Interlaminar fracture characterization in composite materials by using acoustic emission

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Abstract
This paper proposes experimental approaches to evaluate interlaminar fracture resistance and use acoustic emission (AE) monitoring technique to detect the onset of delamination in real time and to determine mixed mode delamination initiation criteria. The main objective is to exploit damage onset surveillance by detecting ultrasonic stress waves generated by growing interlaminar cracks within composite, to measure delamination toughness in pure mode I and II opening and over a wide range of mode I / mode II ratios. Double Cantilever Beam (DCB), End-Notch Flexure (ENF) and Mixed Mode Bending (MMB) samples were used to calculate strain critical energy release rates for mode I, mode II and mixed mode loading. The total strain energy release rate \( G \) and its mode I \( (G_I) \) and mode II \( (G_{II}) \) components were evaluated using beam theory for the DCB and MMB samples and load based compliance calibration for the ENF sample. These results were compared to a finite element model using the Virtual Crack Closure Technique (VCCT). The mode I energy was plotted against mode II in order to outline failure envelopes, which may enable the prediction of delamination onset in composite materials.

Keywords: Acoustic emission, strain energy release rate, delamination onset, mixed modes I and II, virtual crack closure technique,

1. Introduction

The integration of advanced composite materials into primary structural applications, such as in the aircraft industry, makes the proper understanding of their failure behavior under different loading conditions an important attention. Delamination [1-2], which generally originates from geometric discontinuities such as holes and free edges, under the combined effect of normal and shear stresses, is considered to be the mainly widespread mode of life-reduction and is frequently encountered in real applications. At the onset of crack propagation, macroscopic failures are preceded by micro damage such as fiber fracture, matrix fracture parallel to the fibers, matrix fracture perpendicular to the fibers and delamination, which is the separation occurring between the laminae. After initiation, internal or near-surface delaminations can propagate under static and fatigue loads. Delamination growth redistributes the stresses in the plies of a laminate and may influence residual stiffness, residual strength, and fatigue life. When delaminations occur, combinations of mode I, mode II and mode III are usually present. Onset and accumulation of several types of damage are a serious apprehension for designers using composites in crucial structural elements. For damage monitoring, Acoustic Emission technique (AE) appears as an powerful technique to discern the onset of damages due to mechanical loading [3-6]. The specific advantages such as global monitoring ability and the passive nature of AE sensing to make it a preferred technique for real-time monitoring. Acoustic emission methodology uses a piezoelectric transducer to listen for the first signs of damage in a structure. Abrupt internal stresses caused by crack growth liberate stress waves that travel through the material and are detected by a piezoelectric sensor. The detected AE signals are ultrasonic waves generated in composites by failure
modes involving delamination, debonding, fiber failure, matrix failure and fiber pull out. It has been shown that the acoustic energy propagating in form of stress waves is proportional with the square of voltage produced by a piezoelectric broadband transducer, given by $E_{EA} = \alpha \int V(t)^2 dt$, where $\alpha$ is the gain, $V(t)$ is the amplitude of AE signal, and $E_{EA}$ is the energy of the AE signal. Assuming that this acoustic energy is caused by the release of strain energy as the crack advances suggests that is might be proportional to $G_{IC}$, the strain energy release rate, calculated experimentally by $G_I = 3P\delta / 2ba$. One of the major advantages of AE technique as a global in situ monitoring tool is its capability to detect when and where a microcrack was initiated and to locate active defects in larger structural components without having to physically scan them. Thus, in this study, we attempted to determine the failure criteria envelope of delamination onset associated with static loading by using acoustic emission and fracture mechanic approaches, FEM modeling and by calculating theoretical and experimental values of critical strain energy release rate for mode I, mode II and mixed mode loading in a graphite–fiber/epoxy laminate [7-9].

