Effect of ply orientation in single leg (SLB) GFRP composite laminate under bending *

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Abstract :
The stacking sequence, fiber orientation and interlaminar bonding plays an important role in determining the strength of the laminated composites. The main aim of this study is to determine the benefits of tailoring fiber orientation in delamination resistance of Single Leg Bending (SLB) composite laminates. Fracture toughness in Unidirectional and multidirectional Single Leg bending glass/epoxy composite specimen were evaluated under mixed mode (I + II) static loading condition. The study was mainly focused on obtaining fracture toughness of the composite laminate using strain energy released rate parameter. Analyses of failure modes and their influence on the fracture behavior of the laminate were investigated using acoustic emission monitoring technique. The dominating influence of delamination failure mode in SLB specimens was justified using acoustic emission results. All results show the fiber orientation has a major impact on fracture toughness of the SLB composite laminate.

Keywords: Acoustic Emission (AE); Strain Energy Release Rate (SERR); Single Leg Bending (SLB).

1. INTRODUCTION

Laminated fiber reinforced composite materials due to its advanced manufacturing technologies with very low cost, they are used as high performance structural components in aircraft , automotive , civil and ship building industry. However GFRP laminates have less stiffness when compared to other composite laminates, due to their better availability and low cost they are used in most of the structural components. Although laminated composites fail due to the combined effect of debonding, delamination, fiber tear and matrix cracking. Delamination is the most important precursor of the material failure, so delamination heavily reduces the stiffness of the material when compared to all other failure modes

Thus strength and stiffness of laminated composites primarily depend upon fracture resistance. Delamination in composite laminate take place in an unpredicted manner when they are subjected to an impact or thermal load. Fiber orientation of composite laminates is tailored depending upon their application, in such a case delamination initiation, propagation and the crack font differs depending upon the fiber orientation. Even though delamination take place in mode I (peeling mode), mode II (in-plane shear mode) and mode III (out of plane shear mode), a pure mode delamination is not possible. In a practical situation delamination take place in mixed mode condition, mostly dominated by mode I and mode II (mixed mode I +II condition). Many test specimens for determining mixed mode (I+II) strain energy release rate were found over past 50 years. Out the asymmetric double cantilever beam (ADCB) [Xiao *et al.* (1993)] specimen, the cracked-lap shear (CLS) specimen [Lai *et al.* (1996)], the Edge Delamination test (EDT) [Chiang *et al.* (2003)], the mixed-mode flexure (MMF) [Rikards *et al.* (1996)] specimen, the mixed mode bending (MMB) [Kenane and Benzeggagh (1997)] specimen, the mixed mode ELS specimen, the single leg bending (SLB) specimen [Krueger], the Arcan [Nikbakht and Choupani (2008)], the Single leg four point bending (SLFPB) specimen [Szekrényes and Uj (2005)], the Double end-notched flexure (DENF) specimen [Andr´as SZEKR´ENYES] are used for mixed mode testing . Most of the mixed mode specimens like ADCB, EDT, MMB require complicated loading mechanism to produce a pure mixed mode (I+II) loading condition [Crews *et al.* (1988)]. MMB specimen is standardized by ASTM and widely used specimen for mixed mode testing. Simple compliance calibration method of data reduction is not applicable to MMB testing, making the data reduction complicated and erroneous [Szekre´ Nyes and Uj (2007)]. The SLB coupons were first used by [Davidson and Sundararaman (1996)] to determine the SERR due to mixed mode delamination. The simple design and compliance calibration method of data reduction makes SLB widely accepted coupon to determine SERR for mixed mode test [Utomo *et al.* (2007)]. Non destructive Acoustic emission technique is used in this study as a unique tool to determine different damage mechanisms like fiber breakage, matrix cracking, delamination, debonding using the energy of the acoustic signal developed from the stressed composite laminates [Ríos-Soberanis (2011)]. Therefore a detailed experimental analysis is done on unidirectional and various multidirectional GFRP SLB composite laminates under mixed mode loading (I+II) condition to determine SERR. To conform visually observed results and to acquire certain unobservable data acoustic emission accumulation is used.

