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AN EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE MIXED-MODE FRACTURE TOUGHNESS AND LAP SHEAR STRENGTH OF AEROSPACE GRADE COMPOSITE JOINTS

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Introduction

The increasing use of composite materials in various industries, such as aerospace, automotive and renewable energy generation, has driven a need for a greater understanding of the fracture behaviour of bonded composite joints.

An important prerequisite for the adhesive bonding of composites is the existence of a uniform surface free from contaminants and mould release agents. While there are several ways in which this may be achieved, the use of peel plies has emerged as the preferred choice for many industries due to the repeatable nature of the resulting surface, particularly in the highly regulated aerospace industry. However, the use of peel plies can present some problems. It is possible that contamination from the peel ply can be transferred to the composite substrate and adversely affects the adhesive joint [1].

Composite joints are typically evaluated using lap shear type tests. While these tests are relatively simple to perform and post-process compared to their fracture mechanics based counterparts, the results can often be misleading and are greatly dependent on the overlap length, the thickness of the substrate and the type of fillet employed [2, 3].

The aim of this work is to show that composite joint systems can be modelled using material properties determined from fracture mechanics based tests. The fracture parameters will be used to develop numerical models of the fracture tests that accurately predict the wide-area lap-shear test.

Experimental

Materials & Manufacture of Bonded Specimens

A variety of aerospace grade materials were used in the present study. The substrates were manufactured from a carbon-fibre/epoxy prepreg manufactured by Hexcel. A wet peel ply was used to prepare the surface prior to bonding. A new generation two-part epoxy paste adhesive was used to bond the substrates. The composite laminates were manufactured in-house at University College Dublin using a press-clave and vacuum bagging procedure as per the manufacturer's guidelines. Once cured, specimens were cut to a size of 25mm x 150mm using a diamond grinding disc. The peel ply was removed just before application of the adhesive. Bondline thickness was controlled

at 0.15mm using a nylon scrim cloth. The joints were cured in accordance with the manufacturer's guidelines in an air-circulated oven. A special curing jig was used to ensure alignment of the substrates.

Linear Elastic Fracture Mechanics Based Tests

Three linear elastic fracture mechanics (LEFM) based tests were conducted to determine the fracture toughness of the composite joints. The tests employed were a mode I double cantilever beam (DCB) test [4], a mixed mode I+II asymmetric double cantilever beam (ADCB) test [5] and a mode II end loaded split (ELS) test [6]. All tests were conducted at a constant crosshead displacement rate of 2 mm/min at room temperature on a screw-driven Hounsfield 50K tensile test machine. The propagation values for G_C were calculated using corrected beam theory (CBT) from the following equations.

$$\text{DCB:} \quad G_{IC} = \frac{3P\delta}{2B(a + |\Delta_I|)} \cdot \frac{F}{N}, \quad (1)$$

$$\text{ADCB:} \quad G_{I/II C} = G_{IC}^M + G_{IIC}^M, \quad (2)$$

$$\text{where:} \quad G_{IC}^M = \frac{3P^2(a + |\Delta_I|)^2}{B^2 E h^3} \cdot F, \quad (3a)$$

$$\text{and:} \quad G_{IIC}^M = \frac{9P^2(a + |\Delta_{II}|)^2}{4B^2 E h^3} \cdot F, \quad (3b)$$

$$\text{ELS:} \quad G_{IIC} = \frac{9P^2(a + |\Delta_{II}|)^2}{4B^2 E h^3} \cdot F, \quad (4)$$

where P is the applied load, δ the crosshead displacement, B the width of the specimen, h the half-thickness of the specimen, $\Delta_{I/II}$ the crack length correction term, F the large displacement correction factor, N the load block correction factor and E the flexural modulus of the substrate.

Wide-Area Lap-Shear Tests

Wide-area lap shear (WALS) tests were conducted in accordance with a Bombardier Aerospace (UK) test protocol. The bonded composite joints were notched using a diamond blade such that the overlap length was 12.5mm. The width of each specimen was 25mm. Tests were performed on an Instron servo-hydraulic tensile test machine. Hydraulic grips were used to minimise slippage. The samples were loaded at a rate of 0.1mm/min. The extension was recorded using a clip gauge with 50mm gauge length.

Numerical Method

Finite-volume method was used for the numerical simulation of the experiments. A fully implicit time-differencing scheme is employed in the analysis, guarantying unconditional stability. The model was implemented in 'OpenFOAM' package, a C++ library for continuum mechanics [7]. Figure 1 shows a typical mesh used for simulation of mode I DCB tests. As can be seen, tests were fully modelled, and proper material properties attributed to each specimen part. Aluminium loading block and composite substrate were modelled using linear elastic material model with appropriate mechanical properties, whereas adhesive was modelled using elastic-plastic model with classical incremental J2 flow theory with von Mises plasticity. Plane strain conditions were assumed to dominate through specimen thickness, and hence 2D calculations are performed. Loading was applied to the loading boundary using mixed boundary condition, to allow loading block rotation. Crack propagation was simulated using Dugdale mixed-mode cohesive-zone model [8] applied to cell faces in the adhesive domain. Therefore, it is possible to simulate an arbitrary crack propagation path including 'multi-cracking' process.