2. Experimental procedures and FEM Modeling

2.1 Materials
The samples studied are made of 16 layers of unidirectional Cytec AS4/5276-1 carbon epoxy prepreg. Their mechanical properties are $E_{11} = 155.13$ GPa, $E_{22} = 6.2$ GPa, $G_{12} = 4.83$ GPa, and $\nu_{12} = 0.3$. These values were taken from the supplier’s specification sheet, except for $E_{22}$ and $\nu_{12}$, which were taken from MIL-HDBK-754 (AR, 1991). A 50.8 µm Teflon film was placed at the midsection to initiate delamination. The geometry of the specimens used is listed in table 1 for the DCB, ENF and MMB specimens. The main difference between these specimens is their thickness.

<table>
<thead>
<tr>
<th>Table 1. Sample geometry</th>
<th>Unidirectional G40-800</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal</td>
</tr>
<tr>
<td>Width $b$ (mm)</td>
<td>20</td>
</tr>
<tr>
<td>Thickness $2h$ (mm)</td>
<td>3</td>
</tr>
</tbody>
</table>

2.2 Mechanical Testing and Acoustic Emission Monitoring
The unidirectional DCB and MMB samples were tested on a 4206 Instron load frame. A 150 kN A532-1 load cell was used for the DCB samples and a 5 kN 2512 M6 load cell was used for the MMB samples. A MTS load frame with a 2.5 kN load cell was used to test the ENF samples. In the DCB and MMB setups, loading was introduced through hinges glued to the sample with a cyanoacrylate-based adhesive. The ENF samples were simply put on the testing apparatus with care taken to ensure their alignment. Once loaded, the samples did not shift or change position. The MMB support span ($2L$) was 125 mm, the ENF support span was 94 mm and the ENF initial delamination length to half-span ratio $a_0/L$ was 0.5. A thin layer of white nail polish was applied on one side of the sample and 5 mm increments were marked so that, during the tests, the position of the delamination front could be observed with a Dinolite digital microscope. All quasi-static tests were run in displacement control at 0.5 mm/min. The test setups are shown in figures 2, 3 and 4. In all setups, acoustic emission recordings were made with a Physical Acoustics Corporation WD Rk02 piezoelectric sensor which has a large band
frequency response between 100 KHz and 1 MHz. The captured events from the transducer were amplified with a 40 dB gain model 2/4/6 preamplifier and were digitized and recorded by a µDiSP™ acoustic emission system. The sampling period was 500 ns and the threshold was set at 45 dB. Features were then calculated with AEwinTM software, which is able to calculate and represent signal features in real time on a computer. Figure 2 shows the experimental setup for a DCB specimen opening in mode I. The AE PZT sensor was attached to the samples by using hot-melt adhesive. For the MMB samples, a frame was used to convert tension from the Instron load frame to compression on the lever since the load cells can only be used in tension. The position of the sensors on the MMB sample and the ENF sample are shown in figure 3 and figure 4. The interlaminar fracture energy, $G_c$, also known as the critical strain-energy release rate, has typically been evaluated via determining the values of $G_c$, through the application of linear-elastic fracture mechanics (LEFM). The main modes of failure are by way of Mode I (tensile opening), mode II (in plane shear) and mixed mode I/II. The corresponding critical energy values are noted $G_{IC}$, $G_{IIC}$, $G_{I/IIC}$, and values can be measured for pure mode I and mode II loading with the DCB (ASTM D5528) and ENF tests [9]. The critical energy release rate for mixed mode loading is found experimentally with the MMB tests (ASTM D6671). The interlaminar failure energies depend on the ratio of mode I / mode II loading. For double cantilever beam tests, mode I interlaminar fracture toughness is computed using the Modified Beam Theory (MBT) (ASTM D5528-01). The end-notched flexure (ENF) specimen has been widely used to obtain Mode-II fracture toughness, and it is essentially a three-point bending beam with a mid-plane initial crack of desired length $a$. For practical applications, the ENF specimen presents some difficulties such as a sensitivity to friction, difficulty in precisely defining an initial crack length and unstable propagation for long crack lengths ($a/L > 0.7$). The interlaminar fracture toughness computed with the Load Based Compliance Calibration (LCCB) method [9]. The Mixed Mode Bending (MMB) test simply combines mode I DCB and mode II ENF tests. This is achieved by adding an opening mode load to a mid-span loaded ENF specimen. The relative magnitudes of the two applied loads determine the mixed-mode ratio at the delamination front. By applying these two loads through a lever and hinge apparatus shown in figure 4, the test can be conducted by applying a single load on the lever. The ratio of mode I to mode II opening is controlled with the lever length $c$ at which the load $P$ is applied.