2. EXPERIMENTAL PROCEDURE

2.1. Material and Specimen fabrication

In this study unidirectional glass fiber with 50% by volume were reinforced with 45% by volume of LY556 Epoxy resin mixed with 5% of HY951 hardener. Hardener was used for better curing of the laminate within 24 hours. As unidirectional glass fibers diameter is more compared to other fibers, the thicker film insert is used [Cannas *et al.* (2007)]. Mylar sheet of thickness 0.08mm is used as the crack initiator in between the middle layer to simulate crack. Single Leg Bending test for mixed mode (I+II) delamination is not standardized by ASTM. All dimensions required for the study are taken from best literatures on SLB test. The SLB specimen dimension and notations are given in Fig. 1. Laminates were fabricated using conventional hand layup technique. Due to the complicated geometry of SLB specimen special care must be given on fabrication and cutting a part of the bottom leg of the specimen. The following fiber orientations were taken to determine the SERR in this study.

Table I. SLB Specimen Orientations

S. No	Orientation	Stacking Sequence
1	Zero ply	[0°/0°/0°/0°]
2	Cross ply	[0°/90°/90°/0°]
3	Angle ply	[+45°/-45°/+45°/-45°]
4	Quasi Isotropic	[0°/-45°/+45°/90°]

2.2. Test configuration

In each orientation 3 similar specimens were tested and the averages of best two test results were taken to determine SERR. The SLB testing is done in 100KN capacity three point bending UTM machine. The loading was done at a constant displacement rate of 0.25mm/min under controlled conditions. Acoustic emission sensors were also connected to the SLB specimen as shown in the Fig. 1. The plots of the dominating failure modes and delamination area were obtained, simultaneously the critical load P and the displacement u corresponding to the material failure were obtained. The SLB test is done in three stages (i) precracking, (ii) compliance calibration (iii) static SLB test. The quasi static SLB test without precracking produced a high value of SERR and also unstable crack propagation due to the accumulation of resin in between the Mylar sheet insert and the laminate plies. So all specimens were Precracked using a thin stainless steel blade under controlled conditions without propagation of cracks. Pre cracking can be also done under mode I and mode II methods but they creates unpredicted crack initiation and a different crack font, so they are not suitable for the pre cracking test. All pre cracked specimen before the static SLB test was subjected to compliance calibration. Compliance calibration is performed for data reduction purpose at crack lengths of a, a±5mm, a±10mm (where a is the initial crack length, a=30mm) by sliding the SLB specimen over the fixed three point bending fixture maintaining a fixed half span of L= 50mm, without any crack onset or propagation. The same initial crack length (a=30mm) is also maintained for static SLB test with a half span of L=50mm. The a/L ratio for SLB configuration should be maintained greater than 0.49mm for better observation of critical load corresponding to delamination onset [Szekrenyes (2010)]. So the static SLB test was done with a/L = 0.6 until a drop in the load was observed, from which the critical load and displacement was observed. The loading was performed at 0.25mm /min for both compliance calibration and static SLB test.

2.3. Acoustic Emission monitoring

Eight channel acoustic emission setup supplied by Physical Acoustics Corporation (PAC) is used for AE studies as shown in the Fig. 1. AE activities were sensed using a Nano piezoelectric sensor, filtering out frequencies exceeding 750kHz and noise was filtered using a threshold at a value of 45dB. High vacuum silicon grease was used as a couplant. The amplitude distribution covers the range 0-100dB. After mounting two transducers on the sample at a mutual distance of 80 mm between them, so that they were both at the same distance from the center of the specimen length, a pencil lead break procedure was used to generate repeatable Acoustic Emission signals for the calibration of each sensor. AE wave velocity for the specimen was found to be 3126m/s. Parametric Analysis is initially used to track and identify the different failure mechanisms based on the AE parameters such as amplitude, rise time, counts, energy and duration for GFRP SLB specimen.

