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Damage Characterization of GFRP Composite on Exposure to Cyclic Loading by Acoustic Emission

Cross ply (0/90/90/0) and angle ply (0/30/60/0) glass fibre reinforced epoxy (GFRP) composite laminates were exposed to constant amplitude cyclic loading at 8.6 Hz with varying load cycles. The load is imposed on the specimen to simulate the load (considering road tyre interaction) on a leaf of automobile leaf spring. The flexural modulus of the virgin and pre-loaded specimen were obtained by three point bend test as per ASTM D 790. With both the laminates, a reduction in the flexural modulus was observed on exposure to cyclic loading. During flexural trials the response of the material to flexure loading was assessed by monitoring the acoustic emission (AE) from the specimen under flexure. The intrinsic analysis of AE results, exhibited the influence of the fibre orientation in controlling the damage transfer and the extent of damages like matrix cracking, debonding, delamination and fibre failure.

Keywords: *GFRP laminate, cyclic loading, flexural modulus, acoustic emission*

1. INTRODUCTION

GFRP composites owing to their high specific strength, resistance to the environment and good ballistic properties find application in a dynamic environment such as turbine blades, windmills, leaf springs [1] and sports equipment. On exposure to dynamic loading, the GFRP composites exhibit degradation associated with reduction in stiffness owing to the occurrence of damages, including matrix crack [2-4], delamination and fibre failure [5]. However, such damages could be minimized by proper orientation of reinforcement fibre [6] and lay thickness [7]. The resistance to damage transfer decreases with an increase in the fibre orientation angle in the lay-up from 0^0 to 90^0. The fibre volume fraction and its compatibility with matrix exhibits best performance in transverse loading [8, 9]. It is also reported that [10], the formation of micro cracks in brittle epoxy matrices could aid energy dissipation and consequently the fatigue response. Mostly, the damage growth in composites is specified by stiffness degradation [11, 12]. Tong et al. [13], have analyzed the fatigue of the composite structure and have identified that, a critical number of load cycles is required to produce significant change in the composite. According to Raif et al. [9], fiber density, fiber angle and resin permeability are the factors contributing to the fatigue life of GFRP material. The role of fibre reinforcement as crack arrester should be acknowledged in this context.

The damage pattern of the GFRP composite is dictated by fibre orientation in the lay-up. It has been assessed that, the propagation of cracks into the adjacent plies is possible when the interaction angle between the crack and the ply [2, 14] is minimized. Salvia [15], has identified the positive influence of interface shear strength and matrix toughening on the performance of GFRP composite laminate. The inter- laminar/ intra-laminar debonding of composite laminate is controlled by the fibre orientation [6, 16]. Shokrieh et al. [17], have classified the damage as matrix mode (with fiber orientation between 10^0 and 90^0) and fiber mode (with fiber orientation between 0^0 and 10^0).

Application of stress on the composite, either, be it in flexure or in tension, leads to generation of defects in the composite which are normally assessed by NDE technique such as ultrasonic scanning, acoustic emission (AE) monitoring. AE is an intelligent online monitoring technique, in which transient elastic (stress) waves are generated by the rapid release of strain energy within the material under stress. Thus the structural integrity of the composite and damage localization can be assessed by acoustic emission in terms of initiation of damage (cracks), propagation and failure i.e., either continuous mode of defects generated or burst mode of rapid/ sudden failure can be identified by analysing the signal in frequency domain (power spectrum). The power spectrum of the signal will illustrate the developed frequency peaks pertaining to the mode of defects monitored. Also, the AE counts are proportional to the modulus and it can also quantify [18] the fatigue response of the glass epoxy composites to the applied stress. The structural integrity of the composite and damage localization are assessed by the acoustic waves [19]. The damage sequence exhibited by the GFRP is characterized by peak frequency of the stress waves [20]. Thus the AE signal will be a positive indicator of the status of a material under stress.

