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Mixed-mode bending (MMB) test analysis of bi-material bonded joints

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Abstract: The dissemination of composite materials introduces applications of hybrid structures with composite and metal parts. The development of reliable methodologies to evaluate the performance of these structures is required. In this work, the mixed-mode fracture behavior of a bi-material adhesively bonded joint is investigated. A new strain-based equivalent geometry for the mixed-mode bending (MMB) test specimen was proposed and tested. A finite element model of the test was developed and validated with experiments. The virtual crack closure technique (VCCT) model of the MMB test with a bi-material joint produced non-converged fracture mode partitioning. Results showed the great potential of the new methodology for testing mixed-mode fracture of bi-material bonded joints.

Keywords: bi-material bonded joints, mixed-mode fracture, asymmetric MMB test, finite elements method

INTRODUCTION

In recent years, composite materials have become widely used in structural applications. Fiber-reinforced polymers (FRPs) are most commonly applied due to their high strength-to-weight ratio. The dissemination of these materials introduces applications of hybrid structures with composite and metal parts (Budhe et al., 2017). Adhesive bonding is the most efficient technology in terms of weight and performance to join these two materials. The advent of composite-to-metal bonded joints requires the development of reliable methodologies to evaluate the performance of these structures.

Fracture mechanics is an important instrument to improve the design and performance of adhesively bonded structures. Imperfections present within materials are points of stress concentration and therefore fracture initiation. Fracture mechanics models the defect as a crack and evaluates if its size overcome the critical fracture size leading to structural failure. The strain energy release rate (SERR) is the most important property to consider in the calculation of fracture toughness of cracked structures. The propagation of a crack occurs when the available energy at the crack tip (G) exceeds the critical energy for crack propagation (*Gc*) (Chaves et al., 2014).

In-service structures are commonly subjected to a combination of peeling and shear stresses. This means that a combination of modes I and II loadings occurs at the crack tip. A variety of mixed-mode fracture test methods has been developed for evaluation of the mixed-mode (I+II) fracture toughness. Among them, the mixed-mode bending (MMB) test stands out for its easy implementation, reliability and capability of testing a wide range of mode-mixities with only one specimen geometry. The MMB test method was originally developed for evaluation of delamination in unidirectional and multidirectional composites (de Morais and Pereira, 2006). Recently, Shahverdi et al. (2014) addressed the fracture toughness in dissimilar composite bonded joints. Droubi et al. (2017) addressed mixed-mode fracture of metal bonded joints. They showed that the MMB test presented a difficulty due to extensive adherend yielding.

The fracture behavior of a bonded joint can also be predicted using finite elements method. The virtual crack closure technique (VCCT) is based on the assumption that the energy released when the crack is extended a crack tip element size is identical to the energy required to close the crack in the same length. This is an accurate method for calculation of the fracture energy at the crack tip in homogenous materials. However, when the crack is located in a bi-material interface, the mode partitioning become sensitive to the crack extension length. One way to circumvent this problem is the introduction of an interlayer between the crack interface and placing the crack within it (Krueger, 2004). The crack propagation occurs within a homogeneous path where the mode-mixity is not sensitive to the crack extension length.

In this work, the mixed-mode fracture behavior of a bi-material adhesively bonded joint is investigated. The aim is to evaluate the use of the MMB in the characterization of the fracture behavior of bi-material adhesively bonded joints. A new strain-based equivalent geometry of the test specimen is suggested. A composite-to-metal specimen is manufactured and tested. A finite element model of the test is developed and validated with experimental results. An analytical method is applied for fracture characterization. Considerations about the new testing set up are pointed out.

EXPERIMENTAL PROCEDURES

Specimen manufacture

Composite-to-metal test specimens were manufactured. A 6.35 mm thickness carbon steel plate A-36 (σy = 250 MPa) was used as metal adherend. Carbon fiber fabrics with a nominal area weight of 424 g/m^2 (LTC450-C10-C, DEVOLT AMT) were selected to make the composite adherend. Each fabric is composed of two orthogonal laminas of fibers. An epoxy resin (PIPEFIX, Novatec Ltd., Rio de Janeiro, Brazil) was selected for impregnation resin of the composite. The adhesive is an epoxy (NVT201E, Novatec Ltd., Rio de Janeiro, Brazil). Material properties are shown in Tab. 1.

