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The Effect of Woven Structures on the Vibration Characteristics of Glass Fabric/Epoxy Composite Plates

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ABSTRACT

We study the effects of woven structures on the dynamic mechanical properties and vibration properties of the fabric composite plates. Five typical weaving sets including the ordinary plain weaved and the warp interlocked were adopted in fabric processing. The composite plates with the same thickness were prepared by epoxy resin curing, and their fibre volume fractions were examined. Dynamic mechanical analyzer and vibration test technique were used to reveal the dynamical behaviours of specimens in different frequencies of vibration. The storage modulus, the loss tangent, the natural frequency and damping ratio were obtained. The result showed that the woven structure had a strong effect on the fibre volume fraction, resin-rich area and the warp architectures of the composites, which determined the performances of the composites in vibration.

Keywords: Vibration characteristics, fabric composite, woven structures, dynamic mechanical analysis

1. INTRODUCTION

Woven fabrics are designable for the 2D/3D composites with different thickness and structures. These composites exhibit high strength, light weight and other attractive dynamic mechanical characteristics such as high damping and high stiffness. Recently, the composite products are increasingly used for sun-shading devices, plane wings, fuselages or any other beams and shells in modern applications[1].

The dynamic properties of the composite materials have been the objectives of many investigators[2-7]. In designing of the composite materials with desired dynamic properties, storage modulus and damping are the important features. Storage modulus relates to the stiffness of composite structures, damping represents the energy dissipation of the whole composite structure. However, many research works attributed the energy absorbing capacity to the inherent damping characteristics of the composite components. Most efforts were made on the polymer matrix toughening[8-10], or at micro-mechanical level, on the fibre/polymer interface modification[11,12]. Less work has associated to the the composite meso-structures, containing the fibre array and yarn architectures.

The constitutive behaviours of the composites with different fibre architectures can be characterized by using micromechanical analysis. However, the relationship between the dynamic mechanical properties and the micro-structure is not explicit reported. Consider that the woven fabric reinforced composite materials are not entirely homogeneous, large resin rich areas are formed by the interlacing of undulating warp and fill yarns. In the high performance fibre-polymer matrix system, the difference of damping is much larger than that of the stiffness. Large resin rich areas act as the built-in damper elements. Their distribution, depending on the architectures of the weave, determines the damping of the composite structure.

In this study, geometry of textile fabric was focused and effect of weaving structure on the dynamic behaviour in textile composites was considered. Dynamic Mechanical Analysis (DMA) and vibration test technique were used to reveal the dynamical behaviours of specimens. The storage modulus E', the natural frequency f, the damping, tan δ and the damping ratio η were examined. The effect of the fabric structure was discussed and the corresponding analysis was made.

2. EXPERIMENTAL WORKS

2.1 Materials and the initial preparation

The toughened thermo-setting epoxy resin formulation was prepared by using an Bisphenol-A epoxy 618 (from LETAI Chemistry): Tougthening agent of polypropylene glycol diglycidyl ether EA-731 (from CIBA Arocy): Phenolic resin-modified polyamine T31 as curing agent (from LETAI Chemistry) ratio by weight of 60: 26.1: 13.9. The count of the D glass yarns (from TIANJIN GLASS FIBRE CO) is 99 tex.

Five fabrics with the typical woven structures were fabricated in the plain-weaved and in the interlocked with the same yarns as warps and fills. The interlocked woven structure contains several types distinguished by different warp architectures, as shown in Fig.1 (S is short for the "sample"). These fabric composites covered a range of mechanical properties, such as the distribution of mass, stiffness and damping that subject to the vibration.