2.3 FEM Modeling and Virtual Crack Closure Technique (VCCT)

Two dimensional finite element models of the tests were constructed using ANSYS 12.1. The models used the virtual crack closure technique (VCCT) to evaluate the strain energy release rate [10]. This method is based on the assumption that the energy released when the crack is extended from $a$ to $a + \Delta a$ is equal to the energy required to close the crack back to $a$ (figure 1). It is also assumed that a crack extension of $\Delta a$ does not significantly alter the state of the loads and the displacements at the crack tip [10]. This implies that the forces and displacements of the nodes around a crack tip of length $a$ are approximately equal to those of a crack length $a + \Delta a$. The samples were modeled using second order eight node solid quadrilateral elements (PLANE183). For pure mode II loading, contact CONTA172 and target TARGE169 elements were used along the delamination interface to prevent overlapping, which had the effect of making the solution non-linear. Figure 2 shows the mesh arrangement around the crack tip. The VCCT uses vertical nodal displacements $W_l$, $W_l^r$, $W_m$, $W_m^r$, horizontal nodal displacements $u_l$, $u_l^r$, $u_m$, $u_m^r$, vertical nodal forces $Y_l$, $Y_j$ and horizontal nodal forces ($X_l$, $X_j$) from the linear static finite element solution in order to determine the mode I and II components of the strain energy release rate, as shown in Equations 7 and 8 [10]. The mode I and mode II components of the strain energy
release rate are calculated by equations (1) and (2) for 2D eight-noded elements, as presented by Krueger [10]. In these formulas, $\Delta a$ is the length of the elements at the crack tip.

$$G_I = \frac{1}{2\Delta a} \left[ Y_i \cdot (w_i - w_i^*) + Y_j \cdot (w_m - w_m^*) \right] \ldots (1)$$

$$G_{II} = -\frac{1}{2\Delta a} \left[ X_i \cdot (u_i - u_i^*) + X_j \cdot (u_m - u_m^*) \right] \ldots (2)$$

Figure 1: Nodal forces and displacements used in virtual crack closure technique for eight node elements [10].

3. Results and discussions

All tests were run at controlled 0.5 mm/min displacement. For computation of strain energy release rates, three crack onset parameters were compared: maximum load (ASTM D5528), 5% increase in compliance (ASTM D5528) and start of acoustic emission signals. The calculated strain energy release rates were compared for the corresponding load-displacement values of these three parameters. The load displacement curves and acoustic emission emissivity for the DCB test are shown in figures 6 a) and b). Figure 6 c) shows the waveform of the first AE signal associated with damage onset in the sample. The AE energy distributions versus load results for the MMB tests with different lever lengths are shown in figures 6 d) and 6 e). These figures present the results for lever lengths $c = 85.37$ mm and $c = 75.12$ mm. The load and displacement used for calculating $G_C$ according to the 5% compliance increase parameter are taken when the load deviates from or crosses this line. The load and displacement for the maximum force parameter are taken at the peak load point in the figures. As the cumulative acoustic emission signal increases, the load reaches a maximum value and then decreases as the crack is extended. The figures 6 b), d), and e) present plots of the evolution of AE energy, in logarithmic scale, versus the applied loads for $c = 85.37$ mm, $c = 75.12$ mm. The load at which acoustic emission starts is easily identifiable and represents the point at which damage starts to accumulate in the sample. This stress value defines the "Acoustic Emission threshold $\sigma_{AE}$" indicating the onset of micro-failures in the composite under DCB and MMB mode loading. Figures 6 b), d) and e) show that the first AE events appear at a stress level of 37.7 N for DCB test (figure 6.b), 21.85 N for $c = 85.37$ mm and 29.09 N for $c = 75.12$ mm. These results clearly demonstrate that the $\sigma_{AE}$ thresholds depend on the loading mode I and II and their combination. The strain energy release rates were computed and the values are compared in table 2. The $G_{II}/G_{II}$ value is calculated from the maximum applied load. The results from the numerical model are also added in the table 2 for comparison.
Figure 2: Pure mode I loading test (DCB)

