

Experimental Fracture Mechanics for Adhesive Joint Design

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Summary

An experimental study was conducted to investigate the use of fracture mechanics to predict failure initiation of adhesive joints. Most practical plane fracture problems are mixed mode and failure initiation of adhesive joints is a result of such conditions. It is widely accepted that a useful method for characterizing the toughness of bonded joints is to measure the fracture toughness; energy per unit area needed to produce failure. For a given adhesive, mode mixity has a dependency towards fracture toughness and fracture toughness is directly associated with stress. Main goal in this investigation was to demonstrate the capability of utilizing experimental fracture mechanics data to predict the failure initiation of an adhesive joint. First, critical energy release rates for several mode mixities were experimental determined (Tool 1) for selected adhesives using double cantilever beam (DCB), end-notch flexure (3ENF), and mixed-mode bending (MMB) test methods to determine mode I, mode II, and mixed-mode I & II fracture toughness values, respectively. Then, a stress analysis was conducted to determine the mode mixity at a crack tip of the adhesive joint design (Tool 2); crack-tip location must be selected based on previous experimental observations. Further, a relationship between applied load and the energy release rate was obtained from the same model (Tool 3). Once the mode mixity of the crack tip was determined from Tool 2, Tool 1 can be used to determine the critical energy release rate corresponding to the crack tip of a particular adhesive joint. Finally, Tool 3 can be used to determine the critical state of stress or the failure initiation load corresponding to that critical energy release rate. Single-lap adhesive test specimens were fabricated and tested for two adhesive types and the failure loads were compared with the predictions made using the proposed approach. It was concluded that failure loads predicted by mode mixity-fracture toughness curves were in good agreement with those obtained experimentally.

Introduction

An increased use of adhesively bonded joints in industrial applications has renewed the need for research in design and analysis of bonded joints, especially in failure prediction. The loading configuration of a bond reflects its failure behavior; hence, loading modes have been categorized accordingly. Literature often refers to

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loading “modes” when discussing fracture behavior because all loading configurations can be broken down to one or more modes, as shown in Figure 1, making it simpler to analyze. The fracture mechanics approach to analyzing a bonded joint assumes an existing crack in the joint and studying its behavior under different loading modes.

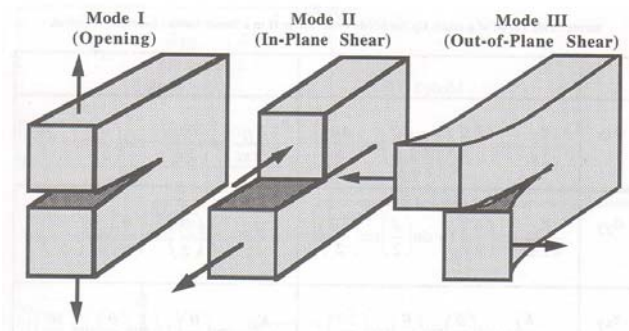


Figure 1: Three modes of loading configurations [1].

Energy per unit area that needs to produce a failure along a plane is often referred to fracture toughness or critical strain energy release rate in literature. Existing standardized tests, such as those from the American Society of Testing Materials (ASTM) and Suppliers of Advanced Composite Materials Association (SACMA), address the interlaminar fracture toughness of fiber-reinforced polymer matrix composites. Similar test methods have been used to obtain fracture toughness values of adhesively bonded joints with minor modifications to specimen configurations and test speeds.

In order to determine the failure load or stress for a given adhesively bonded joint configuration, usual industry practice requires the fabrication of test specimens that closely simulate the joint configuration and testing under the appropriate loading configuration until failure. This needs to be repeated for a different joint configuration. A simpler method for estimating the failure load of any adhesively bonded joint configuration for a given adhesive would make the analysis more convenient and benefit the industry as well as the research community.

Experimental Investigation

Mode mixity has been noted in literature as a percentage of the strain energy release rate value corresponding to mode II portion of the load over the total strain energy release rate, G_{total} and used the same way in this study as shown in equation 1. In order to develop a relationship between mode-mixity and fracture toughness for a particular material, the fracture toughness or critical strain energy release rate, G_C , needs to be determined at each mode-mixity point, ranging from pure mode I,

0% mode-mixity, to pure mode II, 100% mode-mixity.

