A Novel Test Geometry for Characterization of Traction-Separation Behavior in Composite Laminates Under Mode I Delamination

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ABSTRACT

The integration of composite laminates into automotive structures can provide weight reduction and improvement in occupant safety. However, the adoption of such materials requires characterization and efficient modeling of the damage behaviors of composite laminates which may occur during crash events, such as delamination. Numerical modeling techniques such as cohesive zone modeling require a traction-separation response for each mode of loading. The standard test technique used to characterize Mode I delamination, the double cantilever beam (DCB), measures the critical energy release rate; however, additional tests or inverse fitting techniques are required to characterize the full traction-separation response. Additionally, compliance inherent in the DCB specimen can influence the measured energy release rate while the large size of the specimen complicates the high deformation rate testing needed for crash analysis.

In this study, a novel Mode I test specimen adapted from a recent advancement in structural adhesive characterization is applied to evaluate composite delamination. The hybrid Rigid Double Cantilever Beam (RDCB) test specimen presented herein consists of rigid steel adherends co-molded to a composite plate containing a crack initiator. The use of steel adherends eliminates compliance in the composite laminate and ensures the interface of interest is loaded consistently and uniformly during tests, enabling measurement of the Mode I traction-separation behavior of composite delamination in a single test. As an example, the hybrid RDCB geometry is used to characterize the Mode I delamination behavior of a unidirectional E-glass fiber/epoxy laminate under quasi-static conditions, highlighting the ability of this specimen geometry to extract a full traction-separation behavior from a single test.

Keywords: Delamination, Composite Laminates, Mode I Delamination, Traction-Separation Behavior, Cohesive Zone Modeling, Double Cantilever Beam

INTRODUCTION AND BACKGROUND

With increasingly strict emission limits placed on automotive manufacturers, there is a push toward integrating lightweight materials such as fiber-reinforced polymers (FRPs) into production automobiles to reduce vehicle weight and increase fuel efficiency [1]. In addition to being lightweight, FRPs also have greater stiffness-to-weight and energy absorption properties compared to traditional steel components [2]. However, their adoption is slowed, in part, due to a lack of maturity in modeling the damage accumulation and failure modes of composite materials that may occur in extreme events such as impact or crash scenarios. One modeling approach being investigated to predict the delamination behavior of FRP components is cohesive zone modeling (CZM). However, a traction-separation law (TSL) representing the material response of the FRP is required when using CZM, which further necessitates characterizing the delamination behavior of the FRP.

The *de facto* method for characterizing Mode I delamination is the double cantilever beam (DCB) test [3]. While widely used and studied, the DCB test is only capable of directly measuring the Mode I critical energy release rate (CERR) of the FRP. Additional tests or inverse fitting techniques are needed to extract the mechanical properties required to define the TSL for a specific material fully. Furthermore, the compliance of the DCB specimen can affect the calculation of CERR in some data reduction schemes or test conditions [4].

One approach to mitigate the issue of DCB specimen compliance developed by Marzi et al. [4] was to bond aluminum bars to the top and bottom of composite DCB specimens to increase specimen rigidity. While this improves the measurement of

CERR, inverse methods are still required to extract other TSL parameters. However, a recent advancement in the characterization of adhesive behavior presents a potential alternative to the DCB test. The rigid double cantilever beam (RDCB) specimen and analysis technique presented by Watson et al. [5] makes use of metallic adherends, which are effectively rigid compared to the interface material being testing. This rigidity makes it possible to extract the full traction-separation response of an interface from a single test. Additionally, the small size and low inertia of the RDCB specimen make it suitable for high deformation rate testing. In this study, the RDCB specimen geometry was investigated to characterize the Mode I delamination of a unidirectional E-glass fibre/epoxy laminate.

METHODOLOGY

The adherends of the hybrid RDCB specimen (Fig. 1) were machined from mild steel. The co-molding surfaces of the adherends were grit-blasted with 60 grit silicon carbide blasting media to roughen the surfaces and promote good adhesion between the composite laminate and adherends as well as promoting crack development between the composite plies. Two-ply unidirectional composite laminates ($[0]_2$) were individually processed to fit between the bonding surfaces of the metallic adherends using a unidirectional prepreg material (UE400-REM, Composite Materials, Italy). A 12.5 μm thick PTFE film was placed between the plies of the laminate to provide a crack initiator. The laminate was cured between two metallic RDCB adherends under 5 bar of pressure at 140°C for 90 minutes in a specially designed jig to ensure the alignment of the adherends and consistent thickness of the composite. This processing technique not only cured the prepreg material but also molded the FRP directly to the metallic adherends. After processing, cured resin spew and excess composite material were removed from the specimen using abrasive paper. All specimens were imaged using an optical-digital microscope to verify the overall dimensions of each specimen as well as to measure the length of the pre-crack formed by the PTFE tape.

