.4	0.45
Size 3	3.6	3.6	0.45
Size 4	4.8	4.8	0.45

Table 3: Unit cells dimensions.

Figure 13: Representative volume element geometry.

The mechanical properties for the materialsare shown in (Table 4).

material	Poisson ratio	Young's modulus (GPa)	Density (kg/m^3)
Carbon fibre	0.23	240	1750
PEEK	0.42	3.9	1320

Table 4: Unit cells contents mechanical properties.

Modelling was carried out using the Ansys Workbench environment. Unit cells were meshed using 10 node tetrahedral (SOLID187) elements. At the connected region between the fibre and the matrix, the higher-order contact elements CONTA174 and TARGE170 were used. The average aspect ratio for more than 96% of the elements was 1.19. The meshing for the unit cell is shown in (Fig. 14).
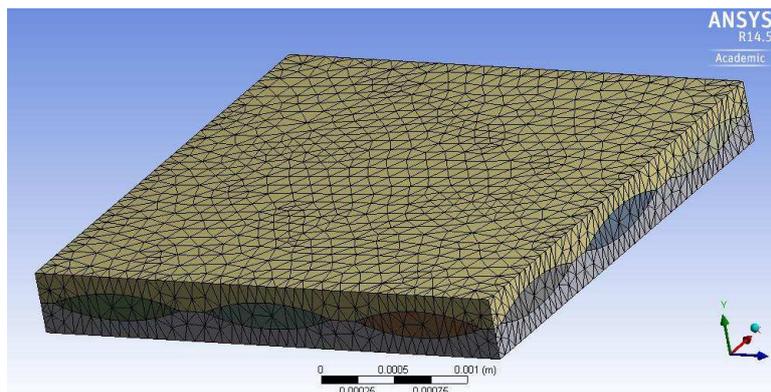

Figure 14: Meshing woven composite unit cell.

Also, the analysis was carried out with assumption of full bonding between carbon fibre bundles and the matrix and frictionless contact between fibres bundles. The curve fitting method for calculating Young's modulus of different homogeneous material was used to obtain the modulus for each unit cell. Results are summarised in (Table 5).

From the unit cells, Young's modulus was calculated for each unit cell size. Also, chi square, which is a method used to check how closely data fits to expected behavior, was found. The chi square values for the unit cells were compared with chi square confidence of 95% to obtain the representative volume element for woven composite materials, as in (Table 5).

size No.	Modulus (GPa)							Chi square	
	model (a)	model (b)	model (c)	model (d)	model (e)	model (f)	average	χ^2	χ^2 (95%)
size1	33.78	34.53	29.36	29.10	33.14	29.15	31.51	1.044	1.145
size 2	38.33	34.20	36.05	37.41	32.07	29.30	34.57	1.68	1.145
size 3	39.07	34.26	38.40	37.82	34.93	34.75	36.54	0.616	1.145
size 3	43.94	40.65	38.75	43.62	37.15	33.91	39.67	1.893	1.145

Table 5: Modulus estimated from different unit cells

The chi square values for different unit cells size were compared with chi square of confibence 95%. The results show that size 1 and size 3 displayed accuracy of higher than 95%, and unit cells in size 3 gives accuracy higher than others.

So, any unit cell in size 3 can be considered as representative volume element; therefore unit cell (a) in (Fig. 11) was considered as representative volume element, and it was used to find the mechanical properties woven carbon fibre composites.

To evaluate the effect of the bonding strength between the fibre bundle and the matrix, a bond-slip model was assumed. So, the interface between the fibre and the matrix was represented through the interfacial shear strength between them. A sinusoidal displacement was applied to the end of the RVE and the reaction force computed. The effective stiffness and loss factor were then estimated from the resulting hysteresis loop.

The interface effect was represented by Coulomb friction between composite contents of fibre and matrix, and friction effects on both modulus and loss factor results are shown in (Fig. 15) and (Fig.16).

The results show the modulus increasing gradually with friction, due to increasing bonding strength between the bundle fibre and the matrix. The RVE shows higher value at fully bonded, because of the strong bonding and good load transfer from the matrix to the strong fibre.