Figure 3: End notch flexure testing

Figure 4: Mixed mode loading test (MMB)
(a) DCB loading, $G_{II} = 0$

(b) Acoustic energy versus load

(c) AE signal associated to damage onset in DCB sample

(d) Acoustic energy versus load, MMB loading, $c = 85.37$ mm, $G_i/G_{II} = 2.41$

(e) Acoustic energy versus load, MMB loading, $c = 75.12$ mm, $G_i/G_{II} = 1.98$

Figure 5: Acoustic emissions energy signals function of loading
Table 2: Strain energy release rates according to onset criteria for DCB test

<table>
<thead>
<tr>
<th>Sample</th>
<th>e (mm)</th>
<th>$G_{II}/G_{I}$</th>
<th>$G_{It}, G_{It} (J/m^2)$</th>
<th>$G_{Ic}, G_{IIc} (J/m^2)$</th>
<th>$G_{Ic}, G_{IIc} (J/m^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCB</td>
<td>-</td>
<td>360.88</td>
<td>0</td>
<td>260.88</td>
<td>440.0</td>
</tr>
<tr>
<td>MMB</td>
<td>85.37</td>
<td>2.41</td>
<td>213.44</td>
<td>89.68</td>
<td>37.21</td>
</tr>
<tr>
<td>MMB</td>
<td>75.12</td>
<td>1.98</td>
<td>326.52</td>
<td>70.41</td>
<td>35.60</td>
</tr>
<tr>
<td>MMB</td>
<td>54.62</td>
<td>1.05</td>
<td>255.00</td>
<td>147.00</td>
<td>139.58</td>
</tr>
<tr>
<td>MMB</td>
<td>32.12</td>
<td>0.24</td>
<td>202.11</td>
<td>95.01</td>
<td>63.84</td>
</tr>
</tbody>
</table>

In order to compare the numerical and experimental values of strain energy release rates, the maximum load values, taken from the load curves presented in figure 5, were used in the numerical model. Figure 6 shows a contour plot of nodal Von Mises stresses for the sample loaded in mode I and a close up view of the crack tip. For the case of mode I loading, the numerical model calculates a strain release rate value of $G_{Ic} = 440$ J/m$^2$ and the experimental test gives a strain release rate value of $G_{Ic} = 360.88$ J/m$^2$. The difference between these two values is 21.92%. Figure 7 shows a contour plot of Von Mises stress for the sample loaded in mixed mode I and II and a close up view of the crack tip. Table 3 compares the $G_I$ and $G_{II}$ components of the strain energy release rate with the experimental values based on the maximum load. Figure 8 shows the critical strain energy release rates obtained with the maximum load on the load-displacement curves, AE damage onset monitoring and with FEM-VCCT modeling for the DCB and MMB tests. The numerical modeling was done for the maximum load cases. For the MMB tests, the interlaminar fracture toughness is obtained by summing the mode I and II components of the strain energy release rates to obtain the critical strain energy rate $G_c$. This quantity is plotted against the loading mode ratio $G_{II}/G_T$, which has a value of 0 in pure mode I loading and a value of 1 for pure mode II loading.
Table 3: Comparison of experimental and numerical values of $G$ for MMB sample $c = 54.62$

<table>
<thead>
<tr>
<th>Method</th>
<th>$G_I$ (J/m$^2$)</th>
<th>Difference (%)</th>
<th>$G_{II}$ (J/m$^2$)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>255.00</td>
<td>-</td>
<td>242.13</td>
<td>-</td>
</tr>
<tr>
<td>Numerical</td>
<td>260.10</td>
<td>2.00</td>
<td>247.20</td>
<td>2.09</td>
</tr>
</tbody>
</table>

