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Interface Delamination Fracture Toughness Experiments At Various Loading Rates

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ABSTRACT

Mode-I and Mode-II fracture experiments of composites under high loading rates are presented. In the standard double cantilever beam (DCB) configuration, specimens are loaded with constant speed of 2.5 m/s (100 in/s) on a customized high-rate MTS system. Alternative high rate experiments are also performed on a modified split Hopkinson pressure bar (SHPB). One of the configurations for the characterization of dynamic Mode-I interfacial delamination is to place a wedge-loaded compact-tension (WLCT) specimen in the test section. Pulse-shaping techniques will be employed to control the profiles of the loading pulses such that the crack tip is loaded at constant loading rates. Pulse shaping also avoids the excitation of resonance, thus avoiding inertia induced forces mixed with material strength in the data. To create Mode-II fracture conditions, an (ENF) three-point bending specimen is employed in the gage section of the modified SHPB.

INTRODUCTION

Composite materials usually contain flaws such as regions with a lack of adhesion, which may affect the deformation behaviors of the material and cause failure. Delamination is known to be a key mechanism that leads to premature failure in composites. To assess the integrity of composite structures, models are being developed to predict the response of these flaws in various loading conditions, for example, the material is subjected to high rate loading under impact.

For the composites of interest, the delamination process is typically brittle. That is the deformation process during fracture is nearly linear elastic. Hence, Linear Elastic Fracture Mechanics (LEFM) provides a framework for modeling delamination and also a scheme for evaluating intrinsic fracture resistance values - fracture toughness K_C or energy release rate G_C. This material property needs to be determined experimentally. If the material is rate-dependent, K_C needs to be characterized as a function of loading rate. For example, the work of Smiley and Pipes [1, 2] show rate effect on G_{IC} and G_{IIC} in graphite/PEEK (APC-2) and graphite/epoxy (AS4/3501-6) laminates. The value of G_{IC} of AS4/3501-6 stays almost unchanged for loading rate less than 1.3x10^{-4} m/s and then drops significantly at higher rates.

For quasi-static loading, standard test methods to determine interlaminar fracture toughness in composite are well established [3, 4]. The ASTM guide recommends crosshead (or hydraulic ram) displacement rate of 1 – 5 and 0.5 mm/min for mode I and mixed mode I-mode II bending (MMB) tests, respectively. Unfortunately, determining the fracture toughness value at a higher loading rate is still a very challenging task because of the inherent dynamic effects in the test. Some guidelines [5] have been provided to extend the applicability of the standard method for K_{IC} at quasi-static [3] to moderately high loading rates, loading-point displacement rates up to 1 m/s (40 in/s). Limited work has been reported in the literature to characterize composite fracture at high rate, and no method is well accepted or standardized up to date.

This paper presents three newly conducted high rate fracture experiments to determine interlaminar fracture toughness of composite laminates.

MTS HIGH-RATE FRACTURE EXPERIMENT

The first high rate fracture experiment was performed on a customized MTS high rate system with an actuator speed up to 5 m/s (200 in/s). The test was basically the same as quasi-static tests that followed the guideline of ASTM D 5528-01 [3] but with some modifications. In addition to loading rate, the other major difference in the loading procedure is that no unloading and reloading are included because the system is in open-loop control during high rate experiment and the test is done within a few mini-seconds. Also, the time is too short to measure the delamination movement through normal visual method. A high speed camera and crack growth gage are necessary to monitor delamination growth.