The loss factor first increases with coefficient of friction (up to value of 0.5) and then reduces as is typical for a classic friction damper.
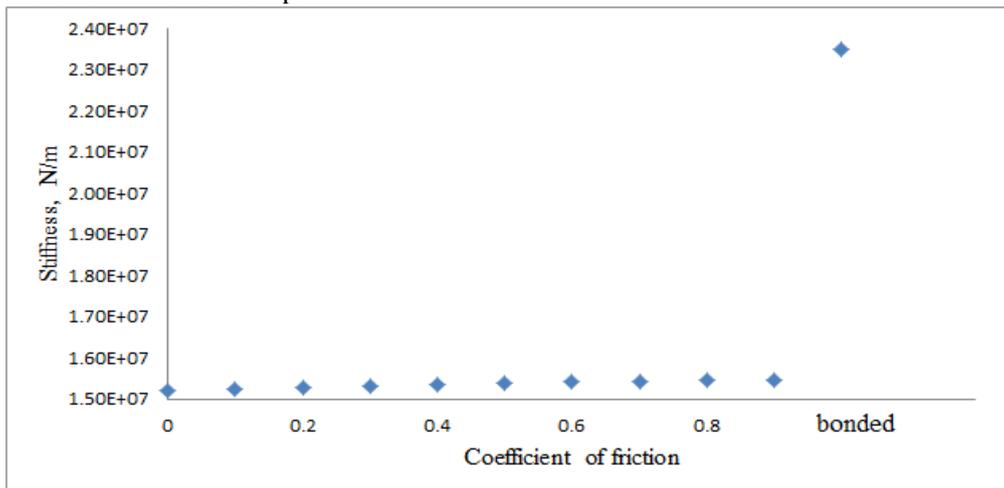

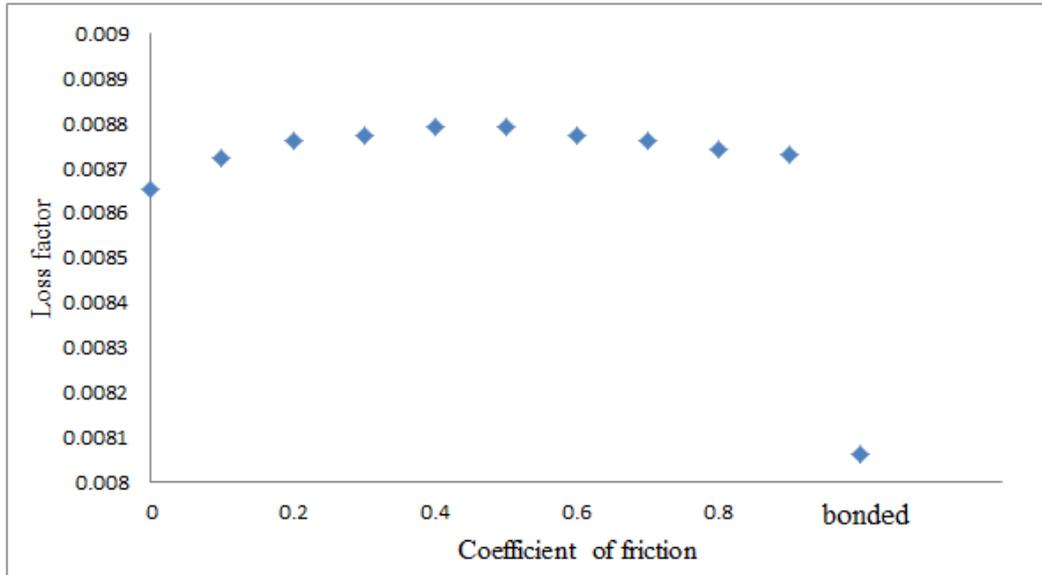Figure 15: Stiffness at different coefficient of frictions.

Figure 16: Loss factor at different coefficient of friction.

3.2 Viscoelastic analysis

The previous analysis was rerun using viscoelastic properties for the matrix. In this calculation, viscoelastic behaviour was represented by using a Prony series that was obtained from the master curves of PEEK. The mechanical properties in (Table 6) were used for the composite content with considering orthotropic thermal expansion for the carbon fibre and isotropic thermal expansion for PEEK matrix.

Composite contents	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m^3)	Coefficient of thermal expansion (1/C)		
				αx	αy	αz
Woven carbon fibre	240	0.23	1750	5.6E-06	5.6E-06	-4E-07
PEEK	N/a	0.42	1320	4.5E-05	4.5E-05	4.5E-05

Table 6: woven composite mechanical properties used in viscoelastic analysis.

The Viscoelastic numerical results are shown in (Fig.17) and (Fig.18), which show the temperature effect on modulus and loss factor behaviour for woven composite materials. It is noted drop in modulus gradually with temperature increase at low temperature, and decreasing steeply at high temperature around glass transition temperature of PEEK. The loss factor increased with temperature and jumped at temperature of 160ºC, then declined. This behaviour is because of effect of both material viscoelasticity for the matrix, and material thermal expansion.

4 COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL

To validate the numerical results, the viscoelastic numerical results were compared with experimental results. Both numerical and experimental modulus and loss factor results at different temperature and frequency of 1Hz are shown in (Fig.17) and (Fig.18).