The resulting interlaminar toughness values show a monotonic increase as the mode II ratio, $G_{II}/G_T$, increases from zero to unity, i.e. pure mode I opening to pure shear in mode II. For each MMB loading case, the numerical model gives a slightly higher mode ratio than the experimental values. This may be explained by experimental uncertainties, mainly on the material properties which were obtained from the manufacturer and were not experimentally validated. The interlaminar toughness curve obtained by AE monitoring shows the strain energy at the onset of delamination. For pure mode I loading, the AE detection occurs at a lower energy level than obtained with the well established maximum load criteria. As the $G_{II}/G_T$ ratio approaches unity, the initiation of delamination is detected at increasingly higher energy level but remains inferior the energy level found with the maximum load criteria. Since AE monitoring is able to detect damage micromechanisms and microscopic activity that occur before the initiation of macroscopic delamination, it will be possible to use it in order to establish more reliable and accurate rupture criteria. A least squares polynomial fit on the data shows the mathematical relation between the interlaminar toughness and the $G_{II}/G_T$ ratio in equations 3 and 4 for the maximum load and AE criterion respectively.

\[
G_c(\text{max load}) = 359.9 - 414.6 \left( \frac{G_{II}}{G_T} \right) + 1545.8 \left( \frac{G_{II}}{G_T} \right)^2 \quad \text{..................................................(3)}
\]

\[
G_c(\text{AE}) = 237 - 307 \left( \frac{G_{II}}{G_T} \right) + 1252 \left( \frac{G_{II}}{G_T} \right)^2 \quad \text{..................................................(4)}
\]

Results for $G_I$ values plotted against $G_{II}$ for DCB and MMB tests are shown in figure 9. The experimental points distribution of the AE data and maximum load data can be viewed as delamination onset failure envelope criterion for mixed-mode I and II loading. The critical energy release rate in pure mode I loading is much smaller than that in pure mode II loading, which makes it a more severe loading mode. For values of $G_I/G_{II} > 1$, delamination initiation is controlled by the mode I portion of the loading. In this region, the acoustic emissions show that micromechanical failures precede delamination initiation, measured by the maximum load. For the cases of $G_I/G_{II} < 1$, the acoustic emission criteria envelope indicates that microcracks generated by mode II loading drive the delamination toughness. When $G_I/G_{II} = 1$, the toughness obtained by AE is very close to that obtained with the maximum load. This suggests that when the loading mode I is equal to the loading mode II, the delamination propagates an unstable manner. It can also be seen that the mode I energy component at which AE is detected for $G_I/G_{II} = 1$ is close to that detected for pure mode I loading. This suggests that the mode I loading component is the driving force for crack propagation. Experimental analysis of the fracture surfaces is needed to correlate microcrack shapes and microscopic failure modes with the failure criteria envelope obtained by acoustic emission monitoring.
Figure 8: Critical energy release rate versus $G_{II}/G_{T}$ ratio for delamination onset

Figure 9: DCB and MMB delamination onset failure criteria envelope
4. Conclusion

This paper presents the methodology and results of tests carried out to calculate the strain energy release rates for unidirectional carbon fiber specimens. This investigation presented an AE approach to detect delamination onset in laminated composites. The method was used to produce quasi-static mixed-mode delamination failure envelopes of unidirectional carbon fibre samples subjected to DCB, MMB and ENF loading experiments. The resulting envelopes were shown to be more conservative than those derived from conventional fracture mechanics methodologies. This is because AE monitoring is able to detect micro damage mechanisms that occur before delamination is observed. Delamination onset criteria based on AE would be more accurate and reliable than the standard load nonlinearity and compliance increase methods, which are sometimes difficult to apply and interpret in composite materials. A numerical model has been developed, which reflects the experimental results.

REFERENCES