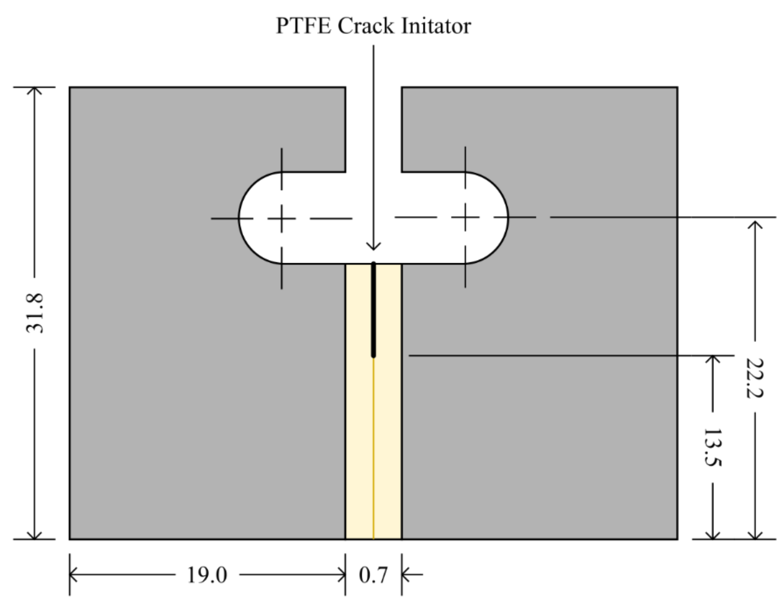

Figure 1: RDCB specimen geometry; adherends shown in grey, composite in yellow. The thickness of the composite (yellow) is not to scale. All units are millimeters.

A hydraulic test frame was used to test specimens to failure at a constant crosshead speed of 0.025 mm/s. Tests were imaged at 1080p resolution and 30 frames per second using a Nikon D3200 camera fitted with a 105 mm macro lens and 2x teleconverter. The displacement of the pins used to load the specimen was tracked optically using open source software (Tracker, Open Source Physics, National Science Foundation) [6] to eliminate the effects of machine compliance. Traction-separation behavior was extracted from the test data using the method described by Watson *et al.* [5]. A bi-linear TSL was then fit to the response of each specimen. The TSL is described using three parameters: interface stiffness (E), peak traction (σ_{max}), and critical energy release rate ($G_{I,C}$).

RESULTS AND DISCUSSION

The force-displacement behavior (Fig. 2) of the five hybrid RDCB specimens tested in this study showed that force trended linearly with adherend displacement, with a plateau at the average peak force of 650 N before failure. However, it is important to note that this plateau occurred over a very brief period of time, and force-displacement data was sparse in this region. This plateau could indicate damage propagation within the delamination interface prior to abrupt crack growth and subsequent loss of load-carrying capacity. The sparse force-displacement data in the plateau does limit how accurately this potential damage accumulation can be characterized, however. Interface stiffness and peak force were consistent among specimens, although displacement to failure demonstrated variability, ranging between 0.12 and 0.15 mm.

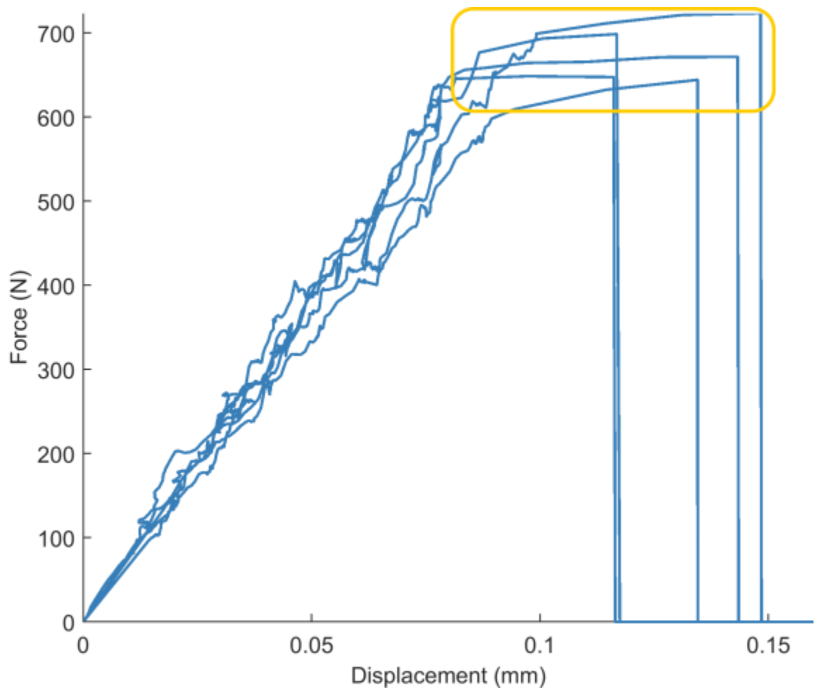

Figure 2: Force-displacement responses of hybrid RDCB tests for Mode I composite delamination. The plateau region is highlighted in yellow.