In the present work, the significance of fibre orientation on the flexural modulus of GFRP laminates exposed to cyclic loading prior to flexure study has been

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investigated and the damage modes are characterized by monitoring the acoustic emission (AE) from the test specimen under flexure loading. Angle ply and cross ply GFRP laminates are exposed to cyclic load up to around $60x10^3$ cycles in the order of $10x10^3$ cycles of the chosen frequency. This dynamic environment is to simulate the loading of a leaf of automobile leaf spring and structure response to flexure induced by the cyclic load due to road-tyre interaction. Virgin and cyclic loaded laminates were subjected to (AE monitored) three-point bend test to correlate their flexural modulus with the various damage modes.

2. MATERIAL AND SPECIMEN PREPARATION

The glass fiber roving of aerial density 1100 gm/m^2 and epoxy polymer resin LY 556, with hardener HY995 was used for the preparation of Glass Fibre Reinforced epoxy Polymer (GFRP) specimens. The resin and hardener were taken in the ratio of 10:1. The angle ply (0/30/60/0) and cross ply (0/90/90/0) laminates were prepared by hand lay-up technique to size of 300x300 mm^2 with fiber volume fraction of 32%. Laminate preparation was carried out between two glass plates and cured for a period of 24 hours with a surface pressure of 1 kN/m^2 by keeping dead weight on the laminate after the initial setting of the matrix. The test specimens (Fig. 1 a, b) were cut by diamond tipped circular saw from the laminate plate to a size of length 150mm, width 10mm, thickness 4mm (L x W x T). The cut specimens were edge finished with fine emery paper to reduce the defects due to rough edges.

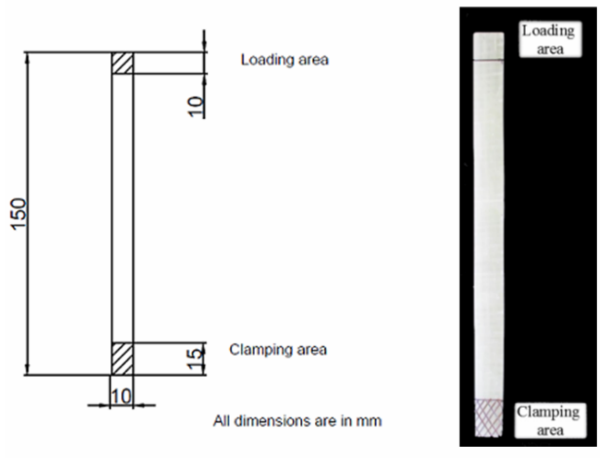


Figure 1. a) Specimen Dimension and b) Cut Specimen

3. EXPERIMENT

3.1 Experimental Procedure

The experiment for the intended work comprised two stages,

1. The flexural modulus (three point bend test by ASTM D 790) and AE output of the virgin specimen were determined.

2. a. Fresh set of virgin specimens were exposed to cyclic loading for a specific number of cycles in the order of $10x10^3$ up to around $60x10^3$ cycles.

b. The flexural modulus and the AE signal of each pre-loaded specimens were obtained similar to the virgin specimen after a specific number of cycles.

An average of five test results of the virgin and the pre-loaded specimen has been utilized for the analysis and discussion.

3.2 Cyclic loading

Low frequency, constant amplitude cyclic loading was imposed on the specimen using a rotating eccentric disc with a constant amplitude of 3mm. The disc was mounted on the spindle of a radial drilling machine and rotated at 516 rpm (to yield frequency of 8.6Hz) in a loading arrangement as shown in the Fig.2. The loading frequency was fixed at 70% of the least first mode (ω_n) natural frequency of cantilever beam model (Table. 1), using the following relation:

$$\omega_n = 1.875^2 \sqrt{\left(EI / \rho A L^4\right)}$$

$$E = \eta_\theta E_f V_f + E_m V_m$$

$$\eta_\theta = \sum a_n \cos^4 \theta$$

where a_n= Number of layers with θ orientation, $I = bd^3/12$, $\rho = \rho_f v_f + \rho_m v_m$

Table 1. First mode natural frequency of cross and angle ply laminate

Sl. No	Laminate	First mode natural frequency (Hz)
1	0/30/60/0	13.39
2	0/90/90/0	12.05

The specimen was clamped in a rigid vice and cyclic load was imposed at free end. To have maximum effect of loading, the clamping length was limited to 10% (15 mm) of the total length (150 mm) of the specimen to simulate a cantilever beam model of the leaf spring condition under service condition. The amplitude of the loading i.e., the displacement of the loaded end of the beam was 3mm. Each loading cycle on the specimen combines the effect of both tensile and compressive deformation of the beam.

