MODELLING OF MODE I FRACTURE BEHAVIOUR OF ADHESIVELY-BONDED GFRP JOINTS USING VIRTUAL CRACK CLOSURE TECHNIQUE AND COHESIVE ZONE METHOD

Ye ZHANG
Title: Research Fellow
University or Affiliation: University of Surrey, Civil Engineering
Address: University of Surrey, FEPS (C5), Guildford, Surrey, GU2 7XH, UK
Email address*: ye.zhang@surrey.ac.uk

Marios CHRYSSANTHOPOULOS
Title: Professor of Structural Systems
University or Affiliation: University of Surrey, Civil Engineering
Address: University of Surrey, FEPS (C5), Guildford, Surrey, GU2 7XH, UK
Email address: mkchry@surrey.ac.uk

Abstract
The Mode I fracture behaviour of adhesively-bonded joints composed of pultruded glass fibre-reinforced polymer (GFRP) laminates has been experimentally investigated using Double-Cantilever-Beam (DCB) specimens. In this study, the corresponding finite element (FE) model was established using Abaqus/Standard and the crack initiation and propagation stages were simulated using two approaches: (i) the Virtual Crack Closure Technique (VCCT) and (ii) the Cohesive Zone Method (CZM). A sensitivity analysis was performed to evaluate the effect of FE model input parameters, including the element size ($l_e$), critical strain energy release rate ($G_C$), interface stiffness ($K$) and interface strength ($\sigma_0$), on the numerical simulation of fracture behaviour. The load-displacement response predicted by CZM agreed well with the experimental results. The other approach, VCCT, also successfully simulated the load-displacement response corresponding to crack propagation; however, it could not provide an accurate prediction of the crack initiation load.

Keywords: Adhesively-bonded joints, GFRP, Mode I fracture, Virtual Crack Closure Technique, Cohesive Zone Method

1. Introduction
The successful use of fibre reinforced polymer (FRP) composites as a structural replacement for conventional materials depends much upon their integrity and durability. However, because of the different constituent materials employed, one of the major concerns in layered FRP composites is interface debonding: cracks may initiate naturally from small material defects (voids, microcracks or inhomogeneities) and propagate along the weakest path, potentially leading to rapid deterioration of the entire structural component and/or assembly.

A direct way to characterize progressive crack growth is to use fracture mechanics theory in conjunction with the finite element method (FEM). Two well-known approaches can be used to perform numerical simulation of debonding [1]. The first, based on linear elastic fracture mechanics (LEFM), is to compute the strain energy release rate ($G$) using the Virtual Crack Closure Technique (VCCT) and to compare it with the critical energy release rate ($G_C$). An alternative approach is to introduce cohesive elements into the FE model, based on the Cohesive Zone Method (CZM). The concept of CZM was established to study perfectly brittle materials and then adopted to ductile fracture, on the basis of elastic-plastic fracture
mechanics (EPFM) [2]. In CZM, fracture is treated as a gradual phenomenon in which separation, resisted by cohesive traction, takes place across a cohesive zone. The extension of this zone ahead of the crack tip is modelled using traction-separation laws. Researchers have often employed both aforementioned approaches to investigate their particular application cases and have compared results [2-4]. Fracture simulations using CZM require significant experience in order to determine input parameters, e.g. the mesh size and the properties to characterize traction-separation laws. As evident is from previous studies [1, 5-7], a sensitivity analysis is needed prior to utilizing CZM in the simulation of fracture behaviour.

In an earlier study [8], the Mode I fracture behaviour of adhesively-bonded joints composed of pultruded GFRP was experimentally investigated using Double-Cantilever-Beam (DCB) specimens. Values for Mode I critical strain energy release rate ($G_{IC}$) corresponding to crack initiation and propagation were determined using different methods. In the present work, 2-D FE models of DCB specimens were established using Abaqus/Standard. The Virtual Crack Closure Technique (VCCT) and the Cohesive Zone Method (CZM) were employed to simulate the Mode I fracture behaviour. A sensitivity analysis was performed for four input parameters: mesh size ($l$), critical strain energy release rate ($G_C$), interface stiffness ($K$) and interface strength ($\sigma_0$). The load-displacement response of DCB specimens was simulated using both VCCT and CZM approaches and compared to the experimental results.