The analysis technique developed by Watson *et al.* [5] relies on the derivative of the force-displacement response to calculate traction-separation behavior. Given the non-smooth nature of the experimental force-displacement data, filtering was required to produce and calculate an accurate, realistic derivative. This filtering did introduce some oscillatory features into the calculated traction-separation response (Fig. 3). Nonetheless, traction-separation behavior closely mirrored force-displacement behavior, with traction increasing linearly with interface separation up to peak traction. The sparsity of data in the force-displacement plateau region lead to the associated plateau of the traction-separation responses being somewhat lower than the maximum computed traction. However, this calculation would likely improve with more temporal resolution in that region.

The quality of the fitted TSLs (Fig. 3) was somewhat compromised as a bi-linear curve was unable to capture the plateau region of the extracted traction-separation responses. A trapezoidal TSL would likely provide a better representation of the delamination response for this material. Regardless, average fitted parameters (Tab. 1) exhibited a low degree of variation between specimens, particularly for interface stiffness and peak traction (less than 10% variation).

Table 1: TSL constitutive model parameters averaged over all specimens. Standard deviation provided in parenthesis

Parameter	E (GPa)	σ_{peak} (MPa)	$G_{I,C}$ (kJ/m^2)
Value	1482 (80)	57.5 (3.4)	1.98 (0.32)

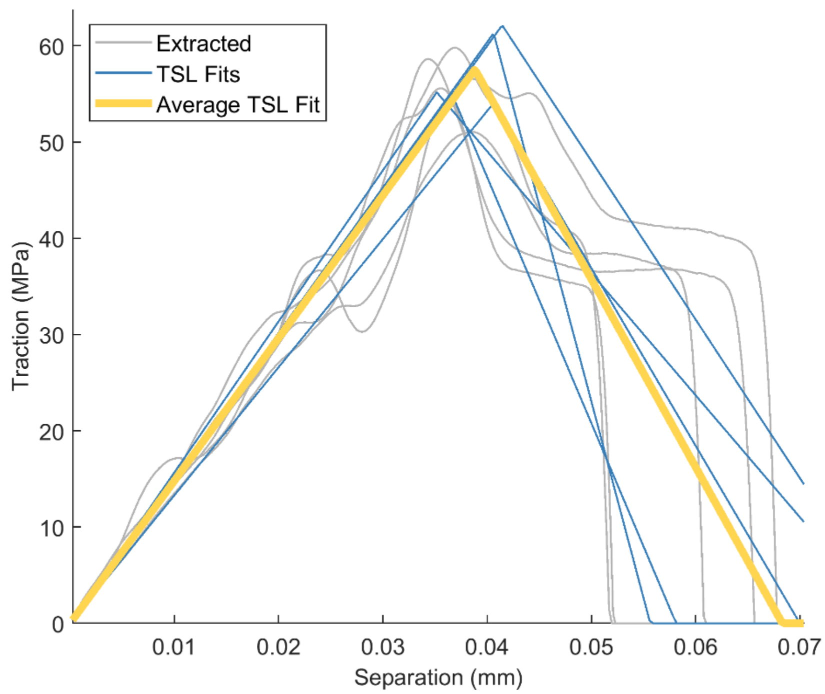

Figure 3: Calculated traction-separation responses (blue curves) for each test (grey curves), plotted with the average TSL (yellow curve).

Work conducted by Marat-Medes and Freitas [7] measured the mode I CERR of a composite laminate processed from the same prepreg material used in the present study to be 0.85 kJ/mm^2 using conventional DCB tests. This value is lower than the value of CERR determined from the hybrid RDCB test (1.98 kJ/mm^2). While this difference could be attributed, in part, due to differences in processing method and parameters, Watson *et al.* also demonstrated the RDCB produced larger values of CERR than traditional DCB testing techniques [5]. Watson *et al.* attributed this to the rigidity of the RDCB adherends, which stores less deformation energy during testing than the DCB geometry and loads the interface of interest more uniformly.

CONCLUSIONS AND FUTURE WORK

The RDCB specimen, originally developed for the characterization of adhesives, has been shown in this work to be capable of characterizing the Mode I delamination behavior of FRPs. A full traction-separation response was extracted from a single test geometry, with experimental tests exhibiting low variation, particularly in stiffness and peak traction. Future work will investigate improving the experimental setup to improve the resolution of force-displacement response, particularly in the plateau region prior to failure to characterize damage propagation better. Follow-on work will apply the hybrid RDCB geometry to study high deformation rate, Mode I delamination response as well as the fitting of a trapezoidal TSL to material behavior.

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