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An integrated inverse numerical–experimental approach to determine the dynamic Mode-I interlaminar fracture toughness of fibre composites

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ABSTRACT

A combined numerical–experimental methodology is presented to determine the dynamic Mode-I fracture properties of Fibre-Reinforced Polymer (FRP) composites. The experimental aspect consists of a modified Wedge-Double cantilever Beam (WDCB) test using a Split Hopkinson Pressure Bar (SHPB) set-up followed by a numerical inverse modelling strategy using cohesive-zone approach. The proposed method is inherently robust due to the use of three independent comparison metrics namely, the strain–displacement response, the crack length history and the crack opening history to uniquely determine the delamination properties. More importantly, the complexity of dealing with the frictional effects between the wedge and the DCB specimen is effectively circumvented by utilising appropriate acquisition techniques. The proposed methodology is applied to extract the high-rate interlaminar fracture properties of a carbon fibre reinforced composite, IM7/8552 and it is further shown that a high level of confidence in the calibrated data can be established by adopting the proposed methodology.

1. Introduction

Delamination is known to be one of the crucial failure mechanisms in FRPs, particularly for structures subjected to impact loads. Understanding this failure mechanism is important, especially for aerospace structures, where their presence can severely compromise the structural integrity. Designing a composite structure against such a failure mechanism requires the knowledge of the material property (i.e., fracture toughness) of the composite interfaces i.e., the layers between the plies susceptible to delamination. The properties of interest for designers include the fracture toughnesses under Mode-I, Mode-II and mixed-mode loading conditions. It is known, in general, that the Mode-I fracture toughness of FRPs is lower than the toughness in Mode-II, hence it becomes a critical property in the design process.

The testing methodologies for Mode-I delamination under quasi-static loading conditions are well-established to determine the fracture toughness of the FRPs. The most commonly used test is the Double Cantilever Beam (DCB) set-up which contains a pre-crack separating the two arms of the specimen [1]. The crack is then extended or propagated by loading the arms using piano hinges or loading blocks in a standard universal testing machine. The recorded load and the load point displacement are then utilised to determine the interlaminar fracture toughness using analytical solutions obtained from beam theory and linear elastic fracture mechanics assumptions. Due to the clarity in the definitions of the test standards and the ease of data acquisition, fairly reliable values for the interlaminar fracture toughness can be obtained using the DCB test for quasi-static loading rates.

On the other hand, characterisation of delamination fracture properties at high strain rates is still a standing issue due to the inherent challenges posed by the high strain rate experimental methodology. In particular, the methodology for the fracture toughness testing at high loading rates is not well-established when compared with the strength characterisation of fibre composites at high strain rates. Over the last

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couple of decades, multiple experimental studies have been conducted to measure the high rate interlaminar fracture toughness using different test approaches that include several DCB-based configurations, compact tension and compression, planar plate impact and edge notched specimens. A comprehensive review of different approaches for measuring the rate-dependent Mode-I interlaminar toughness can be found in [2, 3]. Some common drawbacks of the several test methods proposed in the literature are the inertial effects and the unsymmetrical opening of the cracks at high loading rates. As a consequence, these factors lead to a mixed-mode fracture condition instead of being purely Mode-I, which is not desirable.

Among the different approaches, the DCB or its modified versions were the most commonly used test set-up for the determination of rate-dependent fracture toughness of the interface. For low to moderate rates of loading, the standard DCB test configuration was successfully utilised to measure the interlaminar fracture toughness using a screw-driven or a servo-hydraulic driven testing machine [4–9]. Drop tower-loaded DCB has also been employed for the test, whereby the DCB specimen is mounted so as to enable tearing of "free arms" of the specimen in Mode-I by a vertically-dropping wedge [10].