2. Summary of experimental investigations

2.1 Specimen configuration and experimental set-up

In total, five adhesively-bonded DCB specimens were manufactured and examined following fracture mechanics based testing standards, as detailed in [8]. The specimens were composed of pultruded GFRP laminates bonded with a cold-cured epoxy adhesive system. These laminates consisted of E-glass fibres embedded in an isophthalic polyester resin, with a roving layer in the middle and mat layers on either side, comprising a chopped strand mat (CSM) and a $0^\circ/90^\circ$ woven mat stitched together. As a surface coating, a polyester veil (40 g/m²) had been added to protect against typically aggressive environments. The material properties of the GFRP laminates and epoxy adhesive are presented in [9]. All bonded surfaces were mechanically abraded with sandpaper (grit class P80) using a grinder and then chemically degreased using acetone.

![Diagram of DCB specimen configuration](image)

Figure 1. Geometrical configuration for DCB specimens (in [mm]).

The geometric configuration of the DCB specimens is shown in Fig. 1. The GFRP laminates had a width of 50 mm and a thickness of 6 mm, whereas the epoxy adhesive layer was 2 mm thick. A pair of steel piano-hinged loading blocks was bonded to the DCB specimens with a 0.5 mm-thick layer of the same adhesive as that used for the specimens. A 25-mm pre-crack, $a_0$, measured from the loading axis, was created during specimen fabrication by inserting a 50-mm long Teflon film of 0.05 mm thickness between the lower GFRP laminate and the adhesive layer. Mode I tests were performed on a 5 kN testing rig under displacement control.
at a constant rate of 1 mm/min. Load, displacement and crack length were recorded. Two methods were used to measure the crack length, namely visual observation and a video extensometer. More details concerning the second method are given in [8].

2.2 Experimental results

The dominant failure was a fibre-tear failure, which occurred between the mat and veil layer of the GFRP laminates caused by the lower through-thickness tensile strength of the laminate compared to the strength of the adhesive-laminate interface, see Fig. 2(a). As a result, the crack-bridging fibres of the woven or random chopped mat layer were pulled out of the polyester matrix.

The load–displacement response of five DCB specimens is presented in Fig. 2(b). Loading was manually stopped when the crack length reached 150 mm. All curves follow a linearly increasing trend up to the maximum load, followed by a post-peak unloading part. The descending branch exhibited a saw pattern, as a result of fibre-bridging. For each DCB specimen, the strain energy release rate \( G_I \) was calculated using the Simple Beam Theory (SBT), the Corrected Beam Theory (CBT), the Experimental Compliance Method (ECM) and the Modified Compliance Calibration (MCC) as detailed in [8]. A resistance curve (R-curve) was established by plotting \( G_I \) against the crack lengths \( a \), see Fig. 17 in [8]. The values of the critical strain energy release rate \( G_{IC} \) corresponding to crack initiation and propagation were also determined, see Table 6 of [8].

![Figure 2. (a) Typical failure mode and (b) load-displacement response of DCB specimens [8].](image)

3. Finite element modelling

3.1 Introduction of crack growth modelling

Two approaches implemented in the commercial FEA software Abaqus/Standard version 6.9 were considered for simulating the progressive crack growth. The first approach, designated as the Virtual Crack Closure Technique (VCCT), belongs to the debonding framework of Abaqus/Standard. As shown in Fig. 3(a), the interface to debond is modelled by a pair of contact surfaces which are initially connected through defining a TIE constraint. Under increasing applied load/displacement, the corresponding \( G \) is calculated using the VCCT [8, 12] and compared to the experimentally determined \( G_C \). When the value of \( G \) exceeds \( G_C \), the constraint between the contact surfaces is released and the contact status changes from BONDED into OPEN, thus simulating fracture.

In the second approach, Abaqus/Standard offers a library of cohesive elements to model the cohesive zone along the bondline. As shown in Fig. 3(b), the crack surfaces are connected
through a single layer of zero-thickness cohesive elements which can separate from each other in the presence of shear or/and normal stresses. In this study, the constitutive response of the cohesive elements was defined through a bi-linear traction-separation law as presented in Fig. 3(c), where $K$ represents the interface stiffness, $\sigma_0$ is the interface strength, $\delta_f$ is the failure separation and the area under the curve is the critical strain energy release rate $G_C$. Details regarding the theoretical background of CZM are given in [1-4].

Concerning their applicability, both approaches can be used for the simulation of one or multiple crack growing along pre-determined crack surfaces. The crack growth is self-driven and the minimum crack increment equals to the element size. When facing some particular application cases, CZM has certain advantages over VCCT, e.g. modelling bondline without pre-existing crack, dealing with ductile fracture and being used for 3D models. However, the complex input parameters required to define traction-separation laws and smaller mesh size to ensure the desirable accuracy make CZM a more “expensive” and “user sensitive” approach.