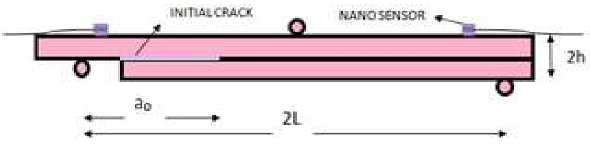


Fig. 1. SLB Specimen.

3. *DATA REDUCTION*

In order to determine the nature of delamination initiation and propagation three different approaches were used (i) Stress intensity factors [Chow and Atluri (1997)] (ii) Strain energy release rate [RameshKumar *et al.* (1997)] (III) J-integral [Lee and Tu (1993)]SERR is the most commonly used fracture parameter to determine the fracture behavior. SERR is the measure of energy required for onset and propagation of the crack while straining (first proposed by Irwin 1952). Complicated analysis of stress field at the crack tip is required in case of Stress intensity factors and J-integral. The fracture behavior through SERR can be found using (i) Classical Plate Theory (CPT) (ii) Timoshenko Beam Theory (TBT) [Martin (1991)] (iii) Compliance Calibration (CC) method [Ilcewicz *et al.* (1988)]. CPT and TBT use standard theoretical flexural modulus (E11) and longitudinal shear modulus (G13) to determine the SERR. The E11 and G13 values for the manufactured multidirectional SLB specimen will not be equal to standard theoretical values, so CPT and MPT method of determining SERR produces error results [Zhang *et al. (1994)*]. In compliance calibration method material properties for the respective SLB specimens were directly determined from the experimental analysis. SERR is determined through a CC method in this study.

3.1. Compliance Calibration (CC) method

The most commonly used expression to determine SERR is given by (1),

$$G = \left(\frac{p^2}{2b}\right) * \left(\frac{dC}{da}\right) \qquad (1)$$

Where b is the breadth, C is the compliance of the SLB specimen determined by C=u/P,

$$C(8bh^3) = A + Ba^3 \qquad (2)$$

A graph is plotted between C8bh^3 and a$^{3.}$ The Parameters A and B are determined by a least square fit of a straight line in the C (8bh^3) vs. a^3 plot. Measured dC/da value from (2) is substituted in (1) to get the actual SERR of the SLB specimen.

4. RESULTS AND DISCUSSIONS

4.1. Compliance Calibration

The load was plotted against displacement of SLB specimen for each crack length. For each fiber orientation specimen the compliance values for successive incrementation in the crack length were obtained by least square curve fitting of load were plotted against displacement. Compliance values for each orientation are summarized in the Table II

Table II Compliance For Different Crack Length.

specimen/a	20 (mm/N)	25 (mm/N)	30 (mm/N)	35 (mm/N)	40 (mm/N)
Zero-1	0.007179	0.008863	0.011659	0.015431	0.019458
Zero-2	0.007434	0.009784	0.012432	0.014734	0.018998
Zero-3	0.006687	0.00781	0.009236	0.011698	0.014603
Quasi-1	0.011837	0.016474	0.021745	0.0222	0.029976
Quasi-2	0.01005	0.011726	0.013969	0.016913	0.022317
Quasi-3	0.011151	0.013268	0.016366	0.019231	0.019133
Angle-1	0.014914	0.018286	0.020971	0.026178	0.031821
Angle-2	0.015625	0.018448	0.021656	0.028965	0.036189
Angle-3	0.016478	0.018353	0.021497	0.025309	0.033863
Cross-1	0.013065	0.015546	0.022262	0.030796	0.041694
Cross-2	0.010623	0.012545	0.017411	0.021211	0.026924
Cross-3	0.011837	0.016474	0.016759	0.022207	0.029911

As glass/epoxy laminate shows more brittle nature compared to other laminate materials, constant amount of load cannot be applied for each successive increment of initial crack length. A little non linearity can be observed in the load displacement curve when the same amount of load is applied for all crack length. This nonlinear behavior produces onset of crack and therefore produces an error in the SERR calculation.

