

FATIGUE AND VIBRATION RESPONSE OF LONG FIBER REINFORCED THERMOPLASTICS

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ABSTRACT

Fatigue behavior of long fiber reinforced thermoplastic (LFT) E-glass/polypropylene (E-glass/PP) composites is presented in terms of stress– number of cycles to failure curves. Samples tested along longitudinal direction showed a higher fatigue life than the transverse samples which can be explained by the preferential orientation of the fibers along the longitudinal direction developed during the processing. Fatigue life decreased with increase in frequency. Hysteretic loss and temperature rise were measured; they depended on the stress amplitude as well as the cyclic frequency. LFT composite showed a lower temperature rise compared to neat PP because LFT has higher thermal conductivity than neat PP and thus faster heat dissipation to the surroundings occur. The hysteretic heating also led to decrease in the modulus of LFT as a function of number of cycles due to the softening of the matrix during fatigue cycling and depended on stress amplitude and frequency of the test.

The dynamic behavior in terms of vibration damping of these materials is also a matter of interest in design and application development. E-glass/PP LFTs were subjected to vibration in a free-free boundary condition. The vibration response (natural frequency and damping ratio) is investigated as a function of the processing conditions such as the fiber orientation.

INTRODUCTION

Thermoplastic composites are being used in a variety of applications such as mass-transit, automotive, and military structures. They have an edge over traditional materials, such as steel and aluminum, in these applications due to their high specific strength, good damping capacity, and corrosion resistance. The matrix in thermoplastic composites is generally comprised of polypropylene (PP), polyethylene (PE), nylon or other inexpensive polymers. E-glass fiber is a commonly used reinforcing material [1]. Long fiber thermoplastic (LFT) composites have seen one of the highest growth rates, approximately 30% per year, in the plastic industry during recent times [2]. Currently, short glass fibers are predominantly used as reinforcement in polypropylene in the automotive industry. But the full strength of the reinforcing short fibers is not realized due to their low fiber aspect ratio. The aspect ratio (ratio of fiber length (ℓ) to diameter (d)) of fibers in LFTs is an order of magnitude greater than that of a short fiber, often exceeding ℓ/d of 2000 and, thus, take full advantage of the strength of the reinforcing fiber [3]. The critical fiber length (ℓ_c) can be obtained from the following equation [3, 4]:

$$\frac{\ell_c}{d} = \frac{\sigma_{\max}}{2\tau_i} \quad (1)$$

where τ_i is the shear strength of the fiber/matrix interface, d is the glass fiber diameter, and σ_{\max} is the fiber fracture strength.

LFTs are frequently used in structural applications where cyclic loading is important. Thus, characterizing the fatigue behavior of LFTs is of great importance. Many factors govern the fatigue behavior of discontinuous fiber reinforced polymer matrix composites (PMC). Some of these include processing conditions, fiber length and orientation with respect to the loading axis, properties of the matrix, interfacial properties, and testing conditions. Two common methods of making LFT composites are extrusion-compression molding and injection molding. The fibers tend to orient along the flow direction which leads to superior mechanical properties along the flow direction. As the degree of fiber misorientation with respect to loading axis increases, the strength of the composite is increasingly dominated by the matrix and interfacial properties [6]. Fiber length also plays an important role in the fatigue behavior of discontinuous fiber reinforced composites. Long fibers carry a significantly higher fraction of the load compared to short fibers. Also, for a given fiber volume fraction, there are less stress concentration sites (fiber ends) for long fibers compared to short fibers [3].

Considerable work has been done on the fatigue behavior of continuous and short glass-fiber reinforced polypropylene [4-12]. Not much work has been done on the fatigue behavior of long glass fiber reinforced polypropylene. Here we present results on the fatigue behavior of LFT (PP/20 vol. % E-glass), made by extrusion-compression molding in terms of stress vs. cycles (S-N) or Wöhler curves. We characterized the fatigue behavior in terms of processing induced fiber-orientation and the effect of frequency on the fatigue life of LFT. Hysteresis loops were also obtained and were used to calculate the energy loss and modulus as a function of number of fatigue cycles.