### 3.2 Overview of FE models

Two dimensional FE models were developed in Abaqus to simulate the Mode I fracture behaviour of DCB specimens. The veil, mat and roving layers of the GFRP laminate were separately modelled using the material properties presented in Table 1 of [10]. The 4-node, 2D solid elements (CPE4) were used to model both GFRP laminates and the epoxy adhesive. In accordance with the fibre-tear failure observed in the experiments, the interface between the mat and veil layers of the upper GFRP laminate was modelled as the bondline where crack initiation and propagation could occur. In the VCCT approach, two contact surfaces were created, placed between the veil and mat layers as shown in Fig. 1. In CZM modelling, the interface between the mat and veil layers was modelled as a single layer of 4-node, 2D cohesive elements (COH2D4) with zero thickness. The boundary conditions of the testing configuration were introduced in the FE model, and a vertical displacement was applied on the top of the upper substrate.

### 3.3 Sensitivity analysis

#### 3.3.1 Overview

To evaluate effects of FE model input parameters on the simulation of the load-displacement response, a sensitivity analysis was performed. For CZM approach, four model families were created to investigate the influence of (1) the element size $l_e$ along the bondline, (2) the critical strain energy release rate $G_c$, (3) the initial interface stiffness $K$ and (4) the interface strength $\sigma_0$. The first two parameters were also evaluated for VCCT. In all cases, a 20 mm
displacement was progressively applied and the resultant load-displacement curve was obtained through an incremental elastic analysis, including geometrically non-linear effects.

3.3.2 Effect of element size

In order to study the effect of mesh refinement, analyses were carried out for four different element sizes: 0.5, 1.0, 2.5 and 5.0 mm. The corresponding element number along the bondline was 500, 250, 100 and 50. In these models, values of $G_C$, $K$ and $\sigma_0$ were set as 1500 J/m², $10^{14}$ N/m³ and 1.0 MPa. The resultant load-displacement curves are plotted in Figs. 4(a) and 4(b) for VCCT and CZM respectively. The load-displacement curve prior to the peak load can be viewed as the crack initiation stage, while the latter part of the curve corresponds to crack propagation. Almost identical load-displacement curves were obtained from models with different element size, except for $l_e = 5.0$ mm. The analysis with the largest element size slightly increased the crack initiation load but had no influence on the crack propagation response. As can be seen, a saw tooth pattern was observed in the curve obtained from VCCT with $l_e = 5.0$ mm. It indicates that as the element size increases beyond a certain size, the stability of the FE solution can be compromised.

3.3.3 Effect of critical strain energy release rate

As presented in Table 5 of [8], $G_{IC}$ obtained from DCB specimens were in the range between 1500 J/m² and 2000 J/m², dependent on the calculation methods. To evaluate the effect of varying $G_C$, simulations were performed for three values: 1500 J/m², 1800 J/m² and 2000 J/m². In these models, the values of $l_e$, $K$ and $\sigma_0$ were set as 1.0 mm, $10^{14}$ N/m³ and 1.0 MPa respectively. The load-displacement curves obtained from VCCT and CZM are plotted in Figs. 5(a) and 5(b) respectively. Regardless of the modelling approach, the increased value of $G_C$ resulted in a higher crack initiation load and also a higher corresponding displacement. When $G_C$ increased from 1500 J/m² to 1800 and 2000 J/m², the area under the load-displacement curve prior to crack initiation increased by approximately 20% and 35%, which is in proportion to the increase of $G_C$. In VCCT models, the values of $G_C$ affected the crack initiation load and displacement to a similar degree, while in their CZM counterparts, the load was less influenced.

3.3.4 Effect of interface stiffness and strength

In CZM modelling, the interface stiffness and strength are two key parameters for defining the traction-separation law of the cohesive elements. The interface stiffness $K$ can be considered as a penalty stiffness when the cohesive element layer has zero thickness. The value of $K$ must be high enough to prevent artificial compliance from being introduced into
the model by the cohesive elements, but not too high as to produce convergence problems. Using a proposed equation [1], the lower limit for $K$ was estimated, resulting in a minimum interface stiffness of $3.2 \times 10^{13} \text{ N/m}^3$ for the DCB specimens in this study. Three stiffness values within an order of magnitude ($10^{13}$, $5 \times 10^{13}$ and $10^{14} \text{ N/m}^3$) were selected and the corresponding simulations were performed. In these models, the values of $l_e$, $G_C$ and $\sigma_0$ were set as 1.0 mm, 1500 J/m$^2$ and 1.0 MPa. The load-displacement curves are shown in Fig. 6(a). Almost the same response was obtained from the three different models, which indicates that, within the investigated range, the influence of $K$ can be ignored.