$$G_{II}\% = \frac{G_{II}}{G_I + G_{II}} = \frac{G_{II}}{G_{total}} \tag{1}$$

Double cantilever beam (DCB), end-notch flexure (3ENF), and mixed-mode bending (MMB) test methods were used in this investigation for mode I, mode II, and mixed-mode I & II testing, respectively, by modifying the standard specimen geometry to accommodate a constant bondline thickness with an initial cohesive crack . In order to verify the proposed failure initiation prediction methodology, adhesively bonded single-lap shear test specimens were fabricated with similar adhesive-adherend combinations and bondline thickness as the fracture toughness specimens. Figure 2 shows a schematic diagram of the side view of a single-lap joint specimen that has a 1-inch overlap. Specimens were fabricated with a tape at the edge of the test section to simulate a considerably small cohesive crack tip. Three types of adherends were used in this investigation: Toray T700/#2510 unidirectional tape and plain weave fabric (Layup: $0_{PW}/[0_U]_8/0_{PW}$), Newport NB321/7781 E-glass/epoxy fabric (Layup: $[0_F]_6$), and phosphoric-anodized and bond-primed aluminum 2024-T3. Two sets of adhesive panels were fabricated using EA9394 paste adhesive and EA9628 film adhesive with a nominal bondline thickness of 0.015-inch.

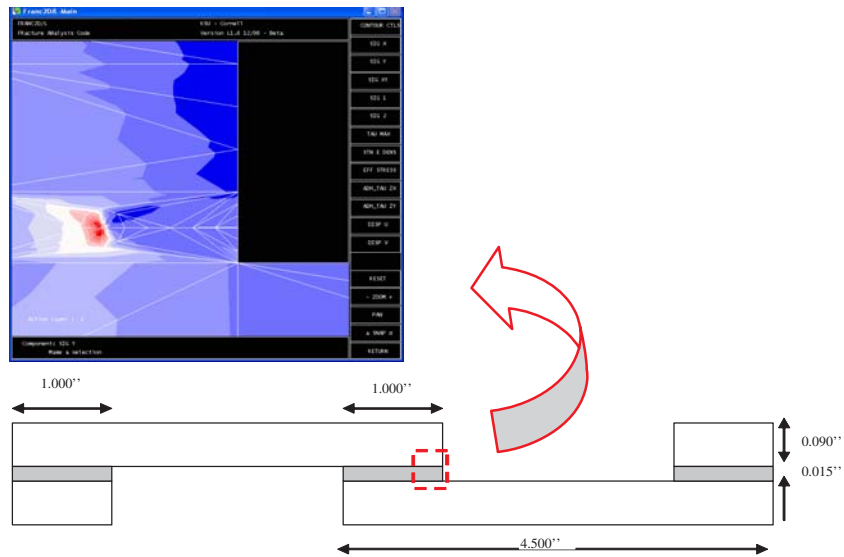


Figure 2: Cohesive crack tip at failure initiation.

Strain Energy Release Rate and Mode Mixity

Fracture Analysis Code 2D (FRANC2D/L) [2] was selected to determine the

mode mixity at the crack and the relationship between load and total strain energy release rate at the crack tip based on its simplicity as a demonstrative tool for the proposed approach. This package was used to model single-lap joint specimens tested with different adherend-adhesive combinations, as discussed in the previous section, simulating a crack at the peeling end. Adhesive region of the specimen was modeled as an isotropic material, while adherend material was modeled as an orthotropic material. Mesh sensitivity towards strain energy release rate for a given crack length was found to be negligible for this case.

Results and Discussion

Experimental mixed-mode critical energy release rate data for both EA9394 and EA9628 using different adherends are shown in Table 1[3].

Table 1: Critical strain energy release rate values for EA9394 & EA9628.

Mode Mixity (%)	G_C (VIS) (kJ/m ²)				
	Aluminum/ EA9394	Carbon/ EA9394	Glass/ EA9394	Carbon/ EA9628	Glass/ EA9628
0	0.422	0.352	0.425	0.350	0.350
25	0.615	0.411	0.378	0.411	0.500
50	0.652	0.600	0.657	0.539	0.605
70	N/A	0.679	0.698	N/A	0.674
80	0.788	0.704	0.634	0.805	N/A
100	1.279	0.924	0.901	0.857	0.824

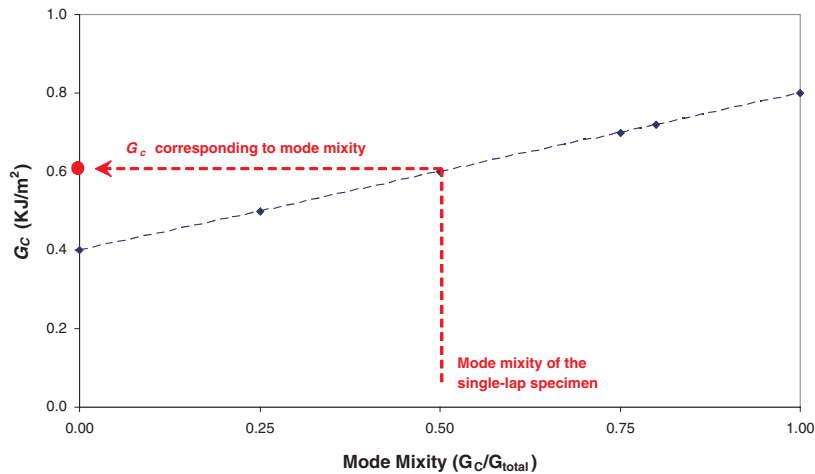


Figure 3: Determination of G_C based on mode mixity of the crack tip.

