Studies on effect of pre-crack length variation on Inter-laminar fracture toughness of a Glass Epoxy laminated composite

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Abstract. Laminates of fiber reinforced polymer composites are good in in-plane properties and inherently weak in through thickness direction. To address this through thickness properties, the inter-laminar fracture toughness ($G_{IC}$ and $G_{IIc}$) of a unidirectional (UD) Glass epoxy composite laminates were subjected to Mode-I and Mode-II loadings. Experiments were conducted using Double cantilever beam (DCB) and End notch flexure (ENF) specimens with varying pre-crack lengths. Mode I energy release rate ($G_{IC}$) were also evaluated with modified beam and modified compliance theories. The experimental results reveal that, $G_{IC}$ fracture toughness increases with increasing in pre-crack length, where as in $G_{IIc}$ the effect of increase in pre-crack length exhibits reduced fracture toughness.

Keywords: Glass-epoxy, Double cantilever beam, End notch flexure, Fracture toughness

1. Introduction

Fibre reinforced polymer composite laminates are a new class of materials have low density and corrosion free. These are the one which are manufactured to get higher mechanical strength and tailored properties [1]. Composites are heterogeneous in composition hence an-isotropic in behaviour. Hence composites have emerged as important structural engineering materials in automotive, marine, aerospace, transportation, infrastructure and civil engineering applications, for their high strength to weight ratio. Composite material characterization plays an important role to improve over metals is still under research development stage [2].

Failure in composites is due to the delamination of the laminates. Inter-laminar fracture is one of the key problems for fibre reinforced polymer (FRP) composites. Its formation greatly reduces the stiffness of a structure, leading to failure during service conditions [3]. Delamination affects the structural performances. The inter-laminar performance is dependent on composite under both tensile and shear stresses. The affect of inter-laminar stresses becomes significant due to geometrical and material discontinuities [4]. Delamination beneath the surface can result in catastrophic failure [5,6]. Fracture mechanics has emerged as an important tool for delamination study. Delamination mainly
occurs by three modes of fracture \textit{i.e.} opening mode, sliding mode, tearing mode and also combination of these modes gives rise to mixed mode. Depending upon the type of load, the energy release rate (\(G_{Ic}, G_{IIc}\) and \(G_{IIIc}\)) are evaluated which corresponds to Mode-I, Mode-II and Mode-III load [7]. Many industries shown the failure occurs due to the presence of Mode-I & Mode-II load [8, 9, 10]. Researchers [9, 10, 11,] estimated Mode-I and Mode-II inter-laminar fracture toughness of laminated composites using DCB & ENF specimens. For materials, pre-crack length will affect the fracture toughness [3]. Hence, in our work an effort is made to study the effect of variation in on Inter-laminar fracture toughness of a Glass epoxy laminated composite under Mode-I and Mode-II by varying the crack length of the specimens.

2. Analysis to determine energy release rate

2.1 Modified beam theory: In general, beam theory over estimates the Mode-I energy release rate for fracture of DCB specimen since this theory uses a model which is perfectly fixed at the delamination front. In practice a rotational moment may occur at the delamination front. A correction factor for the beam theory is applied using the cube root of compliance which is plotted against the delamination.

\[
G_I = \frac{3P\delta}{2b(a + |\Delta|)}
\]  

(1)

Where \(P\) is the peak load at failure, \(\delta\) is deflection at the load point, \(b\) is the beam width, and \(a\) is the delamination length, \(\Delta\) is the correction for the delamination length as suggested in ASTM standard D 5528-94a [12]. This can be found as the x-intercept of the linear least-squares fit of the cube root of the compliance drawn against the delamination length. \(\delta/P\) is the compliance.

2.2 The compliance calibration method for DCB: In this method we estimate the energy release rate by the following equation

\[
G_I = \frac{nP\delta}{2ba}
\]  

(2)

Where \(a\) is the length of delamination, \(C\) the corresponding compliance of the beam, and \(n\) is a dimensionless exponent which is taken as the slope by drawing a linear curve of least-square for \(\log(C^{1/3})\) versus \(\log(a)\). This method details can be obtained from ASTM standard D 5528-94a [12].