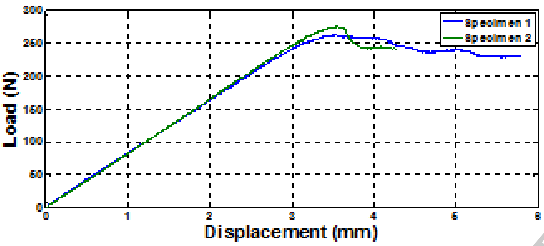
The compliance value (C8bh^3) obtained from load vs displacement plot were plotted against corresponding initial crack length(a^3).The slope of the plot gives value for A and the y axis intercept gives the value for B in the (2). The B value obtained from the plot physically represent the flexural modulus of the respective specimen. In each orientation compliance calibration test was carried out for minimum three specimens and the average of best two values were taken to find out the SERR which is shown in the Table III.

Table III. Parameters A And B For SLB

specimen/a	B (mm^2/N)	A(mm^2/N)
Zero-1	0.004438	110.57
Zero-2	0.003971	128.45
Zero-3	0.002836	110.82
Quasi-1	0.005862	224.27
Quasi-2	0.004303	164.35
Quasi-3	0.002927	224.37
Angle-1	0.005938	261.63
Angle-2	0.007443	249.07
Angle-3	0.006099	269.85
Cross-1	0.005938	163.94
Cross-2	0.007443	170.21
Cross-3	0.006099	197.69

4.2. Static SLB test

The load was plotted against displacement for zero, quasi isotropic ,angle and cross ply orientation SLB specimen respectively as shown in the Fig. 4.



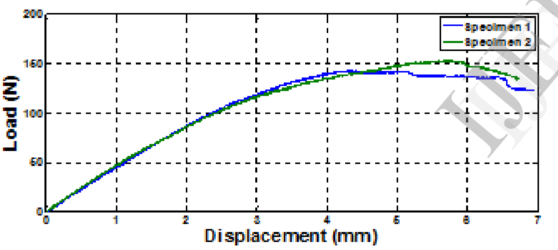


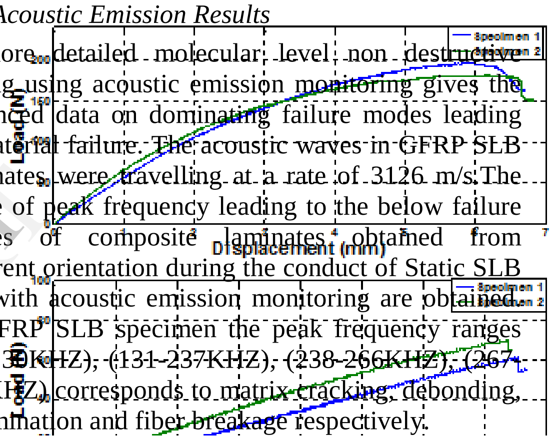
Fig. 4. Critical load for SLB specimens

The static SLB test results for all orientations including critical load, displacement, SERR values were summarized in the Table IV.

Table IV. SERR From SLB Test

Specimen	b (mm)	2h (mm)	P (N)	a (mm)	[illegible]	[illegible]
Zero-1	20	5.1	263	30	0.004204	[illegible]
Zero-2	20	5.1	274.6	30	0.004204	[illegible]
Quasi-1	20.05	4.95	196	30	0.005083	5.406249
Quasi-2	19.85	4.78	182	30	[illegible]	[illegible]
Angle-1	20	5.1	143	30	[illegible]	[illegible]
Angle-2	20.3	5.2	153.2	30	[illegible]	[illegible]
Cross-1	19.02	4.95	61.1	30	0.005963	0.684927
Cross-2	20.05	4.86	69.5	30	0.005963	0.842618