In composite processing, the homogeneous resin mixtures were degassed by a vacuum pump for 20 min, then poured onto

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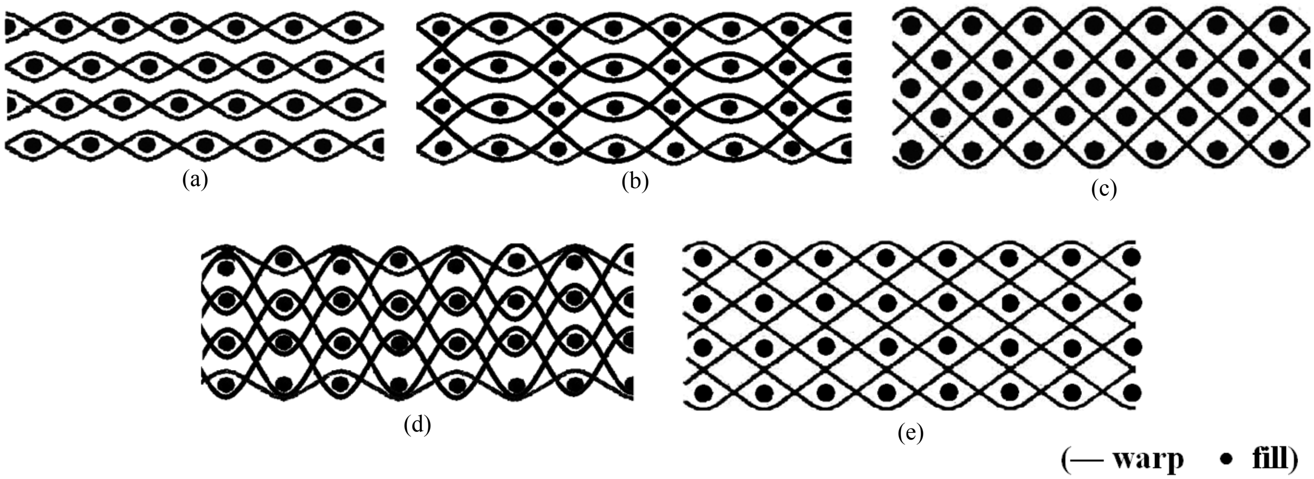


Figure 1. Different woven structures in different samples: (a) S1: plain weaved laminates, (b) S2: modified layer-layer interlocks, (c) S3: cross-cutting interlocks, (d) S4: layer-layer interlocks, and (e) S5: modified cross-cutting interlocks

the fabric preforms in a mold and cured at room temperature for 24 h. The mold was moved into a heating oven and heated from 40 °C to 140 °C at a rate of 3 °C/min. The gaps between the upper and lower mold is constant, so all the composite plate samples have the same thickness of 1.2 mm. After demoulding, the composite was cut into small plates or pieces for the following tests. The glass fibre volume fraction of sample 1~5 were calculated by the density conversion, the values were 33.3%, 28.3%, 33.7%, 32.5% and 22.4%, respectively.

2.2 Testings

Dynamic three-point bending test of specimens 80 × 7 × 1.2 mm (Warp × Fill × Thickness) was carried out on a DMA 242 (NETZSCN Co, Germany), according to ASTM D 4065-01. The bending tests were run on a charpy with the span length 50mm. The tests were carried out in the temperature scan mode at a frequency of 1 Hz, with the heating rate 6 °C/min. The DMA test was executed in the temperature range of 10-80 °C, so as to be comparable with the following vibration test.

In slender specimens, the ratio of the thickness/span was smaller than 0.02, so the shear effects were always ignored. The storage modulus E’ could be calculated by the geometric approaches:

$$E' = \frac{KL^3}{4bt^3} \tag{1}$$

where K, the ratio of drive force/amplitude; L, the span of the charpy, 50 mm; b and t, the width and the thickness of the specimen, 7 mm and 1.2 mm, respectively. The loss tan δ were obtained accordingly.

The vibration test was executed by using resistance strain sensors to detect the dynamic strain in the composite plates. The resistance strain gauges (120 Ω) were sticked on the dual-sides of the cantilever plates. An A/D converter and computer were also used in the vibration testing. The specimens 80 × 20 × 1.2 mm (W × F× T) were clamped in the form of cantilever beams with 60 mm span, and then vibrated by an initial impact from a pendulum (see Fig. 2). Because the cantilever vibration was very weak caused by the softening deformation of the epoxy resin when the environment temperature exceeds 60 °, the vibration test was limited at temperature range of 20 °C ~ 50 °C.