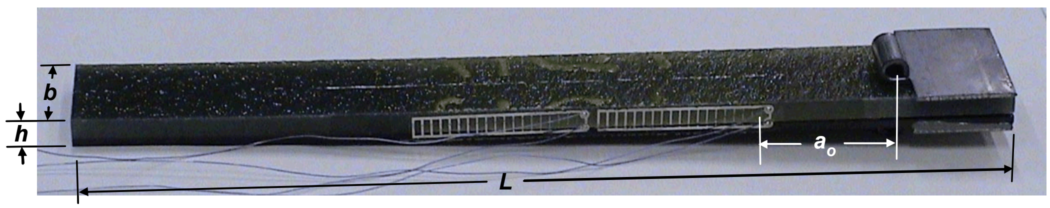
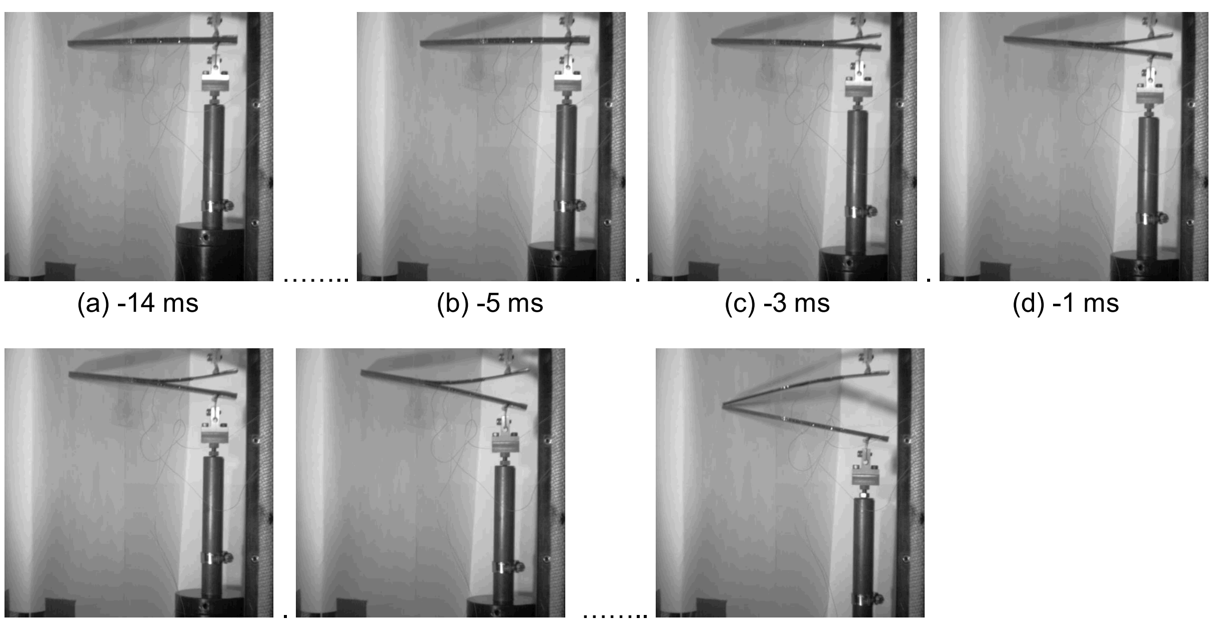


Figure 1. DCB specimen for MTS high rate experiment.

The nominal dimensions of the DCB specimen, shown in Figure 1, are L = 230 mm (9 in.), b = 25 mm (1 in.), h = 4.4 mm (0.174 in.), and a_o = 30 mm (1.2 in.). The original design was to have an initial crack length of 25 mm (1 in.) by inserting a nonadhesive film during layup to form an initiation site for the delamination. It was necessary to precrack the specimen to limit the maximum load during test. The delamination length was measured by using crack growth gages. The custom-designed gage has 20 lines, which covers a distance of 38 mm (1.5 in.). The distance between two adjacent lines is about 2 mm (0.077 in.). Two gages were mounted on the edge of the specimen side by side, which measure the delamination length from 25 to 100 mm (1 to 4 in.), approximately.

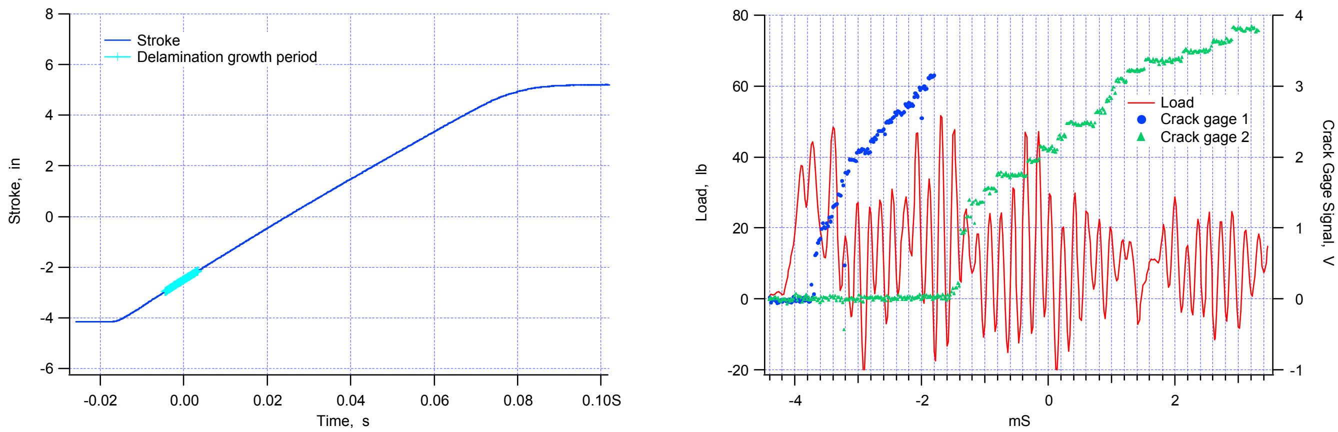


(a) -14 ms (b) -5 ms (c) -3 ms (d) -1 ms

(e) 1 ms (f) 3 ms (g) 16 ms

Figure 2. Delamination growth monitored by high speed camera.

