METHODOLOGY FOR CHARACTERIZATION OF MODE I TRACTION-SEPARATION DELAMINATION BEHAVIOUR IN LAMINATED COMPOSITES

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ABSTRACT

Current test methodologies for characterizing Mode I delamination of fibre-reinforced plastics (FRPs), such as the double cantilever beam (DCB), were developed to assess fracture toughness alone. However, modern computational modelling approaches require additional information. For example, cohesive zone modelling (CZM), a commonly used technique for simulating delamination, requires a traction-separation response describing the entire damage behaviour of delamination. Existing methodologies cannot quantify the complete traction-separation behaviour of delamination, requiring researchers to perform additional tests or resort to inverse modelling techniques to generate the necessary data to use CZM.

In the current study, the results of a project aimed at developing a new testing methodology to characterize the complete Mode I traction-separation delamination response of an E-glass/epoxy laminate from a single test geometry are presented. The proposed composite rigid double cantilever beam (cRDCB) methodology utilizes metallic adherends co-cured to an FRP laminate, allowing the delamination interface to be loaded uniformly and eliminating compliance issues associated with methodologies like the DCB. High-resolution, on-specimen displacement measurement combined with a unique data reduction scheme enabled the cRDCB specimen to capture damage initiation and accumulation, important properties needed to use CZM. The proposed methodology eliminates the need to undertake additional tests or inverse modelling by producing a complete traction-separation response that can be used directly in CZM.

1 INTRODUCTION AND BACKGROUND

Delamination is a widely observed damage mechanism for fibre-reinforced plastic (FRP) laminates used in structural or energy-absorbing applications such as transportation structures. Therefore, the characterization and modelling of delamination are vital for developing lightweight structural and crash-attenuating components from FRP materials.

The standardized method for assessing the Mode I delamination of laminate FRP materials is the double cantilever beam (DCB) test (Figure 1a) [1]. While mature and widely used, the DCB was developed specifically to assess fracture toughness. In contrast, more recently developed methods of modelling delamination require a more detailed description of delamination behaviour. While modelling methods such as virtual crack closure theory and the J-integral [2] can be utilized with only delamination toughness, these methods are not well suited to modelling crack extension, a requirement for modern structural analysis [3]. To that end, more advanced techniques such as cohesive zone modelling (CZM) are used.