A classical damping equation for vibration beams is expressed in

$$\eta = \frac{\ln(x_n / x_{n+1})}{\pi} \tag{2}$$

where, η is the damping coefficient; x_n, x_{n+1} are the amplitudes of sine wave with logarithm damping in different interval, as shown in Fig. 3 (a).

In terms of the Fast Fourier transformation, the vibration frequency spectrum was obtained from damping waveforms measured, as shown in Fig. 3 (b). The main peak corresponds to the natural frequency of the composite cantilever. Each sample contains five specimens, the values of frequencies and damping coefficients are obtained from averaging of the five specimens.

The composite samples were cut into small pieces along the warps or fills, the surface of cross-sections were mechanically polished. A stereo-microscope DH-HV3102VC-T was used for the observation of the yarn cross-section and trajectory.

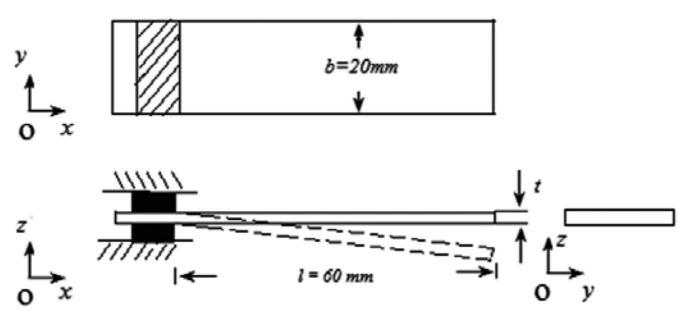


Figure 2. Geometric parameters of the composite cantilever.

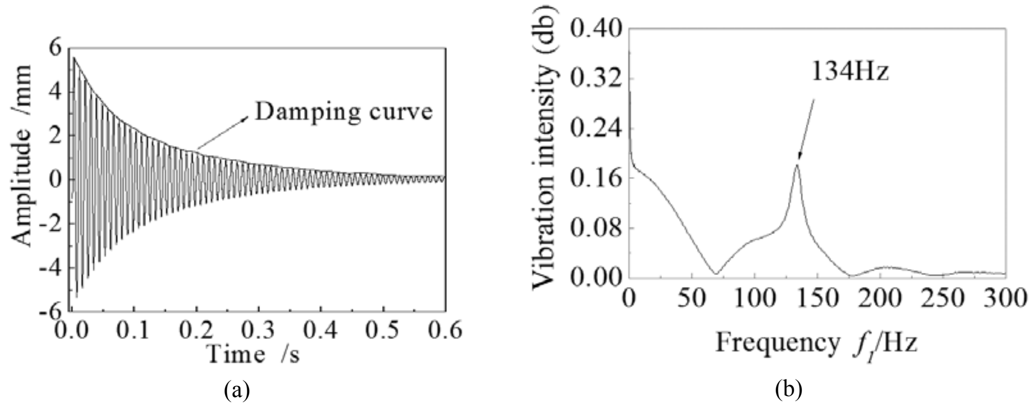


Figure 3. The amplitude-time graph (a) and frequency spectrum (b) of the vibration.

3. RESULTS AND DISCUSSIONS

3.1 Storage modulus and the natural frequency

Since the epoxy resin exhibits temperature dependencies of visco-elastic properties, increased temperature result in the decrease of *E'*. The stiffness of glass fibre can't be affected by the temperature, but in certain lower temperature, the reinforcement of glass fabrics will significantly enhance the stiffness and weaken the visco-elasticity of the composites. Moreover, different woven structures will result in different mesco-structures, which responsed differently to the dynamic loads in DMA or the free vibration test.