The setup is shown in Figure 2(a). A piezoelectric load cell on the crosshead was connected to the top side of the specimen. On the bottom side was the slap-grip fixture attached to the actuator. The slap-grip allowed the actuator to reach a constant speed before engaging the pull rod to load the specimen. A high speed camera recorded the experiment at 1,000 fps. Figure 2 shows a series of pictures of the delamination growth of a DCB specimen in a high rate fracture test. The time shown is referenced to the trigger point, which is based on the stroke signal and *t* = 0 is an arbitrary point during the loading process. In the test, the actuator was continuously moving down but there was no loading on the specimen up to *t* = -5 ms. The loading started somewhere between -5 and -4 ms and the loading point moved with the actuator at the same speed. The specimen was completely delaminated after 16 ms.



(a) (b)

Figure 3 High rate experimental data.

Quantitative data of load, stroke and crack propagation gages are sampled at 50 kHz and recorded. The stroke data is shown in Figure 3(a), which display the full motion of the stroke. The actual loading on the composite beam occurred during only a small portion of the curve, marked with light blue color in Figure 3(a). The load and crack gage signals during the loading period are shown in Figure 3(b). The oscillatory feature of the load signal is very different from the quasi-static test and is difficult to interpret. It includes both the force required to open the crack and the dynamic effects. The dynamic phenomena may come from the stress wave propagation in the material under test, vibrations of the test system, etc. Investigation using modeling and numerical analysis is needed to understand the results.

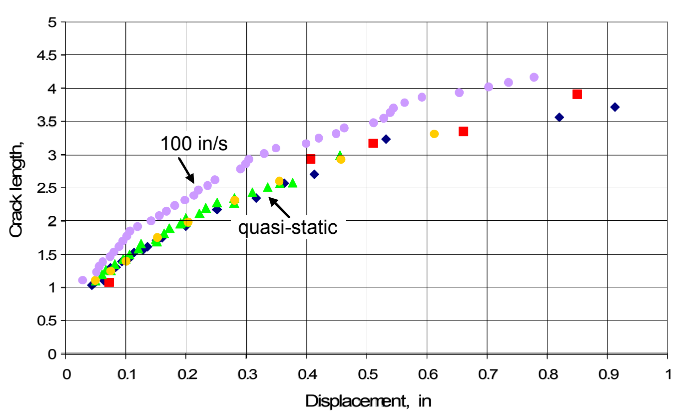


Figure 4 Crack length versus displacement curve.

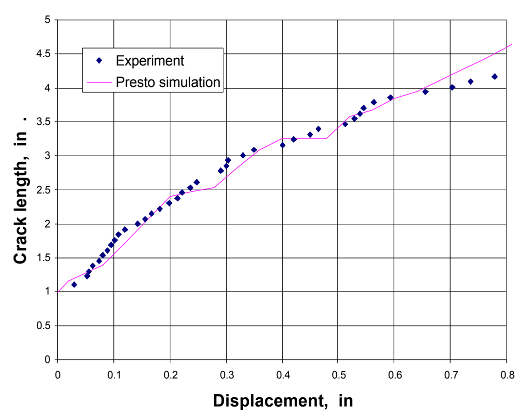


Figure 5 Preliminary simulation results

The signal of the second crack gage followed the first one as expected. Every voltage jump on the curve means the crack has advanced 2 mm (0.077 in.) and breaks one line. The crack length versus the loading point displacement (a-δ) curve is shown in Figure 4. The a-δ curves of several quasi-static tests are also plotted in the same figure, clearly showing the different between two loading conditions. The fracture toughness of the material measured at quasi-static loading is about 500 J/m^2. A preliminary result of high rate simulation using a lower fracture toughness value of 300 J/m^2 is plotted in Figure 5. The simulation matches the experimental data very well except when the crack length is large, *a* > 10 mm (4 in.). This may due to the fact that at constant loading speed each crack length corresponds to a different crack tip opening rate, $\dot{y}_{ct}$, according the following equation [1]

$$\dot{y}_{ct} = \frac{3\dot{\delta}\varepsilon^2}{2a^2} \quad (1)$$

where ε is some arbitrarily small distance from the crack tip, say 0.25 mm. For a DCB specimen test at constant speed of 2.5 m/s at loading point, the changing of crack tip opening rate is shown in Figure 6. More investigations will be conducted to study these issues.