Table 1 – Mechanical properties of the materials (Teixeira de Freitas et al., 2017).

Material	E / E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν / ν_{12}
Carbon steel	200			0.27
Adhesive	2.25			
Carbon-epoxy ply	82	10	3.0	0.24

Surface preparation of the steel plate was achieved with grit-blasting of G-40 steel grit and degreasing with acetone. An anti-friction material was applied over the steel surface to produce the pre-crack. The adhesive was then applied over the treated steel surface. One layer of glass fiber dry chopped strand mat with a density of 300 g/m2 was applied to avoid direct contact between carbon fibers and metal. Then, the hand lay-up process started by alternating application of carbon fiber fabrics layers and the impregnation resin. The lamination process was performed by hand lay-up. The curing process was performed at room temperature for 2 h. A layer of peel ply was applied over the composite in order to produce a smoother surface. The final lay-up consisted of a $[0/90]_{20}$ laminate.

In a bi-material bonded joint, strain equivalence between arms assures pure mode I fracture while pure mode II is obtained when the curvature in the two arms are the same. This condition is produced by designing the joint to satisfy the condition of Eq. 1. The number of layers was calculated based on the strain equivalence between arms.

$$E_2 h_2^2 = E_1 h_1^2 \qquad (1)$$

The composite-steel plate was cut to specimens with 25±1 mm width (*B*) and total thickness (*h*) is 20.3±0.7 mm. Measurements of width and thickness were obtained with a digital caliper from three different regions: 30 mm from the sides and at the half-length of the specimens. Finally, aluminum end-blocks (25x15x7 mm) were bonded to the specimens using a structural adhesive (Scotch-Weld 9323) producing the pre-crack length (a_0). The specimen geometry is shown in Fig. 1.

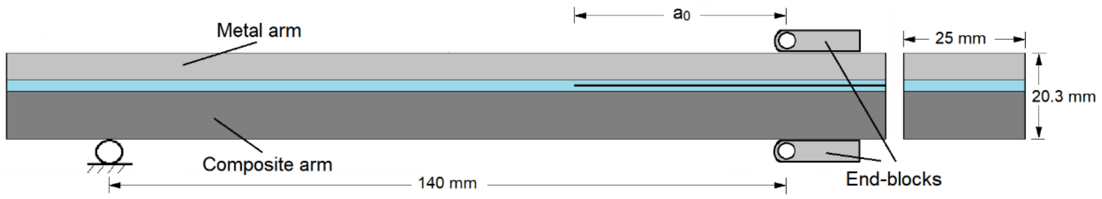

Figure 1 – Specimen geometry.

Experimental set up

In the MMB test, load (*P*) is applied by the yoke on the loading rollers attached to the lever and loaded just above the mid-plane of the test specimen. The lever applies the opening (P_I) and shear (P_{II}) loadings on the specimen in a ratio defined by the lever length (*c*). A typical MMB test apparatus was used in the test (ASTM D6671M, 2013). The test schematic is shown in Fig. 2. The lever weight (*Pg*) is 17.3 N. Tests were conducted in a MTS machine equipped with a 10 kN load cell. Test speed is 0.5 mm/min.

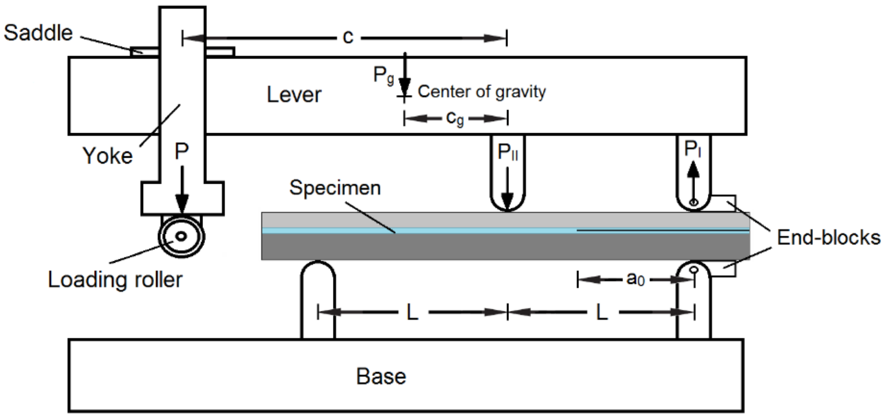

Figure 2 – Schematic of the MMB test.