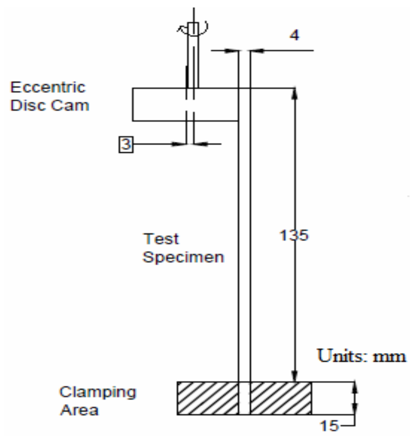


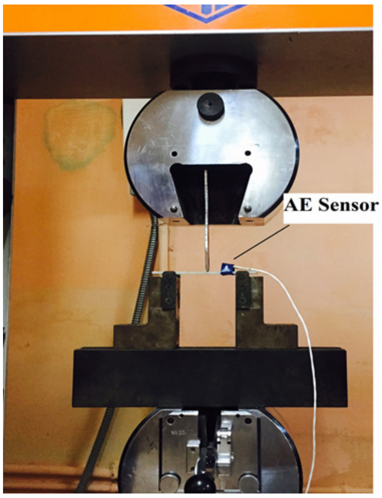
Figure 2. Cyclic loading arrangement

3.3 AE monitored flexural testing

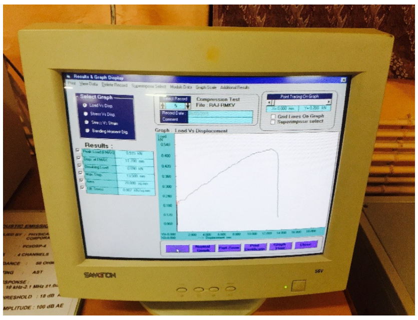
The flexural response of both the virgin and pre-loaded specimen were obtained by three point bend test as per ASTM D790 with a crosshead speed of 0.5mm/min (Fig.3 a, b). The flexural modulus of the specimens is calculated using the following formula. The maximum flexural deflection of the virgin specimen has been utilized to fix the amplitude of cyclic loading to be within safe limit for both the laminate configurations.

$$E=mL^3/4bd^3$$

where E= Flexural Modulus (kN/mm^2), L, b, d = Specimen span length, width and thickness = 100mm, 10mm and 4mm, m = Slope of the load deflection curve from three point test.



(a)



(b)

Figure.3 a) Three Point Bend Test (TPBT) with AE sensor, b) Load displacement curve of TPBT

During flexure loading the acoustic emission from the loaded specimens were monitored. Acoustic emission is the elastic wave generated by the rapid release of energy from sources within the material under stress. Hence the monitoring AE signal from the stressed specimen will reflect the state of material such as yielding, cumulative yielding, threshold crossover and crack propagation. It is an intelligent monitoring technique to identify the status of the material under stress.

A four channel AE system with DiSP TRA data acquisition system with a sampling rate of 10 mega samples per second (MSPS), supplied by Physical Acoustics Corporation, was used to monitor AE data. The ambient noise was filtered using a threshold equal to 18 dB. AE measurements were obtained by using one broadband PAC sensor. The amplitude distribution covers the range of 0–100 dB (0 dB corresponding to 1 mV at the transducer output).

The input parameters used for AE monitoring are as follows: peak definition time (PDT), hit definition time (HDT) and hit lock-out time (HLT). These time intervals enable the partition of the continuous AE stress wave into separate hits, in order to analyse them using signal descriptors, such as counts, amplitude, energy, events, duration and rise time. Values for PDT, HDT and HLT have been selected based on the literature. The AE sensor is positioned at 25 mm from the center point of loading. Positioning was done ensuring minimum attenuation of the signal using the suitable connector. The feature extraction sample signal is shown in Fig. 4 and the parameters used for the extraction are:

1. Amplitude: The maximum AE signal excursion during an AE hit (signal). Unit: dB.
2. Energy: Derived from the integral of the rectified voltage signal over the duration of the AE hit- Unit: Microvolt sec.
3. Counts: It is the count of AE excursion over AE threshold.
4. Duration: It is defined as the time taken from the first threshold crossing to the end of the last threshold crossing of the AE signal from the AE threshold.
5. AE Threshold: The minimum amplitude of the AE signal. Unit: dB

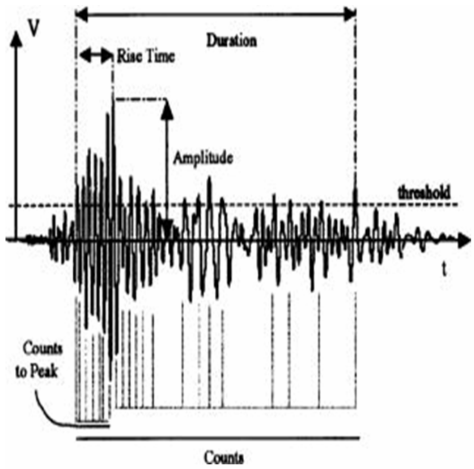


Figure.4 Acoustic Emission Hit Feature Extraction (Source. Physical Acoustics, Singapore)

The failure mode of composite is complex, unlike the case of metallic material the heterogeneous composite exhibits defects isolated in space in different modes and each mode generates respective AE signal feature. The AE signal is related to the amount of strain energy released attributable to the effect of damage to the material. Therefore, each AE waveform will be a composite signal containing different frequencies and amplitude. A unique feature in terms of energy content, duration, and counts representing he respective mode of damage, such as matrix cracking, debonding and delamination, and fibre failure [20]. Thereby, distinct frequency ranges of AE signal are correlated with matrix cracking, fibre matrix debonding/ delamination and fibre failure.

4. RESULT AND DISCUSSION

4.1 AE Energy and Flexural modulus of virgin specimen

The AE energy is the feature derived from the integral of the rectified voltage signal over the duration of AE hit and is similar to signal strength used to quantify the material property. The flexural modulus and the average AE energy of the virgin, angle and cross ply laminate specimens during the three point bend test are given in the Table 2.

Table 2. Flexural Modulus and AE Energy of virgin specimen

Laminate	Flexural Modulus kN/mm2	Average AE Energy μvolt sec
0/30/60/0	42.3	107.31
0/90/90/0	36.3	50.44