MATERIALS AND METHODS

A hot-melt impregnation process was used to produce impregnated glass fiber tows [2]. In this process the fiber tows were pultruded through a heated die during which the individual filaments are impregnated with PP. The pultruded tow impregnated with the PP matrix was cooled and then chopped into LFT pellets approximately 25 mm in length. Glass fiber/PP LFT pellets (Celstran[®] PP-GF-40-03, Ticona), were used as a starting material for an extrusion/compression molding process. A plasticator and 400-ton capacity compression molding press were used.

RESULTS AND DISCUSSION

Microstructural Characterization

The orientation of the fibers is anisotropic. We designate the orientation of the composite parallel to the flow axis as longitudinal, and perpendicular to the flow axis as transverse. A representative micrograph of the LFT along the longitudinal axis is shown in Fig. 1. Most of the fibers were aligned along the flow direction.

Table I: Tensile properties of LFT

| <i>LFT</i> | <i>Ultimate Tensile Strength (UTS) (MPa)</i> | <i>Young's modulus (GPa)</i> |
|---------------------|--|------------------------------|
| | <i>Mean</i> | <i>Mean</i> |
| <i>Longitudinal</i> | <i>113.8±14.3</i> | <i>6.5±1.0</i> |
| <i>Transverse</i> | <i>68.2±10.2</i> | <i>5.0±0.5</i> |

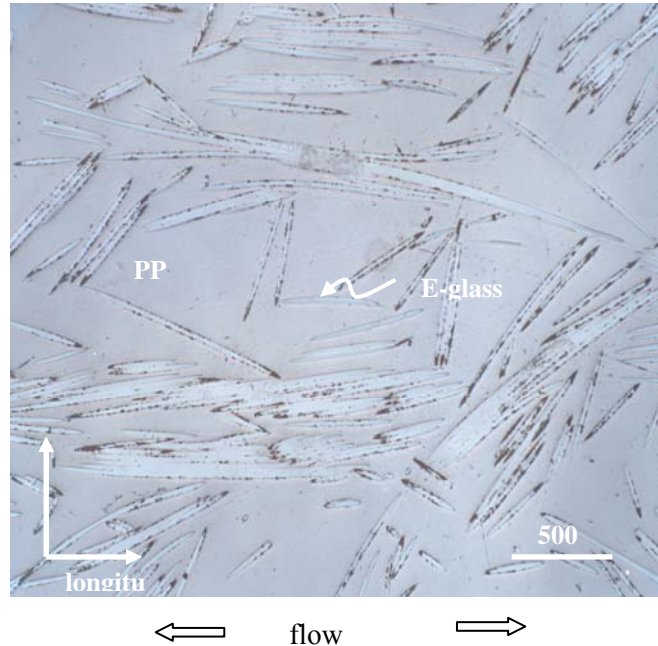


Figure 1 A representative micrograph of LFT. It can be seen that most of the fibers are parallel to the flow direction.

Tensile tests

Results of the tensile test are summarized in Table 1. The longitudinal LFTs had a higher ultimate tensile strength (UTS) and Young's modulus compared to the transverse LFTs. When the sample is loaded in tension or fatigue, most of the fibers in the longitudinal samples are loaded to their maximum strength while in the transverse only a small fraction of the fibers is loaded to maximum strength. Thus, longitudinal samples exhibited better performance in tension compared to the transverse samples.

Fatigue tests

Results of the fatigue tests on longitudinal and transverse samples at a frequency of 10 Hz are shown in Fig. 2. The longitudinal samples showed better fatigue resistance than the transverse samples. Similar results were found for samples tested at 15 and 20 Hz. When the S-N curves are normalized with respect to the Young's modulus of LFT in the longitudinal and transverse direction, as shown in Fig. 3, the plots overlap. This indicates that the enhanced load transfer to the fibers in the longitudinal direction, which results in higher Young's modulus, is responsible for better fatigue life in the longitudinal than in the transverse direction. Similar overlapping of the plots was also found for the samples tested at 15 and 20 Hz. The effect of frequency on the fatigue life of longitudinal samples can be seen in Fig. 4. As the frequency increases, the fatigue life of both longitudinal and transverse LFT decreases. Transverse samples behaved similarly.