FINITE ELEMENT MODEL

A 3D finite element (FE) model of the MMB test was developed in Abaqus®. Brick 8-nodes linear elements (C3D8) were applied in the whole model. Figure 3 shows a representation of the model boundary conditions. In order to simulate the real constraints during a MMB test, the following conditions were applied: the right bottom end was constrained from all displacements and the rotations around x and y axis; the left bottom end was constrained from displacements in y direction; the opening load was applied in the right top end and the shear loading was applied in the center top surface. All the conditions were applied on an area with 2 mm length and 25 mm width.

Simulations were performed according to loading vs. crack length points obtained from experiments. The opening and shear loadings were applied directly on the specimen and can be obtained from the testing geometry. Elastic strain curves were obtained along steel top surface and composite bottom surface in the length direction.

The Virtual Crack Closure Technique (VCCT) was applied for calculation of the fracture parameters. The VCCT is implemented as a crack propagation tool in Abaqus®. The crack propagates when the fracture energy around the crack tip exceeds a critical value. Since the damage progression is not pertinent, very high values of critical energy were entered to assure that the crack will not propagate. This approach allows obtaining the fracture energy at defined crack propagation points.

Applying the VCCT in a crack propagation of a bi-material interface produced element size dependent results. To overcome this problem, it is suggested to model the crack propagation within the adhesive layer (Krueger, 2004). Even so, mesh refinements around the crack tip generated non-convergence, as shown in Fig. 4.

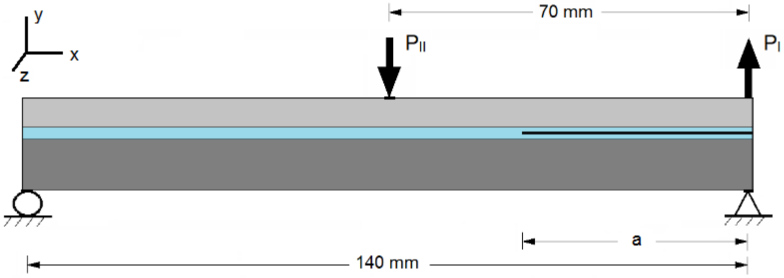

Figure 3 – Finite element model geometry and boundary conditions.

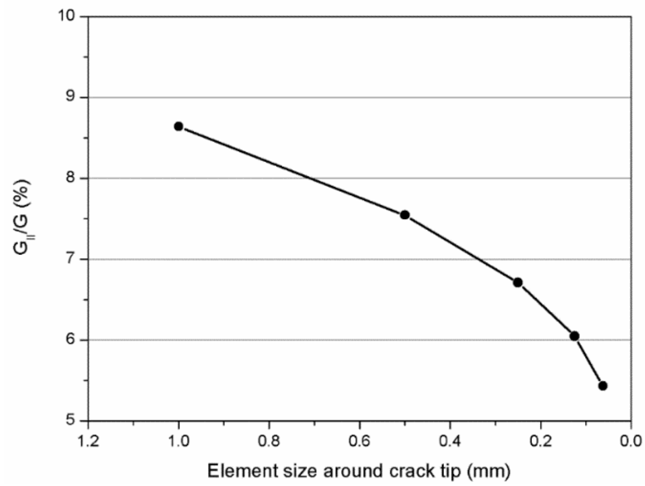

Figure 4 – Finite element mesh sensitivity.

RESULTS AND DISCUSSION

Experiments

Two experimental set ups were tested: composite arm on top and steel arm on top. Different lever lengths were applied in the tests producing a diverse range of mode mixities. A total of six specimens were tested as shown in Table 2. All tests were performed with an initial crack a_0 of 45 mm.

Table 2 – Test parameters.

Test	Set up	Lever length (c)
01	composite on top	31 mm
02	composite on top	49 mm
03	composite on top	100 mm
04	metal on top	54 mm
05	metal on top	64 mm
06	metal on top	72 mm

Figures 5a and 5b show typical fracture surfaces of the specimens tested with composite adherend on top. It is observed that the fracture occurred in the glass fiber mat. Fracture migrated in the beginning of the crack propagation. In the case of placing steel arm on top, Figures 5c and 5d reveal a cohesive fracture in the adhesive near steel interface. Therefore, it is necessary to place the metal side of the bonded joint on top in order to analyze the fracture of the adhesively bonded joint.