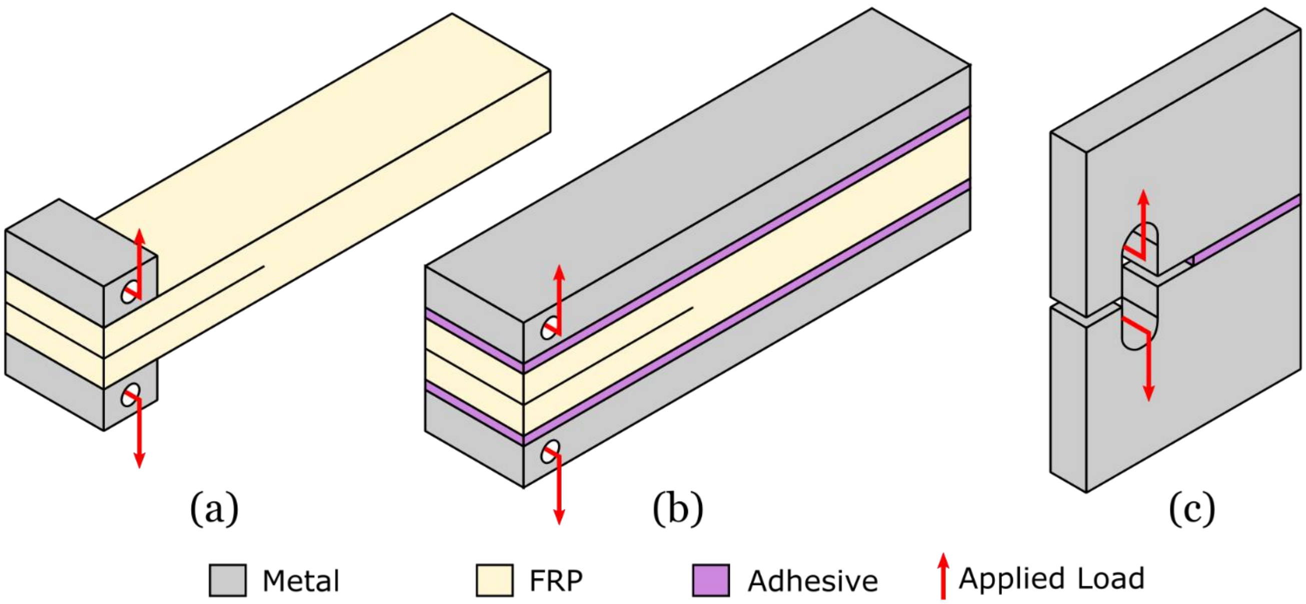

Figure 1. A standardized DCB specimen, (b) a reinforced DCB specimen [6] (c) Watson RDCB for adhesives [7]. Specimens are not to scale.

CZM uses a traction-separation response (TSR) to model the full delamination behaviour, including initial stiffness, damage onset, strength, and damage accumulation up to the point of ultimate failure. While toughness is an important property to define a TSR, it is only one of many. Thus, the DCB method using standardized data reduction schemes is not sufficient to fully characterize the TSR of a delamination interface.

Researchers have suggested improvements or alternative methods to extract a TSR from the DCB specimen. One of the most common is using inverse modelling techniques to fit a TSR to experimental data numerically. However, Lu et al. [4] found that the DCB specimen is not well suited to inverse modelling as it lacks the sensitivity to accurately resolve TSR features such as damage onset and delamination strength. Another common processing method used to extract a TSR involves the application of the J-integral to the crack tip of the DCB [5]. While this method has been successfully applied to assess the TSR of a laminate, several conditions must be met to achieve meaningful results. First, the stiffness of the FRP laminate must be known *a priori*. Second, the arms of the DCB specimen must either be loaded with a pure bending moment (necessitating specialized test fixturing), or the rotation of the arms must be measured during testing [5]. These conditions can make applying the J-integral technique difficult.

Alternative specimens have been developed to overcome the difficulties associated with assessing TSR. Marzi et al. [6] developed a reinforced DCB specimen where aluminum adherends were bonded to the top and bottom of a standard FRP DCB specimen (Figure 1b). The use of metallic adherends helped minimize specimen compliance and provide a known stiffness for the J-integral method. However, the large size of the specimen made high rate testing difficult. An alternative specimen, the rigid double cantilever beam (RDCB, figure 1c), was developed for assessing the TSR of structural adhesives [7]. This specimen uses effectively rigid steel adherends and a specialized analysis technique to assess the traction-separation behaviour of an adhesive from a single test specimen. Additionally, the specimen is small enough to be suitable for high deformation rate testing.

In the present study, the RDCB method was applied to an E-glass/epoxy laminate to assess the TSR of delamination. The modified specimens, dubbed the composite rigid double cantilever beam (cRDCB), make use of co-curing to simultaneously process the FRP laminate and bond the laminate to the metallic adherends. The cRDCB also improves upon the existing methodology by integrating on-specimen displacement measurements to study composite behaviour throughout a test. The traction-separation behaviour of the laminate was evaluated using the methodology presented by Watson et al. [7] to extract behaviour from a single test specimen.

2 METHODOLOGY

The cRDCB specimen (Figure 2) consisted of two metallic adherends co-cured to an FRP laminate. Adherends were machined from mild steel, with the interface surfaces roughened using abrasive paper to promote a good connection to the FRP laminate. The interface surface was roughed to at least 2.0 $\mu m\ R_a$ as measured by a contact profilometer (Surtronic 25, Taylor Hobson, England) to ensure consistency between specimens. The adherends were cleaned and degreased with acetone prior to co-curing.