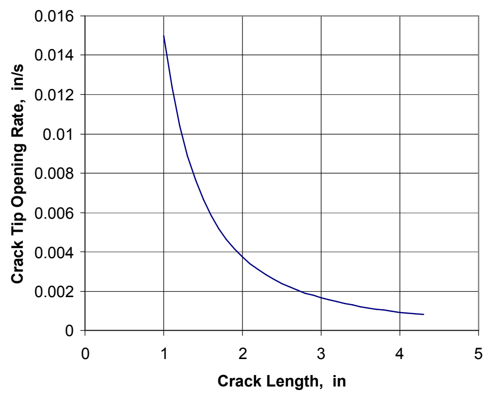


Figure 6 Crack tip opening rate as a function of crack length

SHPB FRACTURE EXPERIMENT

The other two experiments, WLCT and ENF, were performed on a SHPB apparatus. The experiments were based on the techniques developed at Purdue University [6, 7]. In addition, pulse shaping technique was employed for dynamic equilibrium and constant loading rate. Experiments and results are described briefly.

WLCT Experiment

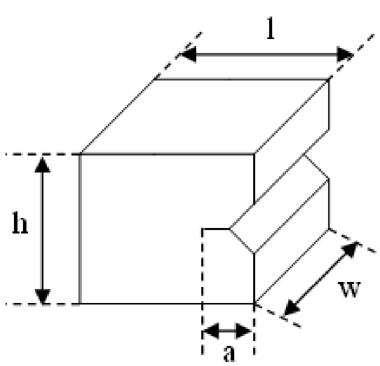


Figure 7 WLCT specimen geometry and test setup.

The specimen and setup are shown in Figure 7. The dimensions are: l = 20 mm, h = 18 mm, w = 10 mm, and a = 6 mm. Metal lines were painted on the side of the specimen to measure delamination growth. The data of a typical test is shown in Figure 8. The crack propagation was also monitored by a high speed camera at about 40,000 fps. The crack propagation can be viewed from two consecutive frames illustrated in Figure 9. The crack propagation speed is about 200 m/s for the test. Figure 10 shows the correlation between crack length and force.

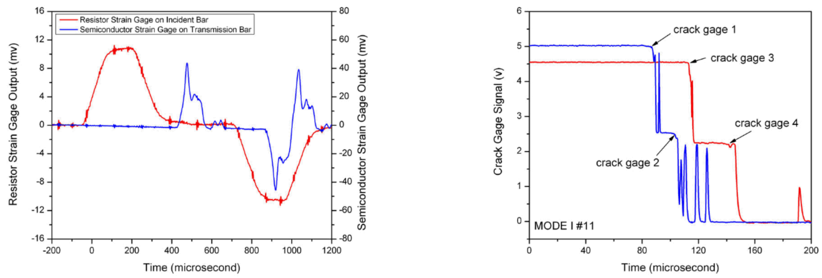
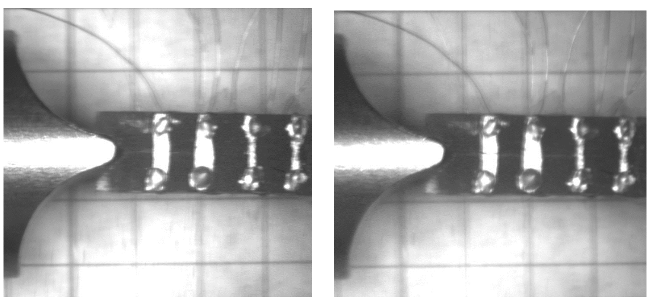


Figure 8 Typical data set for WLCI test.



(a) t = 84 μs (b) t = 96 μs

Figure 9 Crack seen from high speed camera.

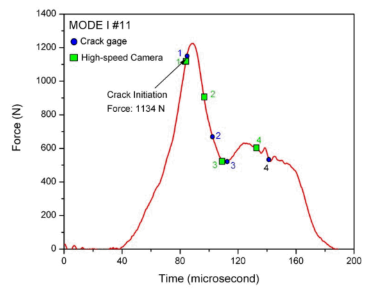


Figure 10 Correlation between force and crack length.