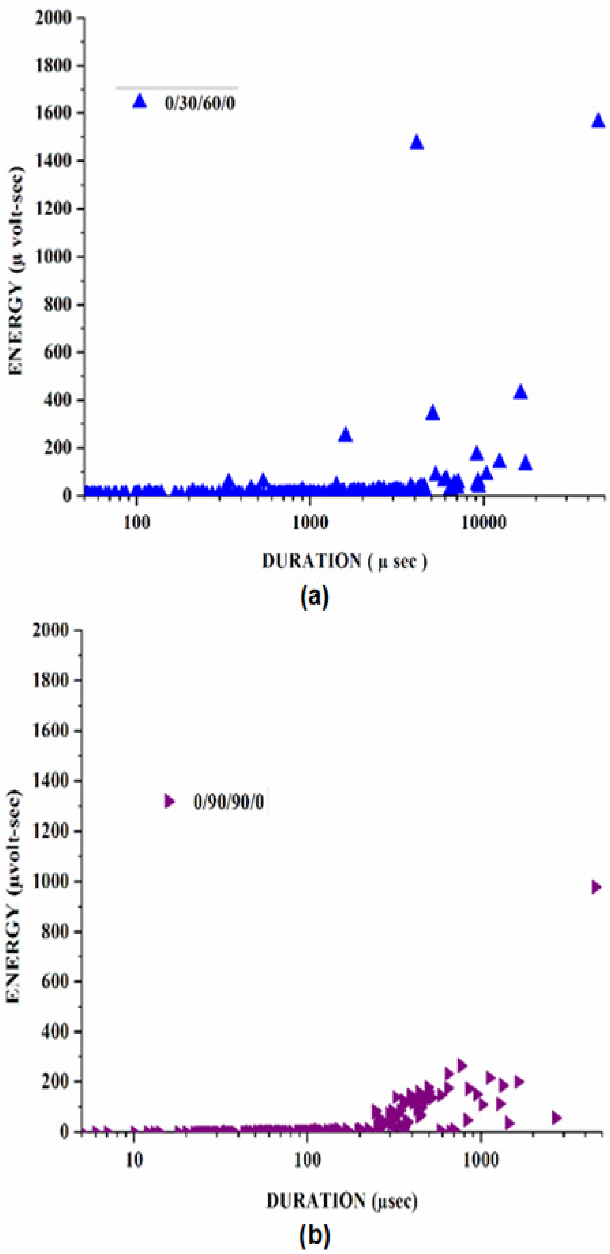


Figure 5. Energy Distribution Plot of virgin specimen (a) 0/30/60/0 Laminate (b) 0/90/90/0 Laminate

The Fig. 5a, b illustrates the AE energy distribution during the flexural test of the virgin specimen.

The average energy release of angle ply is more than cross ply laminate (Table 2) accounting for their respective flexural modulus. However, the relatively higher number of release events with 0/90/90/0 ply is attributable to the dominant matrix damage and associated energy absorption. It is seen that angle ply laminate exhibits low energy emission up to around 7000 µsec, followed by an increase in energy release indicating sustained deformation of the composite under flexure for a longer duration followed by a high energy burst mode of energy emission attributed to the fibre failure (Fig. 5a). The same phenomenon is seen in the flexural response of cross ply laminate, but with lower bound values of energy emission and duration, thus reflecting the level of flexural resistance in comparison to angle ply laminate. It is observed from the duration of AE energy that, the angle ply laminate takes a longer duration of around 10,000 µsec, whereas it is around 1000 µsec in the case of cross ply laminate as illustrated in Fig. 5b. Both the values are the indication of the internal resistance offered to the flexural load in three point bend test, i.e. influence of fibre orientation in the lay-up sequence. The reduced fibre orientation interaction angle in the lay-up sequence offers better resistance to flexural load.

4.2 Flexural modulus of pre- loaded specimen

The typically monitored flexural modulus variation of the laminates after cyclic load is shown in Fig.6. The flexural modulus of both the laminates shows a decreasing trend on exposure cyclic load. Composite material exhibiting a model with resistant to cyclic load or marginal performance increase with cyclic load [10]. It is observed that, angle ply laminate 0/30/60/0 exhibits a better flexural characteristics.

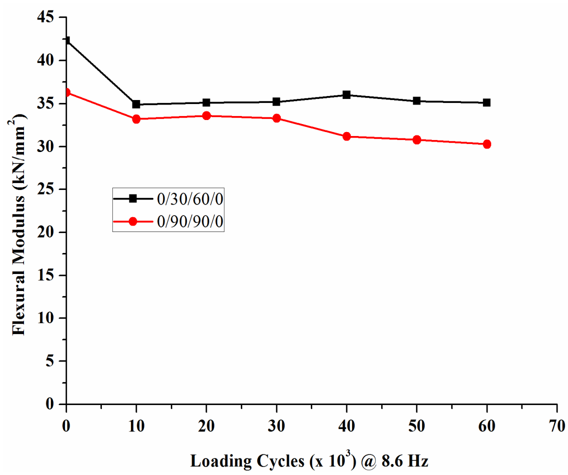


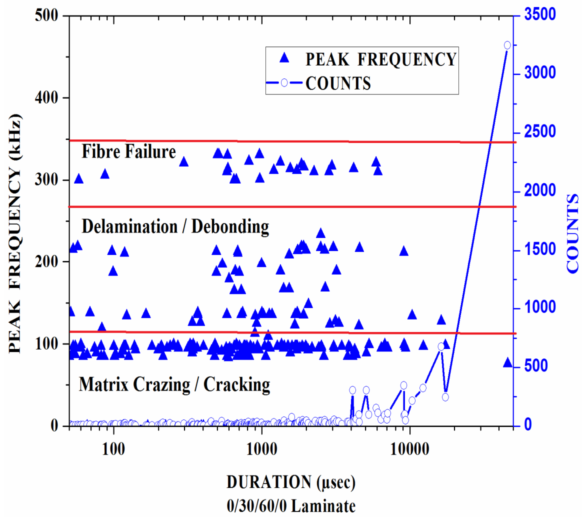
Figure 6. Flexural Modulus of 0/30/60 and 0/90/90/0 laminate on exposure to loading cycles