$[0_4]$ laminates were individually laid up for each specimen from unidirectional E-glass/epoxy prepreg tape (UE400-REM, CIT, Italy). A 12.5 μm thick PTFE film was inserted at the midplane of each laminate to serve as a crack starter. Laminates were then sandwiched between the two adherends and installed into a custom curing fixture. The curing fixture provided confinement for the E-glass prepreg during curing, applied a constant curing pressure throughout the processing cycle, and ensured the resulting specimen had a consistent and controllable laminate thickness of 1.06 mm (S.D. = 0.03 mm). cRDCB specimens were cured at 5 bar and 140 °C for 90 minutes. Before testing, resin spew was removed from the cured specimen using abrasive paper. The cRDCB specimens used in this work had an average fibre volume fraction (V_f) of 47%.

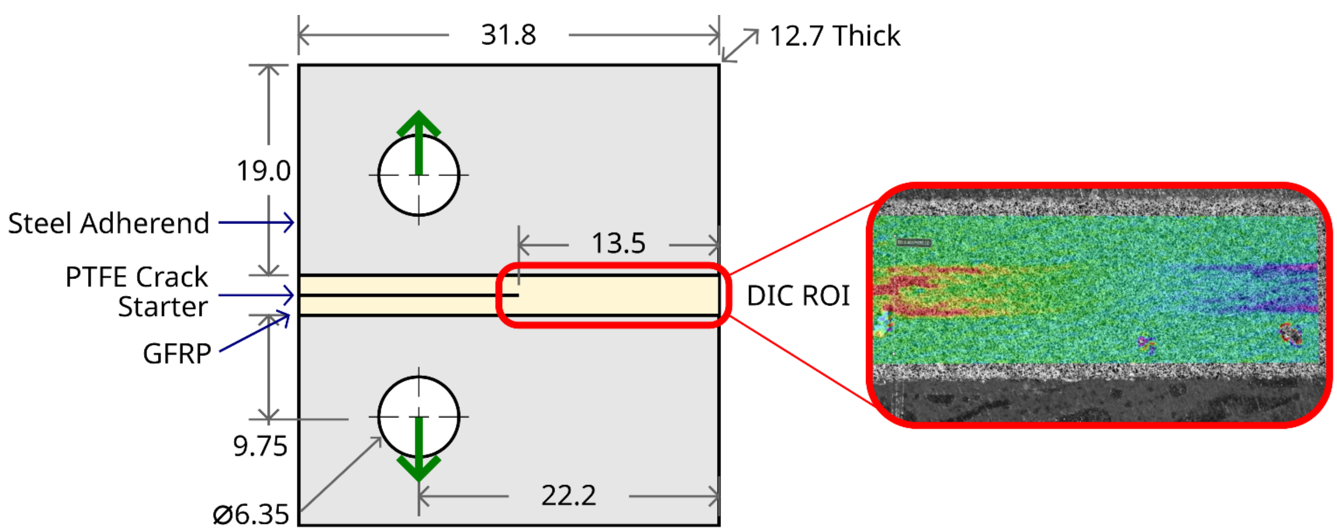

Figure 2. cRDCB schematic and dimensions. Green arrows represent load application via pins, while the red box and right image show DIC region of interest and example strain contours.

Specimens were loaded to failure in a servo-electric test frame (AGX-50, Shimazu, Japan) at a constant cross-head speed of 0.001 mm/s. Digital image correlation (DIC) was used to measure the opening of the specimen at the crack tip and assess the damage behaviour. A 12-megapixel camera (GS3-U3-12S6M, FLIR, USA) with a 180 mm macro lens was used to capture images at five frames per second with a pixel resolution of 0.008 mm/pixel. DIC analysis and measurement were performed using commercial software (VIC-2D, Correlated Solutions, USA) with sub-pixel displacement resolution.

TSRs were extracted from experimental force-displacement responses using the method described in Watson et al. [7], although modified slightly for use with DIC measurements. This methodology requires the computation of the first derivative of force-displacement behaviour. Cubic smoothing splines [8] were fitted to each force-displacement response to filter out experimental noise and ensure a smooth and continuous signal for extraction of the TSR of each specimen.