FRANC2D/L analysis of EA9394 single-lap joint specimen provided the mode

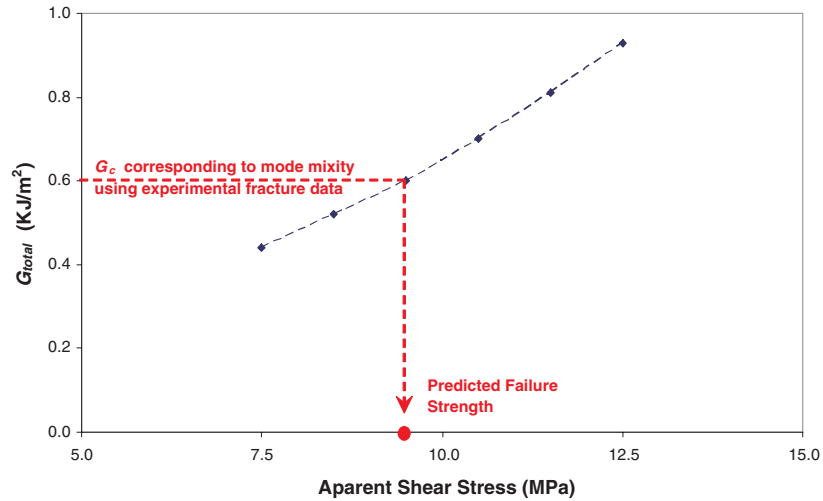


Figure 4: Estimation of failure (initiation) load using G_C and FRANC2D/L Data.

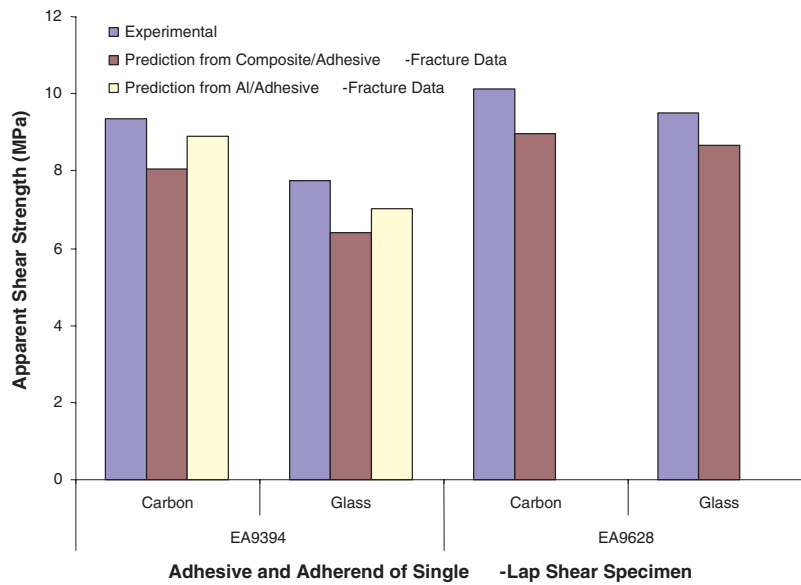


Figure 5: Comparison of predicted and experimental apparent shear strength of single-lap joint specimens.

mixities of 49% and 52% for carbon and glass adherend, respectively. Similarly, they were 50% and 52% for EA9628 specimens with carbon and glass adherends,

respectively. These values were used along with the experimental fracture data shown in tables 1 to obtain the critical energy release rates for the given specimen geometry as illustrated in Figure 3.

Once G_C was obtained, the corresponding failure load was extracted as illustrated in Figure 4. Finally, the predicted failure load for single lap joint based on fracture data with different adherends were compared with those obtained experimentally as shown in Figure 5. It was assumed that failure initiation caused an unstable crack that caused an instantaneous joint failure.

Conclusions & Recommendations

Predicted strengths using fracture toughness curves developed using aluminum adherends showed a better comparison with experimental data than that of composite adherends. Thus, aluminum adherend is recommended for generating the mixed-mode fracture data curve for a given adhesive type.

References

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