For the high rate testing, it is not feasible to use the standard DCB configuration due to the induced inertial effects during load application, leading to unsymmetrical crack propagation. To overcome the above limitation, an alternative DCB test configuration based on a wedge-driven loading technique has been proposed in the literature [11–13]. A wedge-loaded DCB in a Hopkinson Bar or a drop tower impact set-up is found to be suitable for inducing a pure Mode-I crack propagation in composite specimens [3]. However, one of the major drawbacks in the WDCB test is that the friction coefficient between the wedge and the DCB specimen needs to be determined in order to make use of the measured data i.e., the load–displacement response. As an extreme example, while determining the fracture toughness of adhesively bonded joints using a wedge impact test, 65% of the total supplied energy was absorbed by losses associated with the impact and the friction and only 7% of the total energy is spent towards the fracturing of the adhesive [14]. In the work of Blackman et al. [15], the effect of friction is explicitly taken into account using finite element analysis by specifying a friction coefficient between the wedge and the specimen, and the fracture energy is then determined using the measured load. A different WDCB test set-up is utilised to determine the fracture properties of ceramics by directly accounting for frictional effects under quasi-static loading conditions through an inverse modelling strategy [16]. On the other hand, effort has been taken to minimise the frictional effects by using a rollers-assisted wedge-insert fracture test [17]. With this method, the rate-dependent Mode-I fracture toughness of a polymer matrix composite has been determined using a modified beam theory. However, the effect of friction is not completely eliminated, which might possibly lead to an incorrect interpretation of the measured load.

Modified beam theory and linear elastic fracture mechanics were used to determine dynamic fracture toughness utilising DIC measurements [18]. A simulation-guided experimental setup was employed whereby the effect of friction between the wedge and the specimen was analysed. Dynamic Wedge insert fracture (WIF) tests were performed on IM7/8552 and IM7/M91 specimens and the interlaminar fracture toughness were determined using the compliance calibration method [19]. Two strain gauges were used on the surface of the specimen away from the crack, whose peak readings were employed to determine the toughness values, followed by validation using finite element analysis. Using the nonlinear J-integral, the expression for the delamination energy release rate in Mode-I was derived considering large deformation and axial force [20].

Wedge DCB experiments together with beam theories were employed to characterise the Mode-I fracture toughness of composites [21, 22]. Virtual Crack Closure Technique (VCCT) method was used for evaluating the Mode-I fracture toughness for both quasi-static and dynamic conditions [23]. Using the energy balance method and the dynamic J-integral technique involving cohesive elements, interlaminar fracture toughness at high strain rates was determined using electromagnetic Hopkinson bar apparatus [24]. Utilising high-resolution optical deformation tracking, and a beam theory-based analysis of the specimen deflection and crack length, toughness values were obtained [25]. In [26], the test procedure for the interlaminar fracture toughness does not need to measure the crack length and the friction coefficient is determined through data extraction process. However, the methodology requires that the friction coefficient between the wedge and the specimen surface remain constant during the test.

From the literature, it is understood that there is no clear consensus on the appropriate test methodology for measuring Mode-I interlaminar fracture toughness of fibre composites. It is therefore, the objective of the present research to propose a simple numerical–experimental inverse methodology using a WDCB test in a SHPB set-up to determine the Mode-I delamination toughness. The difficulties associated with the wedge-loaded DCB test (i.e., the friction and inertial effects) are circumvented by using an inverse modelling approach along with a carefully planned data acquisition in the experiments.

The paper is organised as follows: Section 2 discusses the details of the experimental setup that include specimen details, description of the test procedure and the associated data acquisition systems. Inverse numerical modelling strategy using cohesive elements is presented in Section 3. The results of the experiments and the modelling procedure are discussed in Section 4 with a focus on three comparison metrics in order to reliably determine the fracture properties of the delaminating interface. The paper ends with conclusions and recommendations for Mode-I interlaminar fracture testing using a WDCB test.

2. Experiments

2.1. Specimen details

A unidirectional (UD) carbon fibre-epoxy composite laminate was prepared for characterising the Mode-I delamination toughness. The panel was manufactured consisting of 24 layers of IM7/8552 prepregs from Hexcel, resulting in a nominal thickness of 3 mm. A 13 μm thick Polytetrafluoroethylene (PTFE) film was placed between the 12th and 13th layer to create the pre-crack. The plate was cured in an autoclave following the manufacturer's instruction. DCB samples were cut from the plate, with a nominal length of 120 mm and 20 mm in width. The pre-crack length, defined by the distance between the edge of the sample and the interior edge of the PTFE film, is 32 mm for all samples.