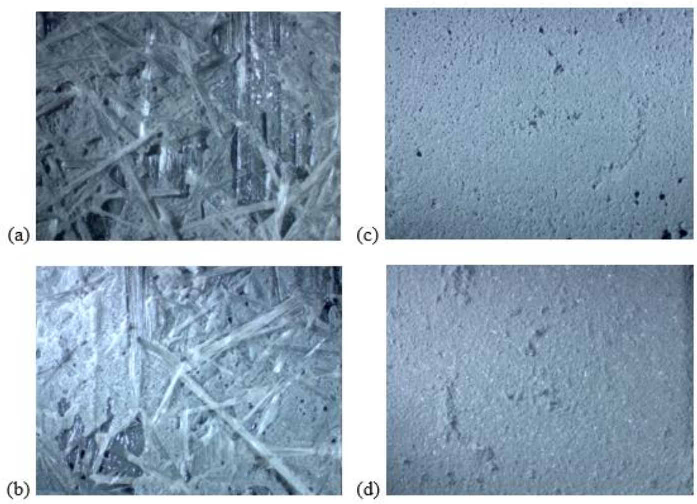

Figure 5 – Fracture surfaces of MMB test with composite on top from the (a) composite and (b) steel sides, and with steel on top from the (c) steel and (d) composite sides.

Figure 6 shows the load-displacement curves of the Tests 04, 05 and 06. These are the valid cases where fracture occurred within the adhesive layer. Some non-linearity is observed in the beginning of the curves due to accommodation of the test apparatus. It is observed that the test loadings are higher when using lower lever lengths. This was expected since by decreasing the lever length one is decreasing the mode I loading component, and the contribution of mode I fracture has a major influence in the crack propagation.

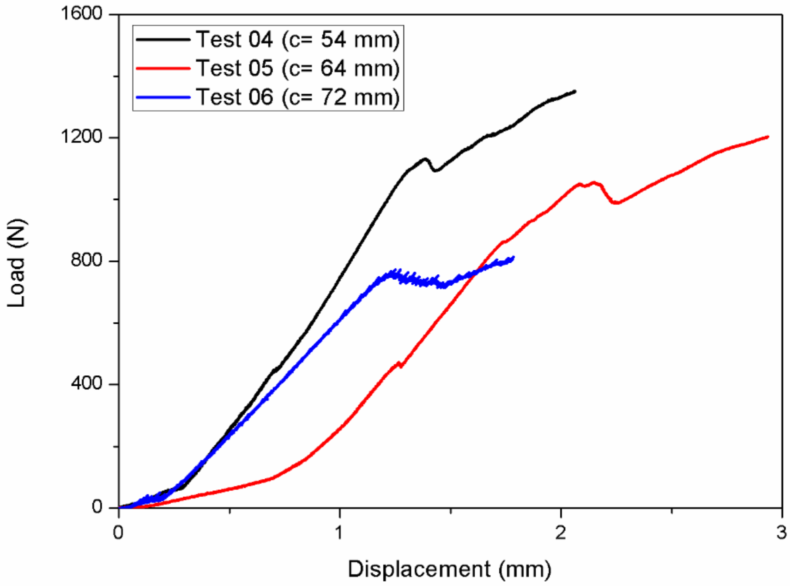

Figure 6 – Load-displacement curves of Tests 04, 05 and 06.

Validation of numerical model

A validation test was performed. The test configuration was chosen to have the steel arm on top in order to avoid crack migration to the composite layers. Strain gauges were applied for experimental validation of the numerical model. Experimental results obtained from the strain gauges were compared with the FE model at loading vs. crack size points. The strain gauges were bonded to the steel (1 to 4) and composite (5 and 6) surfaces. The numerical strain curves were obtained from a path along length of the steel and composite outer surfaces. Figure 7 shows the comparison of numerical and experimental longitudinal strain at 55 mm of crack length. The length axis is defined from the application point of the opening load. There is a good agreement between numerical and experimental results.