Mixed mode strain energy release rate was obtained by substituting the critical load and the displacement in (1). The critical loads corresponding to delamination were found to be maximum in zero ply oriented SLB specimen and minimum in cross ply SLB specimen. The critical load in zero SLB specimens was in the range of 263N to 274.6N and it is four times higher than the cross SLB specimen. When comparing to cross SLB specimen, angle, quasi zero SLB specimen show more stiffness(critical delamination load/corresponding displacement) due to the transverse load bearing angle and zero ply lamina present next to the initial crack tip area. Maintaining the value a/L = 0.6 in static SLB test produces a much more visible and well defined point of critical delamination load on the Load VS displacement plot. Even though the specimens were precracked before commencing static SLB test a slight variation in the peak load can be seen on each specimen due to variation in the resin distribution in the crack tip area. Once the crack has initiated less amount of load is required to propagate the crack, this is observed from an immediate load drop in each oriented specimen from the load vs. displacement plot.



4.3. Acoustic Emission Results

A more detailed molecular level non destructive testing using acoustic emission monitoring gives the enhanced data on dominating failure modes leading to material failure. The acoustic waves in GFRP SLB laminates were travelling at a rate of 3126 m/s.The range of peak frequency leading to the below failure modes of composite laminates obtained from different orientation during the conduct of Static SLB test with acoustic emission monitoring are obtained. In GFRP SLB specimen the peak frequency ranges (70-130KHZ), (131-237KHZ), (238-266KHZ), (267-520KHZ) corresponds to matrix cracking, debonding, delamination and fiber breakage respectively.

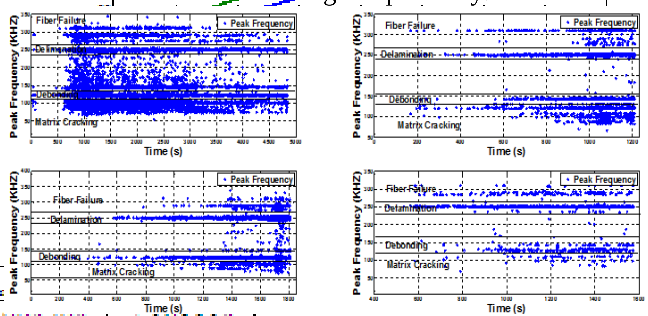


Fig. 5. Peak frequency for SLB Specimen

From Fig. 5, it is justified that delamination failure is predominant in all SLB specimens when compared to all other failure modes. The percentage of failure modes in different oriented SLB specimen are summarized in the Fig. 6.

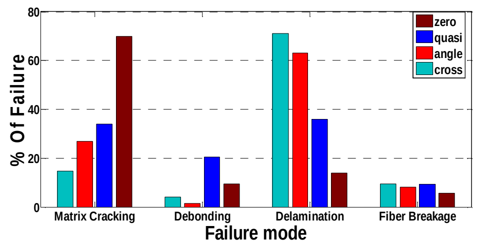


Fig. 6.Percentage of failure mode

From the percentage of failure mode plot, it is confirmed that fiber orientation of composite laminates affects the delamination propagation to a large extend. Under the AE examination, the failure in the zero SLB specimens, Fig. 6, shows that matrix failure and delamination failure were observed. A very large variation in delamination failure mode among different ply laminates is determined. Delamination failure is maximum in cross ply laminates it is about 71% followed by angle ply laminate, it is about 63%. Delamination is more or less equal in zero and quasi isotropic laminates. When compared to zero ply laminate, delamination failure is found five times more dominated in cross ply laminates. Like delamination failure the same drastic variation in matrix cracking failure mode can also be observed. From Fig. 6, Matrix cracking is predominant in the zero SLB specimen, it justifies that a high resistance to delamination is produced by the matrix material near to crack trip.