After an initial drop, the angle ply laminates 0/30/60/0 exhibits a marginal rise in flexural modulus on exposure to cyclic loading, unlike the case of homogeneous metallic material (exhibiting progressive drop in flexural modulus due to cyclic load). However, 0/90/90/0 cross ply laminate exhibits a reduction in modulus up to 10x10^3 cycles followed by a steady value up to 30x10^3 cycles and a drop further. The cross ply laminates (0/90/90/0) exhibit a reduction in flexural modulus. With cross ply laminate the reduction is sequential and the structure is able to sustain the defects up to certain period followed by a drop.

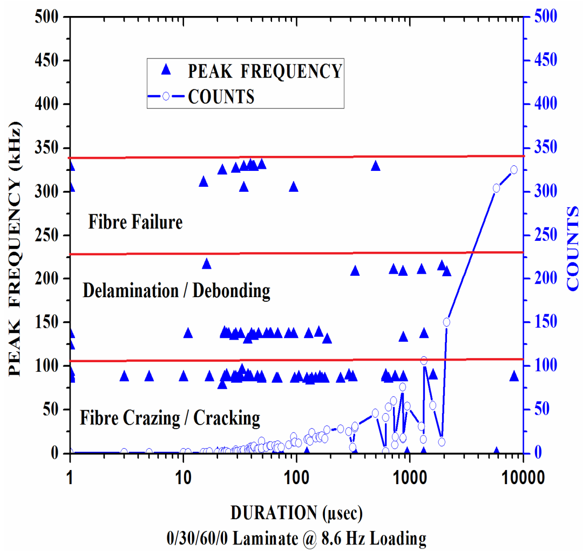
The observed variation of flexural modulus with cyclic loading can be attributed to possible crack arresting mechanism within the composite due to reinforcement. Dominant crack arrest can be seen in the low fibre angle orientation in the lay-up sequence of the laminate specimen.

4.3 Flexural damage characterization by AE

Apart from the modulus characterization of the laminates on exposure to cyclic load, the AE signals can also be effectively utilized to characterize the damage of the angle and cross ply GFRP laminate [20]. Analysing the monitored AE signal in terms of the frequency domain, it was observed that at peak flexural modulus, the signal contains sparse spikes around 300 kHz, less denser spikes around 200 kHz and dominant (dense) spikes around 100 kHz as illustrated in the Fig. 7 (a) and 8 (a).



(a)



(b)

Figure 7. Duration Vs Peak Frequency, Counts of 0/30/60/0 laminate a) Virgin b) Pre- loaded at 40x10^3 cycles

The AE signal of 0/30/60/0 laminate, contains dominant low peak frequency pikes over a longer duration, coupled with medium and high peak frequency spikes beyond 1000 μsec attributed to the continuous matrix crazing, followed by delamination and fibre breakage as demarcated in the Fig. 7a.

Unlike the case of 0/30/60/0 angle ply laminate, the cross ply laminate with higher fibre orientation angle (90^0) in the lay-up sequence mostly exhibiting matrix failure. It is well reflected in the occurrence of dominant low frequency spikes and sparsely populated medium and high peak frequency spikes as illustrated in Fig. 8 a.

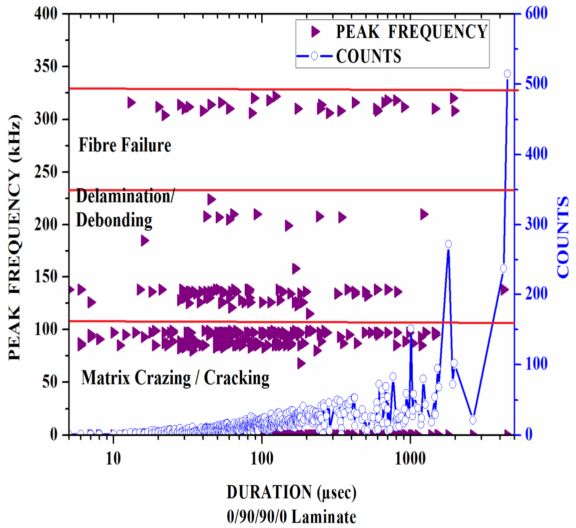
Another AE parameter for analysing the material response is the AE counts, which refers to number of AE signal excursions over the AE threshold. The count value directly depicts the structural integrity and it also states the stress limit at which unrecoverable damage takes place in the composite. Higher the counts, the higher is the stress value indicating the intactness of the fibre matrix system in composite laminate.