It can be noticed that both numerical and experimental results behaved in a similar way as the temperature changes. The modulus decreases with temperature increase and drops rapidly around the glass transition temperature for the matrix. The highest value for loss factor is at glass transition temperature at 160ºC for both methods. However, the experimental modulus values are higher than

numerical results. This is related to neglecting the friction between fibre bundles, which is unrealistic and caused lack of stiffness in the numerical model.
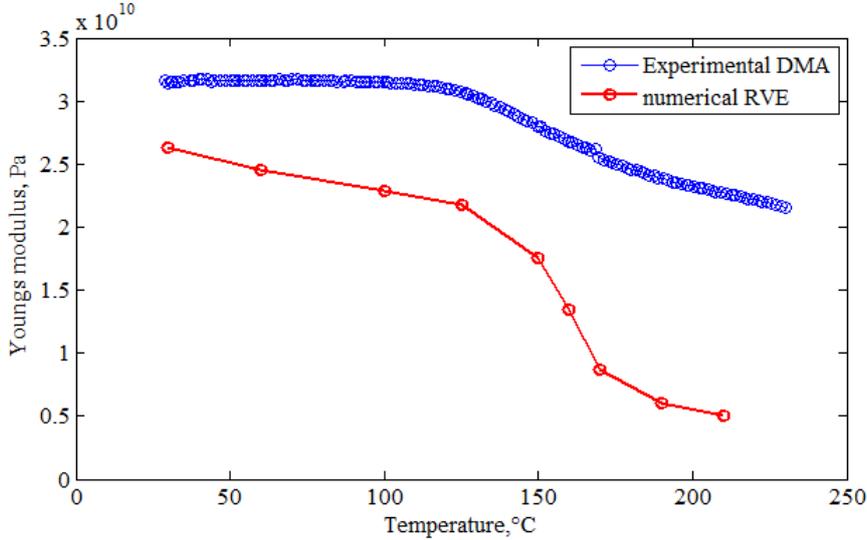

Figure 17: Comparison between numerical and experimental Young's modulus.
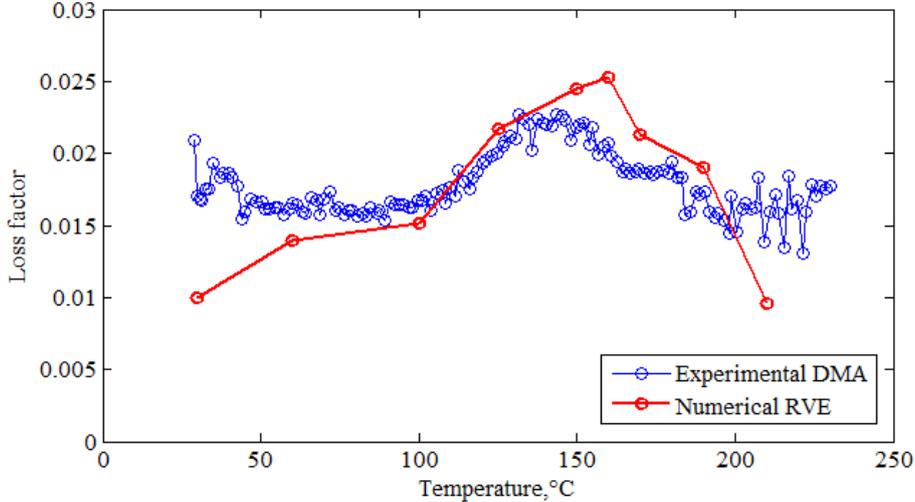

Figure 18: Comparison between numerical and experimental loss factor.

5 CONCLUSIONS

In this work the dynamic mechanical properties of PEEK and composite of woven carbon fibre-PEEK was found experimentally and numerically over a range of temperatures and strain rates.

Flexural test was carried out on woven composite material at room temperature and (150 °C). So, it was observed the materials at temperature 25 °C are stiffer than 150 °C with less ductility. Also, temperature sweep test on woven composite materials exhibits decreasing in modulus with temperature increase, and dropping the modulus, increasing loss factor at glass transition temperature around 160 °C. Moreover, The strain sweep test shows decreasing in modulus, increasing in loss factor with increasing in amplitude at both 25 °C and 160 °C for the woven composite materials.

A numerical RVE with Ansys was developed for the woven composite material by using different unit cells of bundle carbon fibre reinforced matrix, and finding better unit cell to represent the representative volume element. From that RVE the effect of bonds strength between the bundle carbon fibre and the matrix was identified by assuming bond slip between them and representing it by different values of friction. It was found increase in stiffness with increasing friction between the woven bundle fibre and the matrix. However, the loss factor rose to value of 0.5, and then dropped down.

For numerical viscoelastic analysis, the matrix was represented through the use of Prony series of plain PEEK. So, the modulus and loss factor behaviour with temperature change was computed for woven composite material. To validate the viscoelastic numerical results, it was compared experimental results, and it was noted same behaviour for both methods. So, it was observed decreasing modulus, increasing damping with temperature increasing and jumping up damping with dropping steeply in modulus at glass transition temperature for both composite materials. Also, it was observed small differences between numerical and experimental results in the loss factor values with higher differences in the modulus results.

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