The progressive damage in the material is easily monitored from the variation of time versus amplitude and duration of AE data for the zero, quasi isotropic, angle and cross ply orientation SLB specimen respectively as shown in the Fig. 7. From the standard parametric analysis of the failure mode in laminated composites, delamination is possible at moderate to high duration and moderate to high amplitude ranges. In angle ply failure is predominantly in amplitude range 70-85db and at duration range 600-1200μs which corresponds to delamination. Delamination mode is predominant in all orientations as observed in angle ply SLB specimens. The peak frequency results were confirmed using amplitude/duration and time graph.

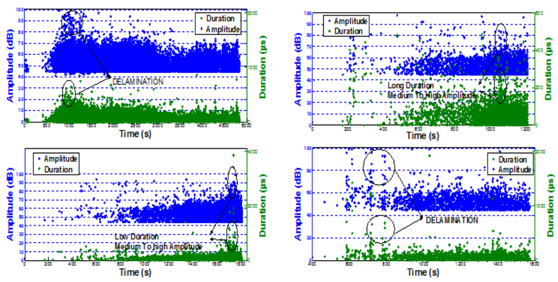


Fig. 7. Amplitude duration plot for SLB specimen

By visual observation and acoustic emission results of SLB specimen, the delamination mode begins from the primary region of cumulative count as indicated in the cumulative count plot for zero, quasi isotropic ,angle and cross ply orientation SLB specimen respectively as shown in Fig. 8. This may be due to the intentionally induced crack, which is provided to develop mixed mode failure. It also justifies, the load drop corresponds to a certain proportion of crack growth and not the crack onset. This nature of delamination growth is observed in all orientations.

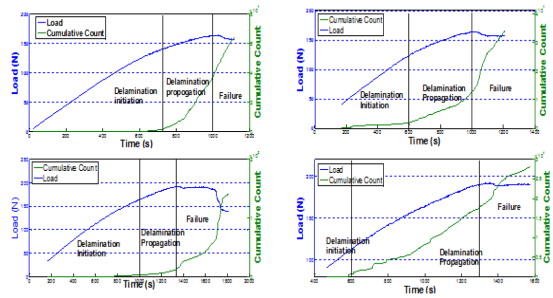


Fig. 8. Cumulative count plot for SLB specimens

From Fig. 9, the location was plotted against time for zero, quasi isotropic ,angle and cross ply orientation SLB specimen respectively .It can be observed stress is concentrated on the crack initiation location which corresponds to the predominant delamination failure mode as observed in peak frequency plots. This same result is observed in all orientation SLB specimens.

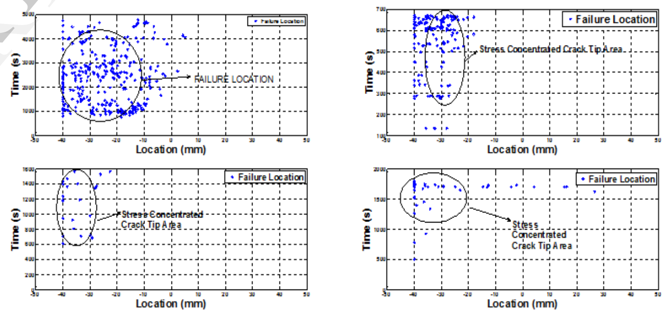


Fig. 9. Cumulative count, load plot for SLB specimens

CONCLUSION

Four different ply oriented SLB GFRP composite laminates were fabricated using conventional hand layup method. Experimental Single Leg Bending test was conducted to determine the fracture behavior of SLB GFRP laminate under mixed mode loading (I+II). The critical load and the corresponding displacement were compared between zero, cross, angle and quasi isotropic SLB specimens. A detailed test procedure for the SLB delamination test is presented for unidirectional and multidirectional GFRP laminates. Compliance calibration method of data reduction is used to determine SERR for SLB coupons. Compliance calibration analysis shows a decrease in the stiffness of the SLB specimen with an increase in crack length. Non destructive acoustic emission testing was done to determine the dominating failure modes and confirm the failure location. AE results confirm that changes in fiber orientation significantly affect the delamination to large extent.

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