Table 3. Peak frequency range and counts of virgin laminate

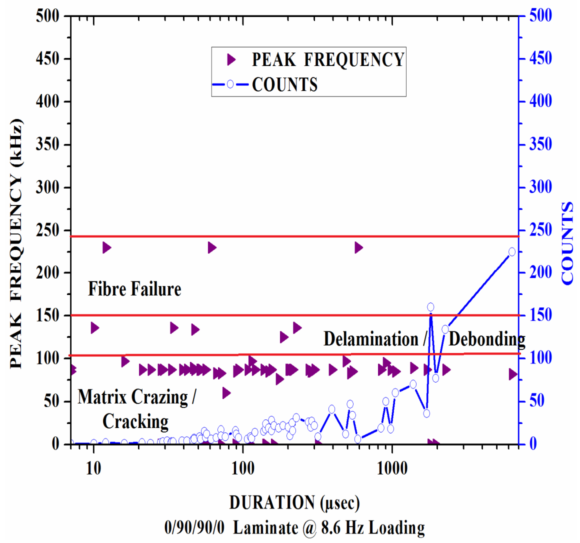
Laminate	Peak Frequency range kHz			Max. Counts
	Band 1	Band 2	Band 3	
	Matrix Crazing	Delamination	Fibre Failure	
0/30/60/0	90-110	110-225	300-330	3250
0/90/90/0	60-110	110-225	300-330	525

The frequency range corresponding to the damages and the counts of virgin specimen is given in Table 3. The frequency range of virgin, angle and cross ply laminate are similar. But, AE counts of the angle ply laminate are higher than cross ply laminate. Even though, the peak frequency ranges are similar for both the virgin specimens, the AE counts along with the duration exhibits the higher resistance offered by the angle ply laminate to the applied flexural load in 3PBT, as illustrated by higher flexural modulus.

Specimen under flexure loading will exhibit matrix crazing in the early phase of loading associated with load transfer by the matrix to the reinforcements. During this period, depending on the fibre orientation and consequent crack arresting the crazing of the matrix will continue to occur. The illustrations on Peak frequency and counts clearly show dominant matrix crazing in the case of 0/90/90/0 cross ply laminate. Normally, with higher fibre interaction angle, matrix damage will dominate. Also, the transverse loading of the laminate with fibre orientation of 90^0 cannot serve as effective crack arrester. It is to be noted, that matrix crazing is almost a continuous phenomenon associated with AE of continuous mode indicated by low peak frequency. Also, it can be seen that generally loading of 0/90/90/0 ply exhibits relatively lower order counts indicating the reduced order of energy release attributable to enhanced absorption of work/energy. Once initiated, on continuous flexure loading matrix crazing is followed by delamination and subsequent fibre-breakage. Fibre breakage is associated with a burst mode of emission indicated by higher peak frequency (around 300 kHz) while delamination is a mixed mode associated with mid peak frequency as illustrated in the Table. 3 and 4. The absence of 90^0 ply in the angle ply laminate (0/30/60/0) offers better crack arresting reinforcement as illustrated by respective higher order peak frequencies and counts (Fig. 7a, Table. 3).