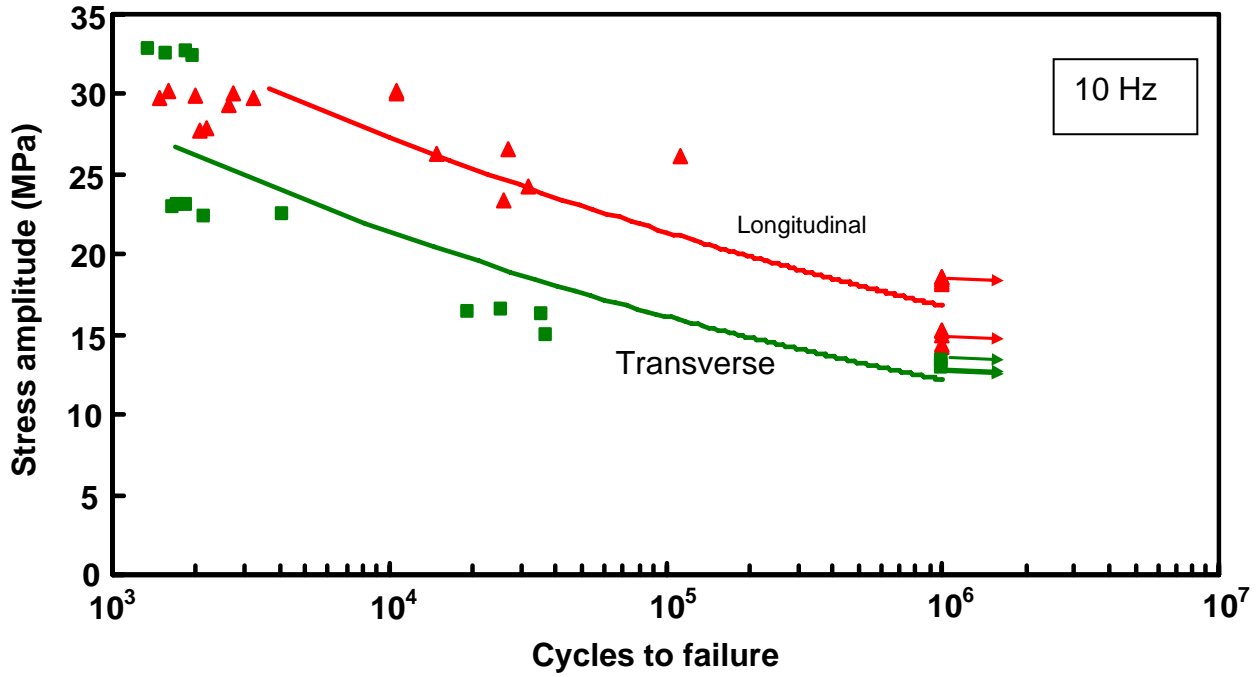


Figure 2 S-N curves for samples sectioned along longitudinal and transverse direction at a frequency of 10 Hz. Longitudinal samples show better fatigue resistance as compared to transverse samples.