In principle, the DMA test of the simply supported beam is similar with the cantilever vibration method. The difference is that the frequency of the DMA load is 1Hz, while the vibration frequencies of the cantilever usually exceed 100Hz. The test result also reveals the response of composite materials to different frequencies.

When the shear effect is ignored, in the vibration analysis of homogeneous composite cantilever plates, the first order Reissner-Mindlin theory will usually suffice. The frequency of the bending vibration in the warp/fill-thickness plane can be expressed by

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{I}{\rho A}}(\frac{1.875}{l})^2 \quad (I = E'bt^3/12) \qquad (2)$$

thus,

$$f_1 = \frac{t\sqrt{3E'\rho}}{12\pi\rho}(\frac{1.875}{l})^2 \qquad (3)$$

where *I*, the bending inera; *E'*, the dynamic bending rigidity; *t*, the thickness of the plate, 1.2 mm; *l*, the length of the cantilever, 60 cm; and ρ, the density of the composite.

Figures 4-5 shows the *E'* and the *f* of each sample in the warp and filling directions. It is found that the value of the vibration frequency of each specimen along with *E'* have decreased in varying degrees with the temperature increasing, indicating that the visco-elasticity of composite varies significantly from the fabric structures.

The value of natural frequency curves follow the variation of the *E'* in different samples, but the decline rate of the vibration frequency is faster than that of the *E'*.

The sample 1, 3 and 4 have the similar fibre volume content, and 3 and 4 are the two typical angle-locked woven structures. In each tested temperature, the *E'* and tan δ of samples 3, 4 are much larger than that of the sample 1. It is convincing that the interlocked structures have a better bending stiffness and a higher damping than those of the laminated plain-weaved woven structures.

3.2 Loss tangent and the damping coefficients

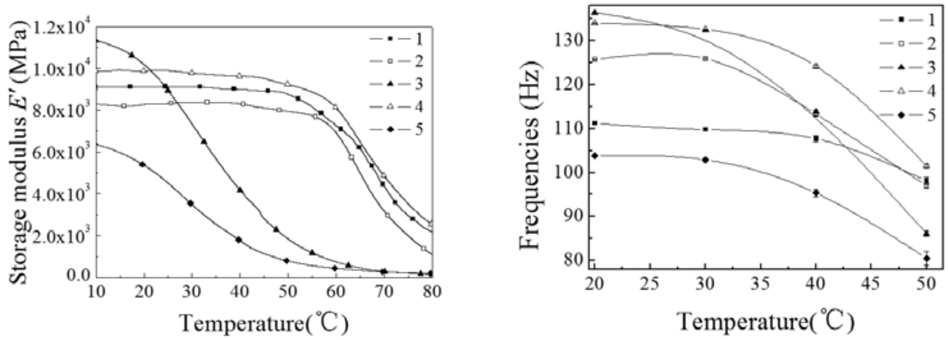
Figs. 6-7 shows the variation of tan δ and damping coefficient η. In the curves of tan δ, the peak of the loss tan δ indicates glass transition temperature, T_g. This peak point divides the entire temperature range into two segments–the below T_g zone and the above T_g zone. The temperature span we adopted was in below T_g zone, the variation of tan *δ* were obtained in comparative analysis with the damping coefficient η.

In the isotropic material, η indicate the material inherent damping, and has equal value to the tan δ.

It is shown in Figs. 6-7 that the η of each specimen is significantly greater than the value of tan δ in corresponding temperature. Moreover, the value of η and tan δ of different specimen have decreased in varying degrees with temperature increasing. The temperature rising of tan δ and η in sample 1 (plain-weaved woven laminates) is the slowest. In samples 2~5 (interlocked structures), the difference of the tan δ and η is growing with the corresponding temperature increasing, indicating that the influence of fabric structure to the composite internal friction is larger in the interlocked structures. Especially for the sample 5, which has the smallest fibre volume content, the value of tan δ and η keep fastest-growing in the test temperature range. The peak of tan δ curve even emerge at 50 °, which is significantly lower than the T_g temperature of the epoxy resin, showing the significant changes in the composite micro- or mesco-structures.