(a)



(b)

Figure 8. Duration Vs Peak Frequency, Counts of 0/90/90/0 laminate a) Virgin b) Pre- loaded at $40x10^3$ cycles

Table 4. Peak frequency range and counts of pre-loaded laminate at $40x10^3$ cycles

Laminate	Peak Frequency range kHz			Max. Counts
	Band 1	Band 2	Band 3	
	Matrix Crazing	Delamination	Fibre Failure	
0/30/60/0	80-100	125-225	300-330	325
0/90/90/0	50-100	100-150	Around 235	250

The AE data of the pre-loaded specimen at 40x103 cycles as shown in Fig. 7 (b) and 8 (b), have been chosen for discussion. At this particular loading cycle the chosen laminate exhibits varied response. Except the peak frequency range of fibre failure of pre-loaded angle ply laminates, all other values in Table. 4 exhibiting the effect of cyclic loading on both the laminates in comparison to virgin laminate values (Table.3). However, with pre-cyclic loading, both the laminates exhibit short duration and smaller counts. Thus the AE counts act as a clear indication of the damage induced by the cyclic loading in the respective laminates. The number of counts in the angle ply laminate is higher than the cross ply laminate, exhibiting its damage resistance attributed to the reduced fibre orientation angle in the lay-up sequence. Whereas, the lower number of counts in the cross ply laminates exhibiting the presence of orthogonal interaction offers poor resistance.

Moreover, the distribution of the peak frequency before and after the cyclic load illustrates the occurrence of damage in the fibre matrix system. The denser peak frequency distribution (Fig. 7a and 8a) in virgin specimen indicates the presence of intact fibre-matrix system. The sparse peak frequency distribution (Fig. 7b and 8b) in the pre-loaded specimen indicates the damage induced by the imposed cyclic load.

5. CONCLUSION

The cyclic load induced flexural response and damage in the cross ply (0/90/90/0) and angle ply (0/30/60/0) laminate of GFRP composite are characterised by flexural modulus and corresponding AE features.

The following concluding remarks are made from the test results.

1. The flexural response of the angle ply laminate is better than cross ply laminate, which is attributed to the dominant crack arresting reinforcement with smaller fibre orientation angle in the lay-up.
2. The load induced damage is effectively characterized by micro level examination than macro testing (three point test).
3. The flexural modulus reduction of pre-loaded specimen indicates the occurrence of damage in the laminate.
4. The glass epoxy composite exhibiting a model with resistant to cyclic load or marginal increase in the performance [10] with cyclic load for specific load cycles. This is in contrast with homogeneous metallic materials.
5. The damage sequence in the glass epoxy composite on exposure to service environment are matrix crazing, delamination/debonding and fibre failure.
6. The energy, peak frequency and counts of AE can be reliably used for characterizing the damage sequence of the composite laminate.
7. Three ranges of peak frequency (50- 110 kHz, 100-225 kHz and 235- 330 kHz) are observed to classify the damage sequence modes as matrix crazing/cracking, fibre matrix delamination/ debonding and fibre failure respectively.
8. The influence of fibre orientation on the performance of the laminate is reinforced by the AE signal analysis.

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КАРАКТЕРИЗАЦИЈА ОШТЕЋЕЊА КОМПОЗИТНОГ МАТЕРИЈАЛА ОД ПЛАСТИКЕ ОЈАЧАНЕ СТАКЛЕНИМ ВЛАКНИМА ПРИ ИЗЛАГАЊУ ЦИКЛИЧНОМ ОПТЕРЕЋЕЊУ АКУСТИЧНОМ ЕМИСИЈОМ

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Епокси ГФРП (glass fibre reinforced plastic) композитни ламинати са укрштеним влакнима (0/90/90/0) и влакнима оријентисаним под углом (0/30/60/0) били су изложени динамичком оптерећењу, са константном амплитудом при 8,6 Hz, са променљивим циклусима оптерећења. Оптере–ћење је постављено на узорак лиснате опруге ауто–мобила у циљу извођења симулације оптерећења (узимајући у обзир интеракцију друма и пнеу–матика). Модул савитљивости сировог и претходно оптерећеног узорка добијен је испитивањем на савијање у три тачке методом ASTM D790. Код обе врсте ламината запажено је опадање вредности модула савијања приликом излагања динамичком оптерећењу. Код испитивања на савијање реакција материјала на оптерећење савијањем оцењивана је праћењем акустичне емисије од стране узорка изложеног савијању. Анализа резултата акустичне емисије показала је да постоји утицај оријентације влакана код контролисања преноса оштећења и обима оштећења као што је пуцање матрице, раздвајање, деламинација и пуцање влакана.