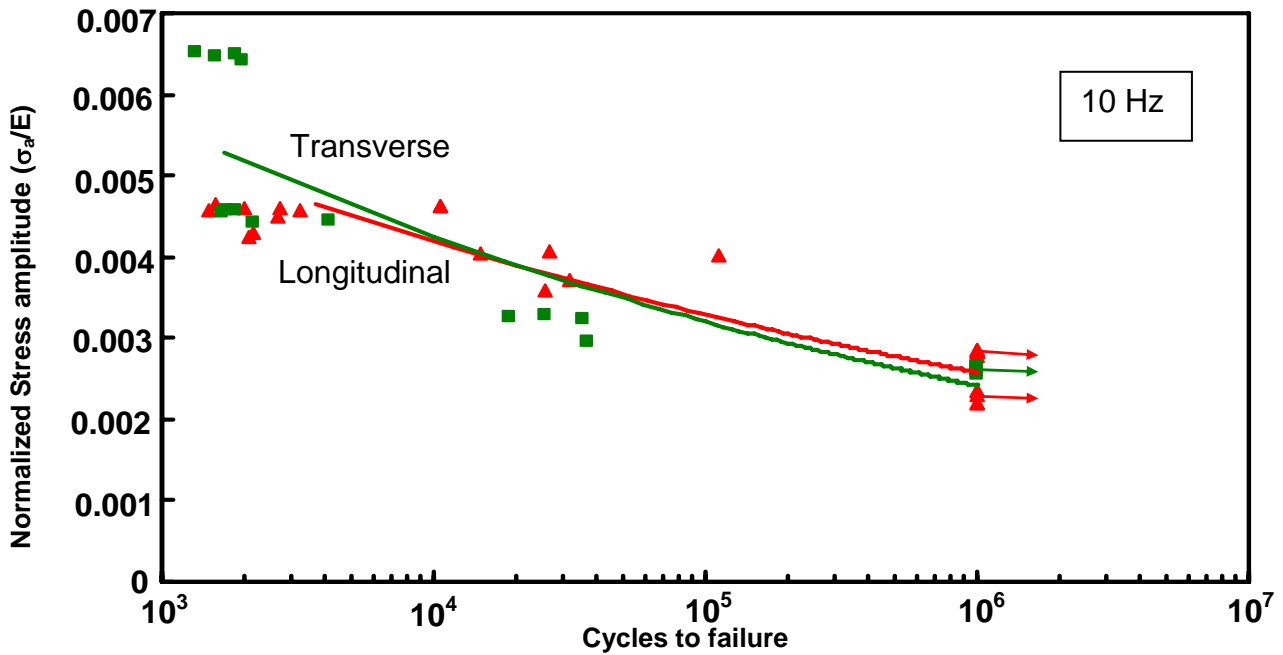


Figure 3. S-N curves normalized with longitudinal and transverse modulus of LFT at a frequency of 10 Hz. The normalized curves for both longitudinal and transverse LFTs overlap.