3 RESULTS AND DISCUSSION

All cRDCB specimens demonstrated linear force-displacement response followed by a short period of non-linear behaviour (Figure 3a) prior to abrupt crack extension. Linear behaviour corresponded to elastic loading of the material at the crack tip, while the non-linearity indicated the onset and accumulation of damage ahead of the delamination crack tip. Peak force (1070 N, S.D. = 104 N) and displacement to peak load (6.31e-3 mm, S.D. = 1.19e-3 mm) both exhibited good consistency. DIC measurements introduced noise into displacement measurements, especially given the low deformation of the cRDCB specimens. While small in amplitude, this noise made force-displacement measurements unsuited for direct extraction of traction-separation behaviour as the derivative of force with respect to displacement must be calculated. Therefore, each displacement response was smoothed using a cubic smoothing spline (solid lines, Figure 3a) before extracting traction-separation behaviour.

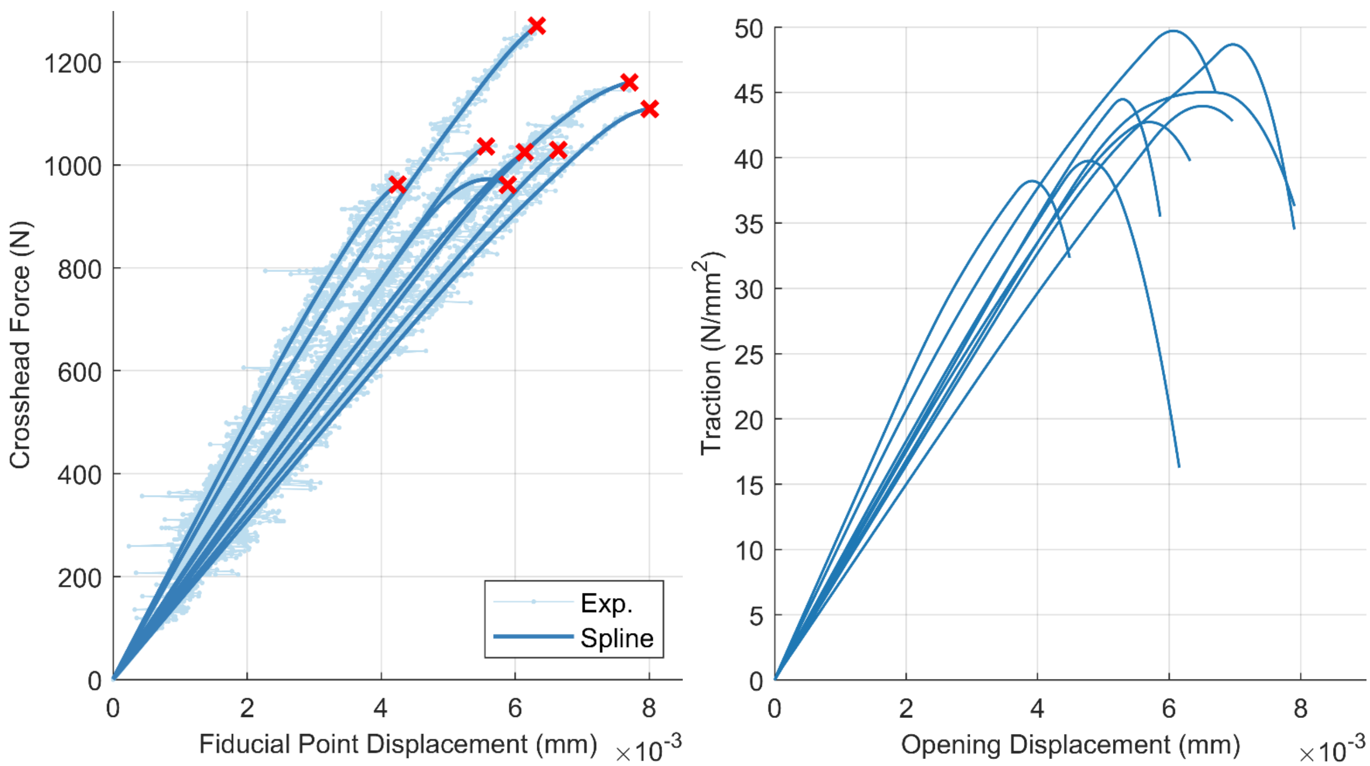

Figure 3. (a) Measured force-displacement responses (n=7) overlaid with smoothing spline. Red markers indicate the point of rapid crack growth. (b) Traction-separation responses extracted from smoothing splines using the method of Watson et al. [7]