Concerning the interface strength, there is no clear procedure on how to obtain the value of $\sigma_0$ from experiments. In the present work, the out-of-plane strength of GFRP laminates might be considered as an appropriate parameter on which the interface strength can be based, and an experimentally obtained value of 9.4 MPa was provided in [11]. However no unequivocal evidence can be accessed for the estimation of $\sigma_0$. By setting $l_e$, $G_C$ and $K$ equal to 1.0 mm, 1500 J/m$^2$ and $10^{14} \text{ N/m}^3$, several FE simulations were performed with various values of $\sigma_0$ ranging between 0.5 MPa and 10.0 MPa. It was noticed that when $\sigma_0$ was higher than 3.0 MPa, the FE models had difficulty in converging and the solution procedure was aborted. Therefore only load-displacement curves obtained from FE models with $\sigma_0 = 0.5$, 1.0, 1.5 and 3.0 MPa are presented in Fig. 6(b). It is shown that as $\sigma_0$ decreases, the crack initiation load is lowered and crack initiation is delayed; however, no influence on the part of the load-displacement response corresponding to crack propagation can be found. Indicatively, when

![Figure 5. Effect of $G_C$ on load-displacement response obtained from (a) VCCT and (b) CZM.](image_url)

![Figure 6. Effects of (a) $K$ and (b) $\sigma_0$ on the load-displacement response obtained from CZM.](image_url)
the interface strength $\sigma_0$ is increased fivefold (from 0.5 MPa to 3.0 MPa) the corresponding predicted crack initiation load improved by around 60%.

3.4 Comparison of numerical and experimental results

Based on the experience gained from the sensitivity analysis, the parameters used to simulate the Mode I fracture of the particular DCB specimens tested in [8] were selected as: $l_c = 1.0$ mm, $G_C = 1500$ J/m$^2$, $K = 10^{14}$ N/m$^3$ and $\sigma_0 = 1.0$ MPa. A displacement of 45 mm was incrementally applied and the load-displacement curves obtained from both FE-based approaches are presented in Fig. 7.

The load-displacement response corresponding to crack propagation was successfully modelled by both approaches and very good agreement with the experimental results may be observed. However, concerning the crack initiation load, a significant overestimation was produced by the VCCT approach. As can be seen, the load-displacement curve obtained using VCCT exhibited an entirely linear trend until the peak load, with no evidence of ‘softening’. This may be attributed to the binary contact conditions defined in VCCT, which implies that until the contact status of the pair of elements adjacent to crack tip changes from BONDED to OPEN, the stiffness of the DCB specimen has to remain constant with no stiffness degradation. As a result, the nonlinearity of the experimental load-displacement response prior to the peak load cannot be modelled by this approach. By contrast, fairly good correlation was observed in Fig. 7 between the CZM and experimental results. However, it should be emphasised that the successful simulation using CZM was based on the use of a value of $1.0$ MPa for $\sigma_0$, although there is no clear evidence in support of this choice.

![Figure 7. Comparison of load-displacement response obtained from experiments and FEA.](image)

4. Conclusions

The Mode I fracture behaviour of adhesively-bonded GFRP joints, which was experimentally investigated using DCB specimens, has been simulated numerically using 2D FE models. These were established using Abaqus/Standard and two approaches, VCCT and CZM, were employed to simulate the fracture behaviour. A sensitivity analysis was performed in order to evaluate the effects of FE model input parameters on the simulation. The following conclusions were drawn:

1. Both VCCT and CZM can be used to simulate progressive crack growth. Compared to VCCT, CZM allows more diverse conditions to be modelled, e.g. allowing for ductile fracture behaviour and a bondline with or without the initial crack. However, the complex input parameters required to define the traction-separation law and a finer mesh to ensure desirable accuracy make CZM a more “expensive” and “user sensitive” method;
2. The element size ($l_e$) effect was negligible when the number of elements along the bondline was in the range between 100 and 500. Similarly, the effect of the interface stiffness $K$ on the response is also limited, provided its value is of the same order of magnitude as that given by the equation presented in [1]; For CZM modelling, the interface strength $\sigma_0$ is the dominant quantity of interest with respect to crack initiation; a lower $\sigma_0$ value results in a lower crack initiation load. On the other hand, the load-displacement response corresponding to crack propagation was mainly determined by the value of $G_C$, with less damage expected as $G_C$ becomes smaller.

3. Utilizing carefully selected input parameters, both VCCT and CZM are able to provide a successful simulation of the load-displacement response corresponding to crack propagation. The crack initiation load, however, was significantly overestimated by VCCT, whereas a fairly good correlation with experimental results was obtained by CZM, notwithstanding the difficulty involved in the selection of an appropriate $\sigma_0$ value.

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6. References