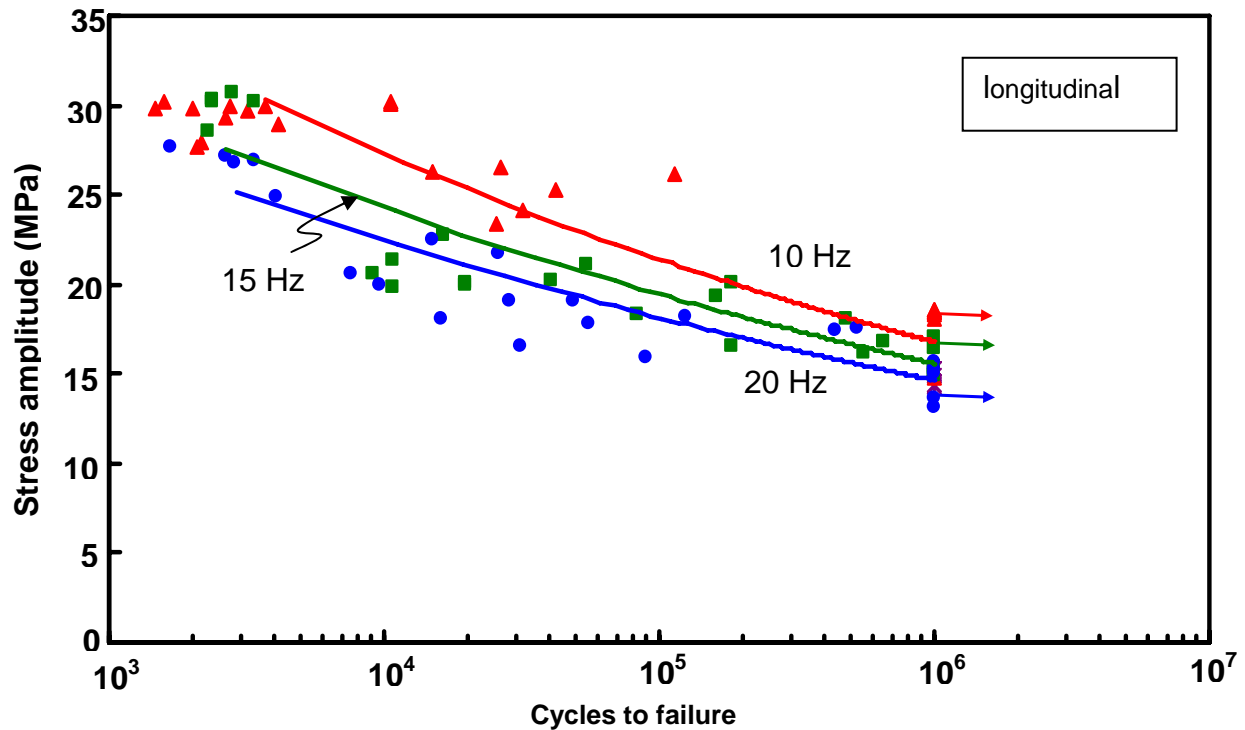


Figure 4 S-N curves for longitudinal samples tested at frequencies of (a) 10 Hz, (b) 15 Hz, and (c) 20 Hz. Fatigue life decreases with increasing frequency.

Vibration Tests: The vibration tests were conducted on LFT beams of average length and width of 20.32 cm x 2.54 cm respectively. The samples were cut in longitudinal and transverse direction, and their respective positions in the LFT plaque are shown in Fig. 5. The average thickness of the longitudinal direction samples was 0.35 cm, and the transverse direction samples - 0.4 cm. An impedance head Bruel & Kjaer (B&K) Type 8000 mounted on a trunnion was used. The impedance head was connected to a B&K type 4809 electrodynamic shaker using a stringer rod. The beam samples were supported at their geometric center, in free-free boundary condition by mounting them in a double cantilever configuration with the aid of bees wax to the impedance head. The input force and output acceleration signals from the impedance head were fed to a dual channel frequency analyzer B&K 2032 through two Kistler-Type 5004 dual mode preamplifiers. The frequency response function (FRF) was measured in baseline and zoom modes. Random noise excitation was adopted, amplified by B&K Type 2706 power amplifier. The FRF was measured by mounting the sample at its geometric center. The damping ratio values were measured using the half power method [13]. The -3dB reduction of amplitude at resonance was determined. The damping ratio $\xi = (f_2 - f_1) / 2f_n$, where f_1 and f_2 are the upper and lower frequencies, and f_n is the resonance frequency.

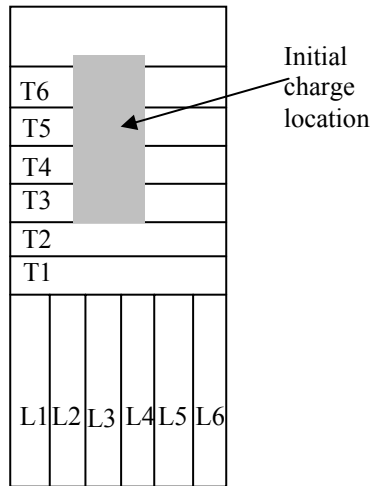


Figure 5. Position of longitudinal and transverse samples.