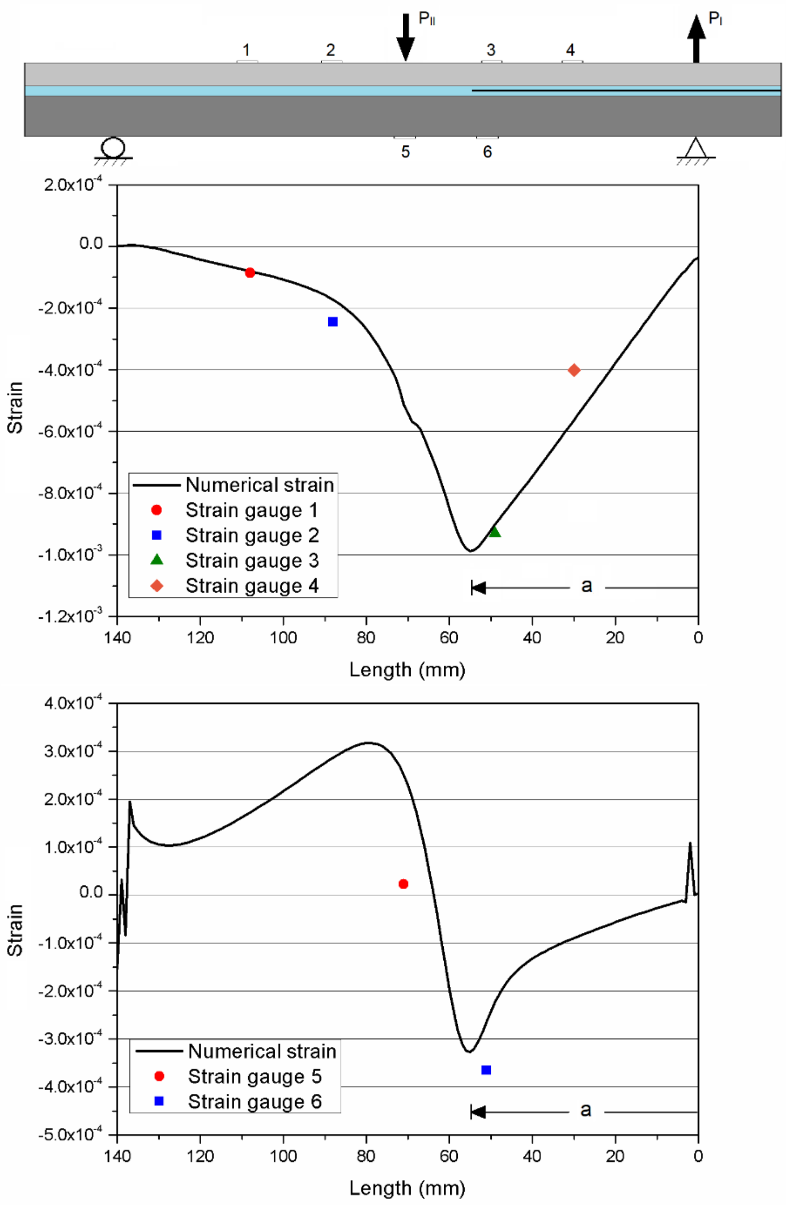

Figure 7 – Strain along steel (left) and composite (right) surfaces at the crack length of 55 mm.

CONCLUSIONS

The fracture of a composite-to-metal adhesively bonded joint was investigated using the MMB test. A new methodology for the MMB test set up using a strain-based equivalent geometry is tested. A finite element model of the test is developed and validated with strain gauges. Conclusions were attained regarding the new test set up.

The MMB test showed potential for testing mixed-mode fracture of bi-material bonded joints. The new strain-based specimen design was successfully applied to the MMB test.

The use of a composite-to-metal joint in the MMB test requires a set up with metal arm on top. This ensures a cohesive fracture within the adhesive layer and prevents crack migration to composite delamination.

The metal yielding point imposed limitations of the maximum contribution of mode II loading in the crack propagation. The fracture toughness can be obtained from crack propagation points were the crack propagation observes the assumption of the linear elastic fracture mechanics. The limitation may be overcome by changing geometric parameters of the test specimen.

A numerical calculation of the fracture toughness using the VCCT for modelling the MMB test with a bi-material joint produced non-converged results. Analytical and numerical reliable methods for the calculation of fracture toughness are still required.

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