2.3. Beam analysis for ENF: The strain energy created in the body and the compliance of the structure, the expressions shown in equation (3) is for Mode II energy release rate for ENF specimen was taken from Japanese industrial standards [13]. Where, \(L\) is the span of the beam

\[
G_{II} = \frac{9a^2P\delta}{2b\left(2L^3 + 3a^3\right)}
\]  

(3)

3. Experimental methods for Mode-I & Mode-II fracture

UD Glass epoxy composite laminates were produced using Hand layup technique. The laminate contained a pre crack which was introduced by Teflon film of 14\(\mu\)m thick placed between the central plies [14]. The total number of 14 layers is used to obtain 4.5mm thickness. The fibre volume content
was about 50%. The plates were cut with jig saw cutter machine to obtain DCB specimen according to ASTM standard D5528-01. Length of specimen taken is 160mm and width 20mm. Pre-crack lengths of 20mm, 25mm and 30mm were used. The specimens were attached by means of pins and fixtures on to the machine and loaded in accordance with ASTM standard [12] are shown in Fig 1. In the test the forces are applied perpendicular to the crack front. In similar manner the ENF specimens was prepared with same dimensions and with same pre-crack lengths as of DCB according to Japanese industrial standards [13]. The ENF specimen is fixed in digital UTM using fixtures is shown in Fig 2.

3. Results and discussion

The typical load versus of DCB specimens is plotted in Fig.3. The peak load at failure for each case was chosen as the highest load point of the linear portion of the load versus displacement plot. It is observed from the load versus deflection behavior of DCB that the load increase slightly and stay steady state as the delamination propagates, this behavior is similar to earlier studies [15,16] for FRP composites. DCB and ENF of 6 set of specimens are used with varying pre-crack lengths for mode-I and Mode II fracture tests. Similarly, the inter-laminar fracture studies were conducted using analytical and numerical techniques by earlier researchers [17, 18]. The peak loads at failure for the DCB were estimated from the experimental results and used to estimate the Mode I critical energy release rate. Fig.3, indicates clearly the load bearing capacity is higher for 20mm pre crack length as compared to other crack lengths. The values of maximum load ($P$), evaluated correction for the delamination length ($\Delta$) and load point deflection ($\delta$) obtained will be substituted in the modified beam theory equation (1) and modified compliance equation (2) to estimate energy release rate. The results obtained from the modified beam theory and modified compliance method are listed in Table 1. From the table 1, percentage of error between both the theories will be less than 3%. Also, the inter-laminar fracture toughness depends on the pre-crack crack length of the DCB specimen [17]. Fig.4 shows the load vs. displacement for ENF specimens which were tested with different length of pre-cracks. From Fig.4, the load withstanding capacity is maximum for 20mm crack length. The energy release rate were estimated under Mode-II by substituting maximum load, displacement from Fig.4 and span length of ENF specimen using equation (3). Table 2 shows the results of inter-laminar fracture toughness under Mode-II loading for various pre-crack lengths. Also from Table 2, the result shows inter-laminar fracture was significantly depends on the pre-crack lengths of the ENF specimen.
Table 1: Mode I energy release rate for DCB specimen

| Crack length (m) | Ultimate load (N) | Fracture toughness by modified beam theory (KJ/m$^2$) | Fracture toughness by compliance method (KJ/m$^2$) |
|------------------|-------------------|-----------------------------------------------------|---------------------------------------------------|
| 0.020            | 1020              | 8.159                                               | 8.01                                              |
| 0.025            | 980               | 8.734                                               | 8.67                                              |
| 0.030            | 920               | 9.067                                               | 8.95                                              |

Table 2: Mode II energy release rate for ENF specimen

| Crack length (m) | Ultimate load (N) | Fracture toughness (KJ/m$^2$) |
|------------------|-------------------|------------------------------|
| 0.020            | 1860              | 3.63                         |
| 0.025            | 1700              | 2.44                         |
| 0.030            | 1510              | 1.37                         |

5. Conclusion:

Glass epoxy laminates were successfully fabricated with varying crack separation using hand layup technique. It is observed that the DCB specimen modified with varying pre-crack length show higher Mode I fracture toughness as compared to standard pre-crack length. But in Mode II fracture toughness the effect of variation in pre-crack length was significant. Mode I energy release rate ($G_{IC}$) obtained from modified beam and modified compliance theories are closely matching with each other. It also indicates that in Mode-II loading crack propagates faster as compared to Mode-I loading, this is due to no fiber bridging was observed during Mode II test. Further work can be carried out under mixed mode conditions.

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