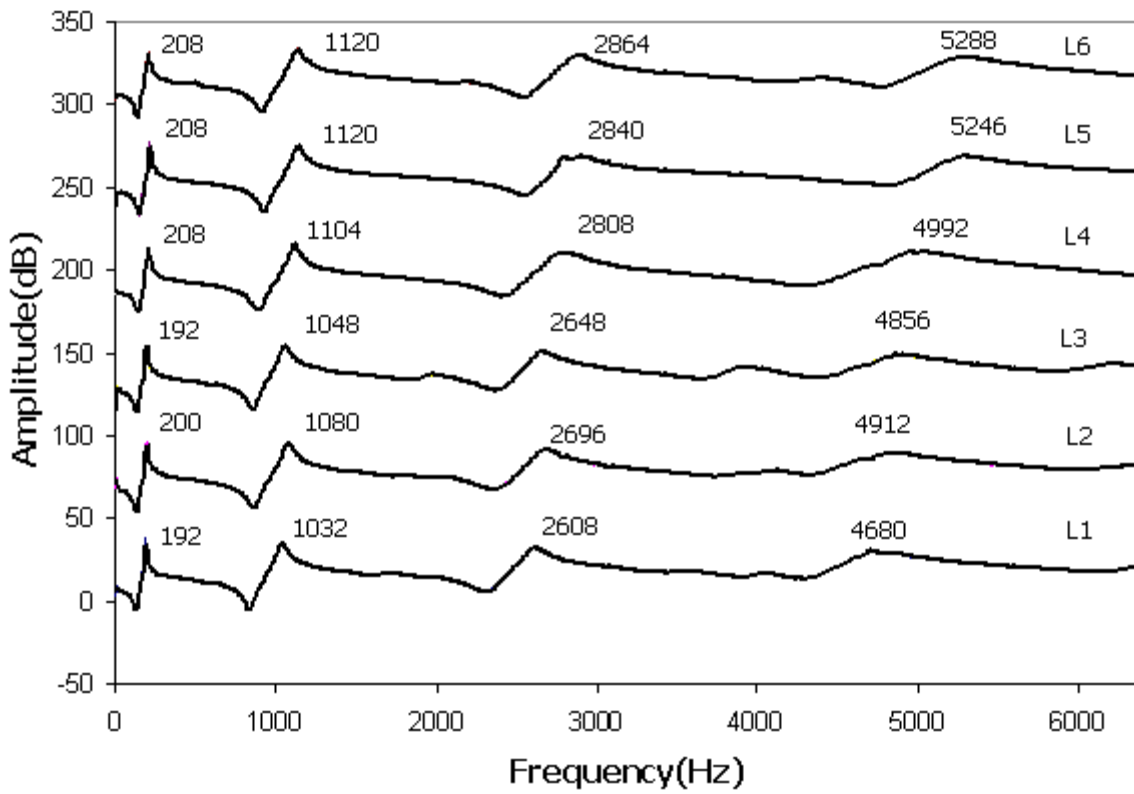


Figure 6. Frequency response function of longitudinal samples (L1-L6).

Vibration Results & Discussion: The FRF of various samples cut in the longitudinal direction (referred to as L-series samples) is shown in Fig. 6. Up to four flexural modes of vibration were discerned for all samples. The average modes appeared at approximately 200, 1084, 2744, and 5000 Hz respectively. The average sample thickness is 0.35 cm. The plot shows that the first frequency is identical in all the samples, however there is a shift in the FRF of the samples from the L1 side to the L6 side (Fig. 6), for the higher modes (modes 2 to 4) indicating an increase in stiffness. This could be caused by localized higher concentration of fibers during the compression process / charge flow variation from one end to the other. The preferential orientation of the fibers developed in the compression molding process was observed through several scanning electron microscopy pictures taken at various positions of the samples. Figure 7 shows a representative illustration of the preferentially oriented fibers. The damping ratios of the LFT glass/PP samples measured using the half-power bandwidth method [13] are shown in Fig. 8. The damping ratio increased with increase in mode number, i.e. from mode 1 to mode 4. The average damping ratio values were consistent for each mode and were found to measure 0.014, 0.016, 0.025 and 0.027 for mode numbers 1 to 4 respectively.