Figure 1. A typical mesh for DCB test simulations.

Results and Discussion

Fracture Tests: Experimental Results & Numerical Model

Figure 2 shows the failure envelope for the composite joint system under investigation. All joints resulted in interfacial

failure. The total fracture toughness was essentially constant at approximately 200 J/m² until the condition of pure mode II loading was reached. At this point, the measured fracture toughness almost doubles to 400 J/m². However, the reason behind this increase was believed to be due to mechanical interlocking between the peel ply prepared surface and adhesive. From visual inspection of the fracture surface, segments of the wet peel ply resin were sheared off from the substrate. This damage was not seen during mode I or mixed-mode loading.

Figure 2: GI/GII failure envelope for composite joint system.

All tests, except ELS, are simulated numerically using the procedure explained in previous section. Cohesive-zone parameters are taken as follows: fracture energy G_{Ic} is set to the values obtained experimentally, ie. 200 J/m², while cohesive strength is equal to the tensile strength of the adhesive obtained from the standard tensile tests. The mode-mixity was governed by parameter $\beta = \tau_{max}/\sigma_{max}$, where τ_{max} and σ_{max} , represent adhesive shear and normal strengths, respectively. Numerical simulations are then validated against experimental results comparing the load and crack length histories. In general, a good agreement between measured and predicted results was obtained. For example, Figure 3 shows comparison between experimental and numerical load and crack length histories for a DCB test, where fracture toughness was set to 200 J/m², and cohesive strength of 30 MPa.

Figure 3. DCB test: load and crack length predictions.

WALS: Experimental Results and Numerical Model

Numerical procedure used to simulate classical fracture tests is then applied to WALS test configuration. It has to be noted that only part of the specimen between clip gauges was modelled. The reason for this was significant slippage in the grips which could not be controlled nor measured. Fracture toughness was kept constant and equal to 200 J/m^2 , while normal cohesive strength was set to 30 MPa. In order to investigate the mode-mixity effects, parameter β was varied from 0.1 to 1.0, ie. from predominantly mode I towards mode II fracture. Figure 4 shows comparison between experimental and numerical load histories.

Figure 4. WALS test load-extension histories.

As can be seen, a good agreement between experimental data and numerical predictions is obtained in terms of the load slope. A small mismatch is probably due to material properties used to describe adhesive and composite; modulus of elasticity for composite was back-calculated from DCB tests, but this value is usually higher in tension. In addition, adhesive was modelled using properties obtained from the tensile tests on bulk material, whereas in the reality the layer between composite arms is a mixture of the adhesive and scrim cloth.

More importantly, however, loads at failure differ significantly between mode-mixity ratios used in simulations. It is clear that shear strength plays significant role in predicting the fracture process in WALS tests. If the small β is used (predominantly mode I fracture), load at failure is not predicted at all well and is almost 3 times lower than the experimental one. On the other hand, if the shear strength is 50% and higher than the normal cohesive strength, load at failure is overestimated significantly. It is clear that $\beta=0.3$ gives the best prediction in terms of failure load for the values of mode-mixity ratios investigated. This value corresponds to the shear stress of 9 MPa, which is very similar to the value calculated using WALS test protocol.

To investigate this point further, an additional hypothetical simulation was performed, with the same shear strength, $\tau_{\max}=9 \text{ MPa}$ and twice lower cohesive strength (as a consequence, normal cohesive strength is twice lower,

too, and β twice larger). As can be seen, the result is almost identical to the previous one, suggesting that the shear cohesive strength might be the parameter that governs the fracture in WALS tests. However, this finding needs to be investigated further, especially using different bondline thickness and overlap length.

Conclusions

While lap shear tests can provide a relatively quick and easy way to evaluate adhesive joints, the results can often be misleading. In the case of the present work, fracture mechanics based tests were carried out and numerically simulated in order to obtain parameters describing fracture process that can be used to accurately model the behaviour of lap shear joints. However, lap shear joint simulations showed that shear cohesive strength seems to be playing the leading role in defining the load at failure, while mode-mixity ratio can vary and has no effect as long as the shear cohesive strength is kept constant. Nevertheless, further investigation is needed in the search of the procedure that could conceivably be transferred to a structural component of any geometry used in the aerospace industry.

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