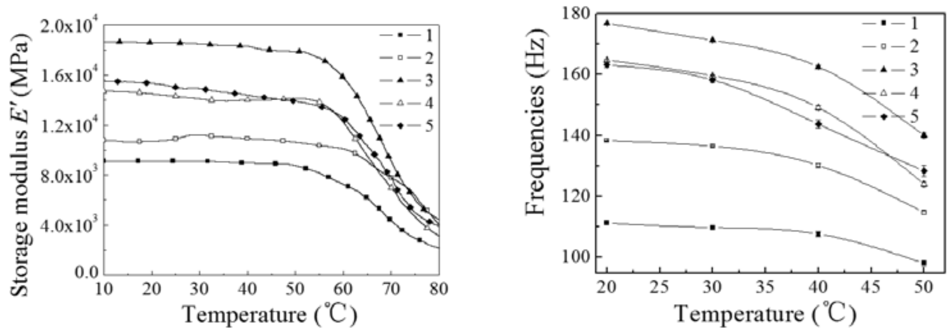
3.3 Woven Structures

The internal geometry structure of composites including orientation and cross-section of yarns has the most important effects on the mechanical properties. Woven fabric consists of two types of interlaced yarns, the lengthwise set is called warp and the crosswise set is called fill. In the weaving process of each fabric samples, the warp tensions were kept the same.



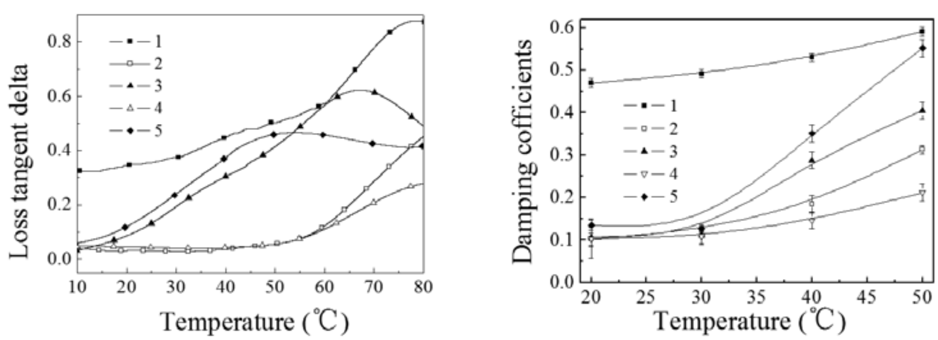
(a) (b)

Figure 4. The storage modulus *E'* (a) and the natural frequency *f* ; (b) of the samples in the warp direction.



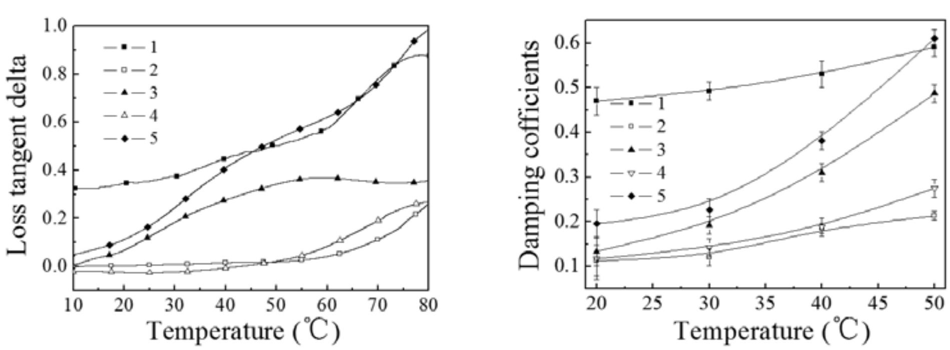
(a) (b)

Figure 5. The storage modulus *E'* (a) and the natural frequency *f* ; (b) of the samples in the fill direction.