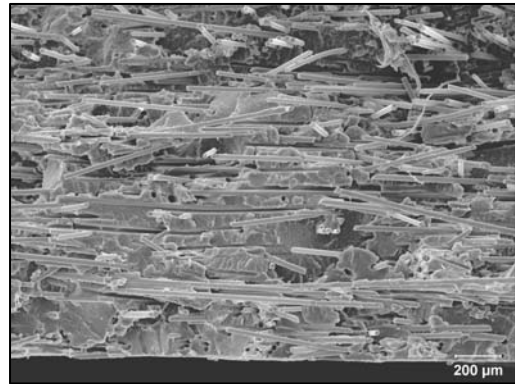


Figure 7. Highly orientated glass/PP fibers in the L-series

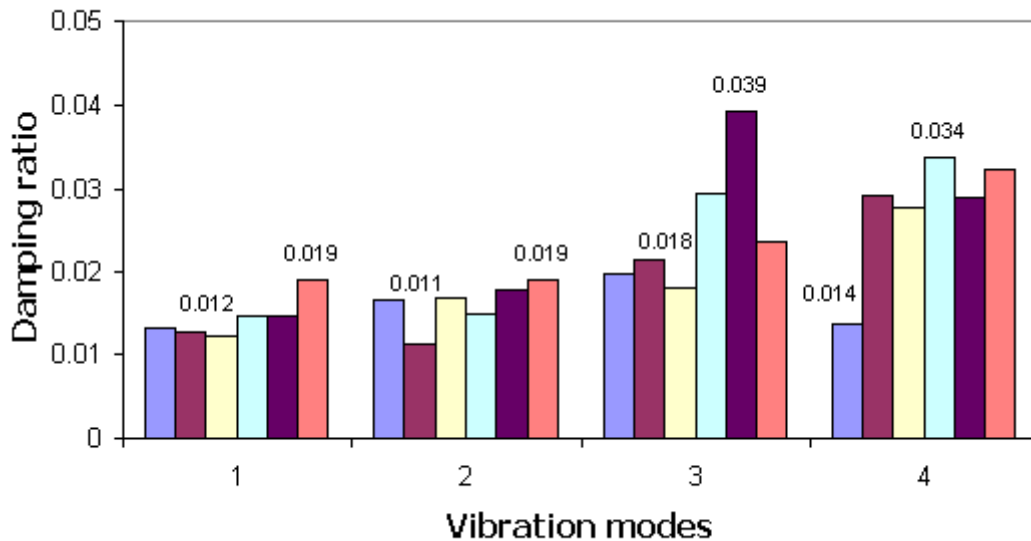


Figure 8. Damping ratio at various vibration modes of longitudinal samples (L1-L6).

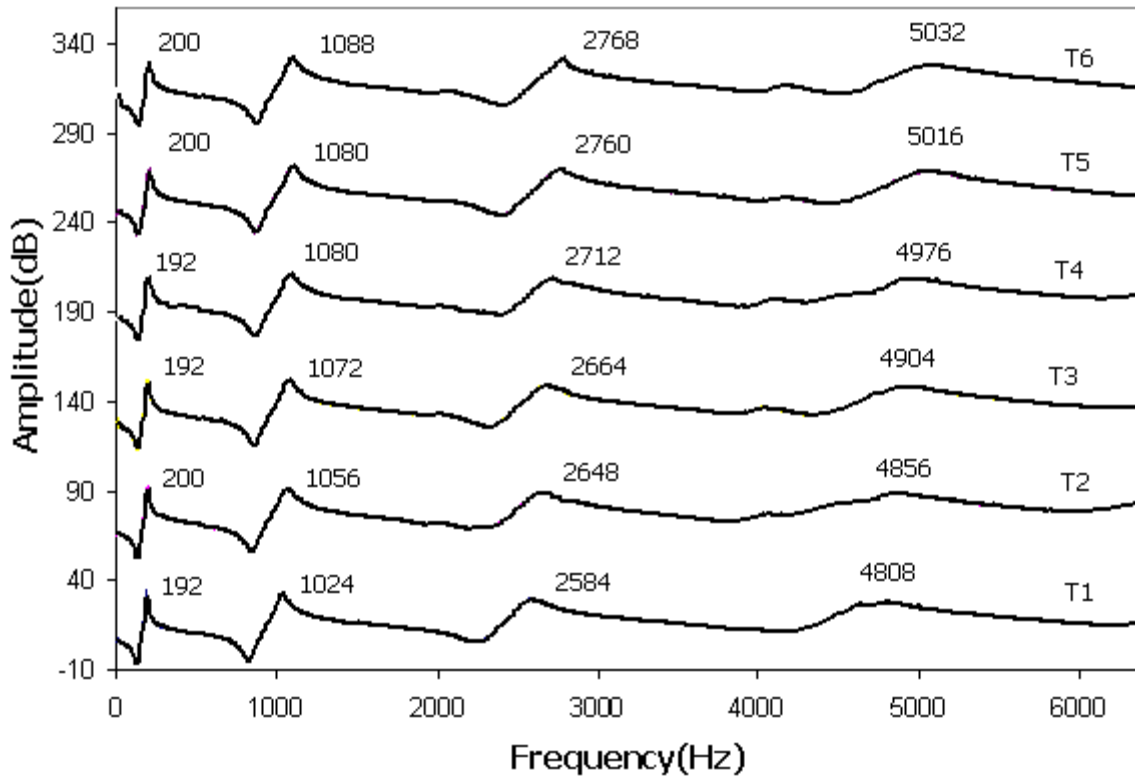


Figure 9. Damping ratio at various vibration modes of transverse samples (T1-T6)