ENF Experiment

The dimensions of the specimen, shown in Figure 11, are: l = 60 mm, h = 10 mm, w = 10 mm and a = 10 mm. A thin layer of typewriter correction fluid is painted just ahead of the crack, so crack growth can be monitored by the high speed camera. Three point bending setup is also shown in Figure 11. The distance between the two outer support points is 50 mm. Experimental results are shown in Figures 12 – 14.

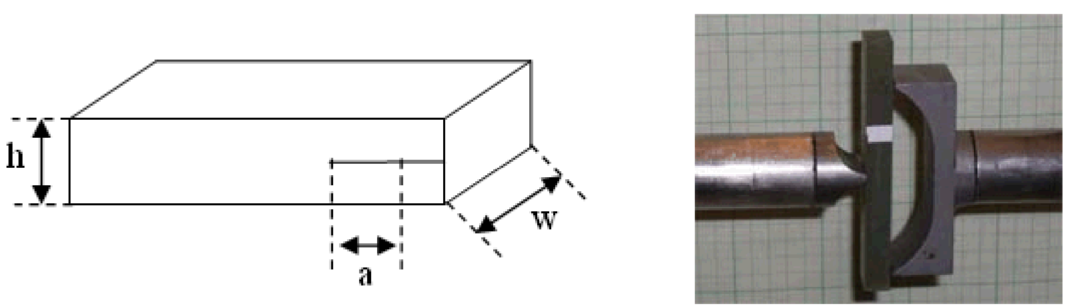


Figure 11 ENF specimen and setup.

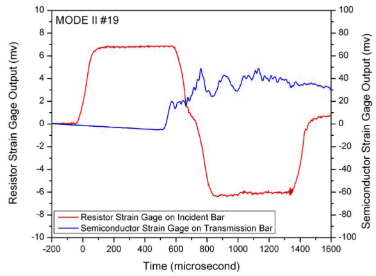


Figure 12 Typical data set for ENF Fracture test on SHPB

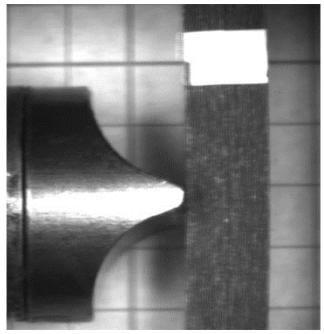


Figure 13 The 1st frame show Crack propagation t = 228 μs

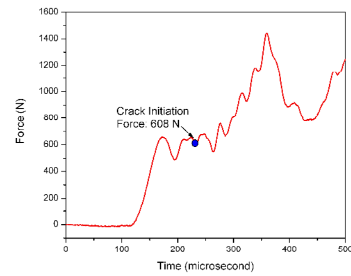


Figure 14 Correlation between force and crack length

SUMMARY AND CONCLUSIONS

Three high rate experiments to determine fracture toughness are performed: (1) Mode I DCB test on high rate MTS system, (2) Mode I WLCT test using SHPB, and (3) Mode II ENF test using SHPB. Future work includes data analysis, modeling and understanding the experiments and results, and developing efficient procedures to determine high rate fracture toughness.

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REFERENCES

[1] Smiley, A.J. and Pipes, R.B., "Rate Sensitivity of Mode I Interlaminar Fracture Toughness in Composite Materials", J Composite Materials, vol. 21, 670-687, 1987.
[2] Smiley, A.J. and Pipes, R.B., "Rate Sensitivity of Mode I Interlaminar Fracture Toughness in Graphite/Epoxy and Graphite/PEEK Composite Materials", Composites Science and Technology, 29, 1-15, 1987.
[3] ASTM D 5528-01 "Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites", American Society for Testing and Materials, West Conshohocken, PA, 2001.
[4] ASTM D 6671/D 6671M-06 "Standard Test Method for Mixed Mode I–Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites", American Society for Testing and Materials, West Conshohocken, PA, 2006.
[5] Pavan, A., "Determination of Fracture Toughness (G_{IC} and K_{IC}) at Moderately High Loading Rates", *Fracture Mechanics Testing Methods for Polymers Adhesives and Composites*, Editors: D.R. Moore, A. Pavan, and J.G. Williams, ESIS Publication 28, Elsevier, 2001.
[6] Sun, C.T. and Han, C., "A Method for testing interlaminar dynamic fracture toughness of polymeric composites', Composite: Part B 35, 647-655, 2004.
[7] Tsai, J.L., Guo, C. and Sun, C.T., "Dynamic Delamination Fracture toughness in Unidirectional Polymeric Composites", Composite Science and Technology 61, 87-94, 2001.