(a) (b)

Figure. 6. The loss tan δ (a) and the damping coefficient η (b) of the samples in the warp direction



(a) (b)

Figure 7. The loss tan δ (a) and the damping coefficient η (b) of the samples in the fill direction.

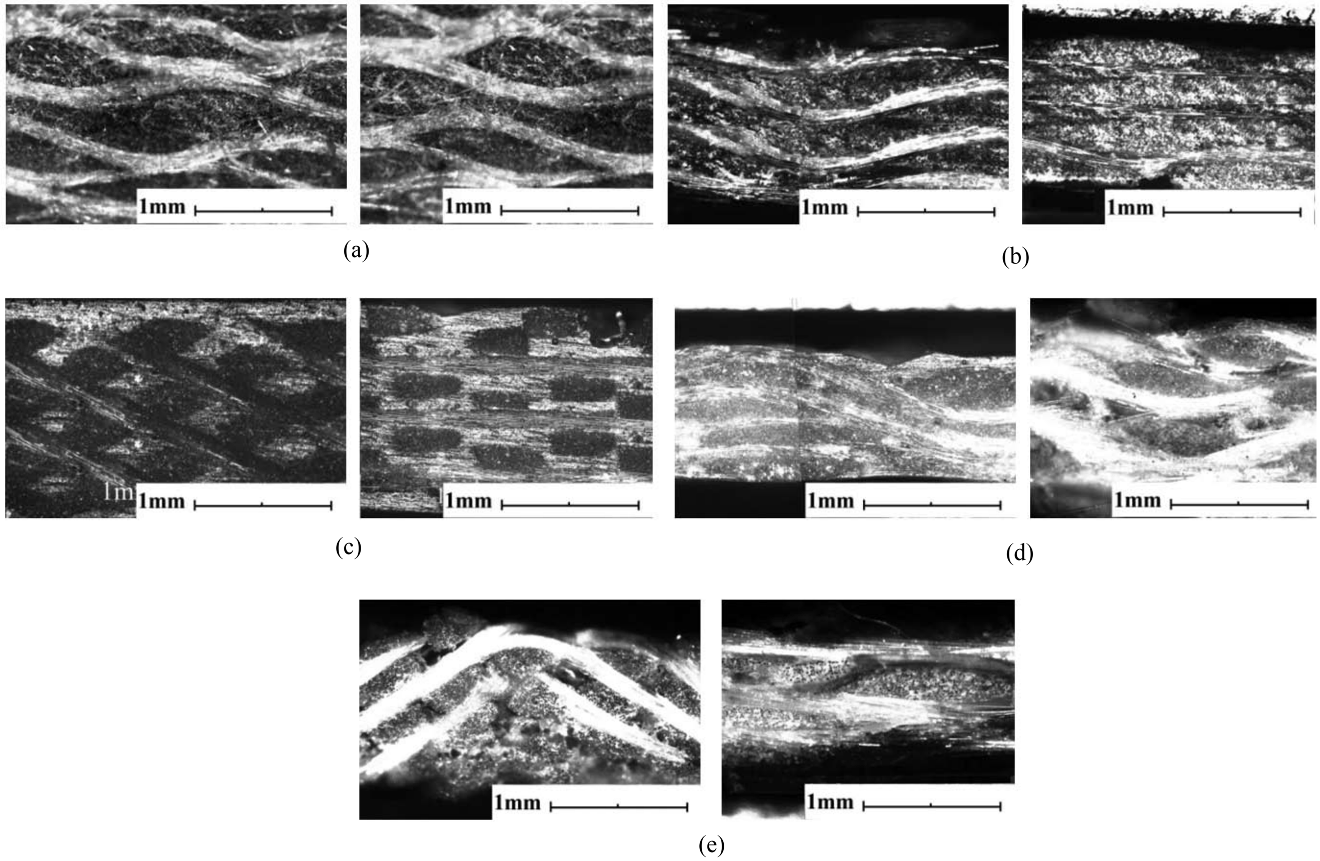


Figure. 8. The mirco-graphs of the longitudinal (left) and latitudinal (right) cross-sections of the composite samples: (a) S1: plain weaved laminates, (b) S2: modified layer-layer interlocks, (c) S3: cross-cutting interlocks, (d) S4: layer-layer interlocks, and (e) S5: modified cross-cutting interlocks.