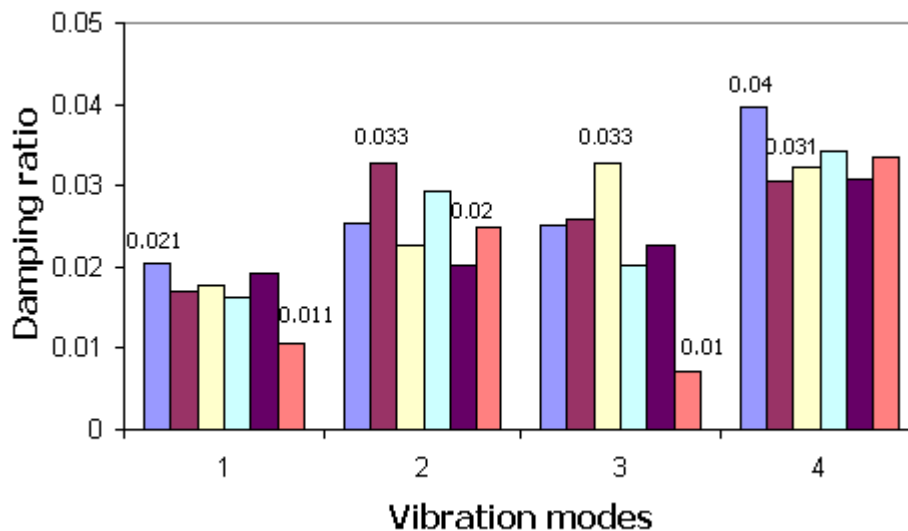


Figure 10. Damping ratio at various vibration modes of transverse samples (T1-T6)

Frequency response function (FRF) of various samples in the transverse direction (referred to as the T-series samples) is shown in Fig. 9. The transverse samples were about 15% heavier than the longitudinal samples. However, the first mode was identical to that observed for the L-series

samples. The first mode was observed at 200 Hz, which is similar to the longitudinal samples. The frequencies for the higher modes (modes 2-4) were lower in case of the T-series than the L-series samples. The average of the higher modes for the transverse samples was 1076, 2712 and 4965 Hz respectively. These are about 1-4% lower than the longitudinal direction samples, although the average thickness of the transverse samples was 0.40 cm. This suggests that the T-series samples had lower amounts of long fibers (20-25 mm length) that provide directional stiffness. The stiffness variation may be attributed to shorter fiber lengths expected in the transversely sectioned samples, where the preferential orientation runs along the width. In the case of the longitudinal samples, more of the 25 mm fibers are aligned along the length of the sample. The damping ratios of samples are shown in Fig. 10. The damping ratio values for the T-series samples were in the similar range as the L-series samples. An average damping ratio of 0.017, 0.025, 0.021, and 0.035 for modes 1 to 4 respectively was measured. The small increase in damping of the T-series samples in comparison to the L-series samples is attributed to the thickness variation.

SUMMARY

Fiber orientation developed during processing played an important role in the fatigue and tensile properties of LFT. Longitudinal LFT showed better tensile and fatigue behavior than the transverse LFTs. An effect of cycling frequency on the fatigue life was also observed. Samples tested at lower frequency showed superior fatigue life as compared to the samples tested at higher frequency. This is because of the hysteretic heating taking place at high frequencies and also due to the lower thermal conductivity of the polymer matrix. At higher frequency less time was given for the heat dissipation to the surroundings which led to temperature rise and failure of the sample. Fiber pullout, fiber fracture, and matrix fracture were the energy-absorption mechanisms during tensile as well as fatigue testing.

The vibration response of extrusion-compression molded LFT glass/polypropylene samples was measured in terms of frequency response and damping ratio. The results qualitatively indicated that LFT glass/PP exhibited higher order mode sensitivity to preferential fiber orientation developed due to the compression molding process. Within the resolution of the global nature of the vibration test, the first mode did not show any conclusive dependency on fiber orientation. The vibration response may be used as a screening tool to assess part-to-part variations based on the response of the higher modes. The damping ratio values for the LFT glass/polypropylene samples ranged from 0.014 to 0.035. The damping ratio increased with increase in mode number.

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