Following the maximum load, all cRDCB specimens demonstrated rapid crack growth, with the crack tip extending approximately 10-12 mm between two captured images (less than 0.20 seconds). Due to crack growth speed, unload information about the interface could not be assessed. Consequently, force-displacement responses were truncated at the point of rapid crack growth, limiting the extent to which TSRs could be evaluated (Figure 3b). Despite the limited data, traction-separation behaviour could still be evaluated for load up, damage onset, peak traction, and the start of unloading behaviour.

The extracted TSRs exhibited a similar degree of consistency as the force-displacement results. The average peak traction was 44.1 N/mm^2 (S.D. = 3.94 N/mm^2), which was similar to the transverse strength of the GFRP laminate predicted using analytical stress concentration factor calculations. In contrast with force-displacement data, TSRs exhibited a clear peak and were able to capture early unload behaviour as damage accumulated at and ahead of the crack tip. Unfortunately, complete TSRs, including unloading behaviour to zero traction, could not be extracted due to the rapid crack growth, limiting the damage behaviour that could be assessed, especially phenomena such as fibre-bridging. However, the cRDCB specimen did capture damage onset and early accumulation well, features that DCB specimens have difficulty resolving [9].

The average measured toughness for cRDCB specimens was 0.174 J/mm^2 (S.D. = 0.044 J/mm^2). This value is relatively low for typical GFRP laminates, but it is important to note that the cRDCB specimen was not capturing behaviours like fibre bridging that only develop at large crack extensions. When compared to reported Mode I toughness values for a similar material assessed at the start of crack extension [10], cRDCB toughness values were comparable. It is also important to note that this initial toughness can be difficult to assess for DCB specimens, as measuring the crack tip extension (a necessity for DCB specimens) is challenging at low damage levels.

Rapid crack growth was likely caused by elastic strain energy stored due to compliance in the system. While the cRDCB specimen was intended to be effectively rigid, the high stiffness of the composite material could result in some energy being stored in the deformation of the adherends, composite, and the test frame itself. As damage in the delamination interface accumulated, the stiffness of the cRDCB specimen diminished, reducing the energy storage capacity of the system for the same load and displacement. As a result, stored energy was released in the only method possible, crack extension. The crack growth speed was likely amplified by a race condition between the diminishing stiffness of the specimen as the crack extended and the energy stored as compliance in the system.

4 CONCLUSIONS AND NEXT STEPS

Early developmental work into the cRDCB specimen for Mode I delamination of GFRP laminates has successfully demonstrated the ability to extract the TSR of a delamination interface from a single test. In addition, the use of a single test improves characterization efficiency compared to existing methods like the DCB specimen, which requires additional test geometries to define a TSR. The rapid crack growth observed in the experiment limited damage characterization at large crack extensions, excluding behaviours such as fibre bridging. However, the cRDCB specimen successfully assessed early-stage damage initiation and damage accumulation at the crack tip of a delamination interface.

Despite the rapid crack extension issues experienced in this study, the cRDCB specimen exhibited promise as an effective and efficient means to assess the delamination TSR of an FRP laminate while being small and rigid enough for high-deformation rate testing. Future work will look to resolve measurements during rapid crack-growth using high-speed imaging. Additionally, the extracted TSRs will be integrated into finite element models to enable the prediction and assessment of FRP delamination, including validation of the TSRs extracted from cRDCB specimens against standardized test geometries like the DCB.

5 ACKNOWLEDGEMENTS

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