Fig. 8 shows the mesco-apparatus of the plate samples. It is found that all the fabrics have the undulated warp structure. The samples can be further divided into 3 weaving sets, in each set group, the cross-sectional of warp toes and fill toes have the following characteristics:

In plain-weaved laminates (sample 1), the warp and fill toes have the similar undulated structure; they have the same convex shaped cross-sections. The layers were arranged in misalignment when being laminated, a large number of resin-rich areas were distributed uneven in the gap between the layers. However, each unit-cell was composed by two adjacent warps and fills, the bending amplitude and bending variation of yarns in different unit-cells is very little. So the structure is estimated to have a good dimensional stability and a stable high damping at various temperatures.

In the cross-cutting interlocked structures (sample 3 and 5), the warp yarns turning up and down follow the path of broken lines, and the fill yarns are straight. Because the sample 3 and 5 have different fill yarn densities, their cross-sections varies greatly – In sample 3, the warps have cross-sections of rectangular shape, while the fills diamond shaped. The integration between the yarns is very tight; the stiffness of the composite is strong for there is rarely any rich-resin area. In sample 5, the reduction of the fill density causes the weak connection of interlaced yarns. As shown in Fig. 8 (e), the cross-sections of warps and fills are all oval-shaped, resin-rich areas are compressed into the gaps of the adjacent toes. The structure is estimated to have a good damping, but very sensitive to the rise of temperature.

In the layer-layer interlocked structures (sample 2 and 4), the warp yarns follow the path of a wave forms. The warps have various bending amplitudes in waviness. Because the adjacent warps usually located in different layers, the bending of the weft yarn is inevitable. The cross-section of yarn toes in sample 4 is flatter than that of sample 2, due to the larger fabric stresses. This structure is considered to have good stiffness and elasticity in flexure vibration.

On the basis of the micro-morphology results and the experiments, we conclude that: The volume content of glass fibre has significantly improved the composite *E'* and natural frequencies, while tan δ and damping are more dependent on a number of characteristics of yarn architecture. In the similar interlocked structures, high fibre volume would cause a good stiffness, large natural frequency, and small tan *δ*, damping coefficients. In the samples with similar fibre volume contents, small deflection of yarn with bending variation would cause a small internal friction of the material and low damping.

CONCLUSIONS

The result of the storage modulus *E'* and loss tan δ of the DMA test of each sample are consistent with that of the natural frequency *f* and damping η in the vibration test. Especially, in the interlaced woven composites, the f and η are more sensitive to the rise of ambient temperature than the E' and tan δ

At the same fibre volume content, the stiffness and natural frequency of the interlocked structure are higher than that of the laminated plain-weaved woven structure below the glass transform temperature of the epoxy resin matrix 80 °.

In the interlocked structures, the E' and f in latitudal samples are much greater than those of the longitudes, while for the damping η and tan δ, the anisotropy is not significant.

The fabric structure in 3D woven composites acts an important role in determining the vibration characteristics of the composites. The volume content of glass fibre has significant effect on the composite E' and vibration frequencies, while tan δ and damping η are more dependent on the yarn architectures. The interlocked woven structures have better vibration performance than that of the plain-weaved wovens. In engineering applications, the yarn architectures of the interlocked structure is recommended to increase the bending and reduce the bending variation among all the warps.

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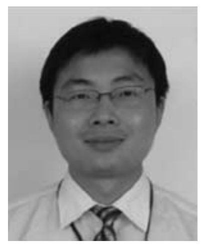

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