2.2. Test setup and data processing

The dynamic WDCB test setup is illustrated in Fig. 1 The sample is mounted between the input and the output bars on a Split Hopkinson Pressure Bar (SHPB) test system. The striker is accelerated to around 10 m/s by a piston driven using compressed gas. A compressive pulse is generated on the input bar once it is hit by the striker. The compressive pulse travels along the input bar, and the wedge moves forward when the pulse arrives. The sample is then loaded by the movement of the wedge, following which a pure Mode-I opening crack growth is expected. A cardboard pulse shaper was used to ensure a smooth ramping up of the pulse edge. An example of the velocity profile applied on the wedge is shown in Fig. 1c. The strains on the bars are recorded with an oscilloscope, and the displacement of the wedge is calculated using the Hopkinson bar theory, details of which can be found in [27].

As discussed before, a portion of the total force applied by the wedge on the specimen will be spent in overcoming the friction between the wedge and the laminate. Therefore, the force that is purely responsible for the opening of the crack is not possible to be measured directly with the SHPB system. This, in turn prevents the interpretation of the measured load data from the SHPB system. Thus, in this work,

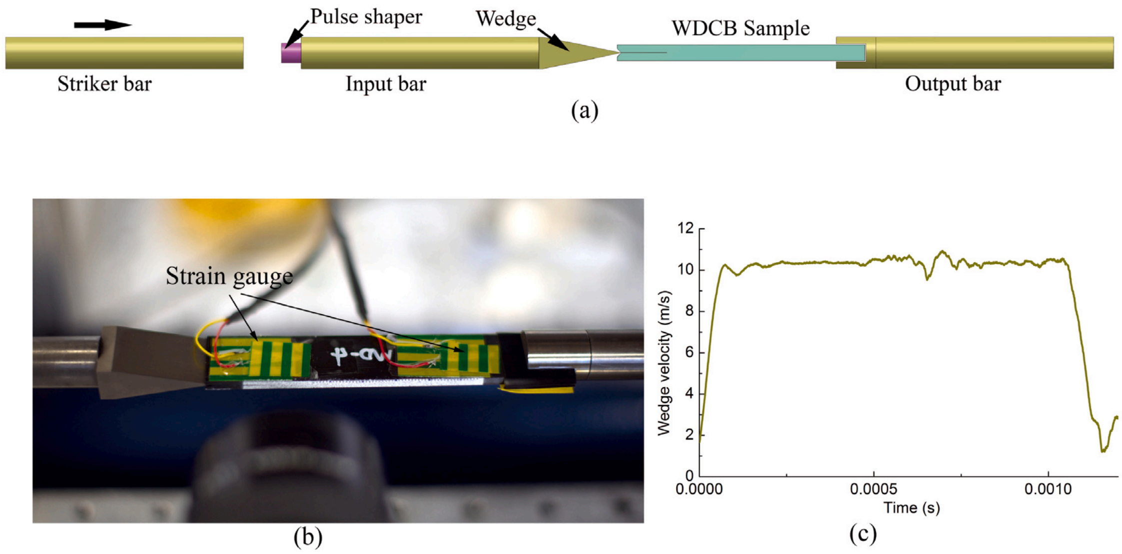


Fig. 1. Experimental setup of the WDCB specimen in a SHPB system: (a) schematic of the wedge-loaded DCB in SHPB, (b) DCB specimen with the mounted strain gauges and (c) velocity profile of the wedge loaded by the input bar.

instead of calculating the fracture energy, GIc with the measured force according to the traditional method [1], an inverse modelling approach is adopted, which relies on the measurement of the following parameters: (a) strain history from the strain gauge mounted on the DCB top surface, (b) crack length using the images recorded by the high-speed camera and (c) crack opening at the initial crack tip location by tracking two corresponding points using DIC image correlation. A Kirana ultra-high speed camera was used to capture the images with a frame rate of 500,000 frames per second. A strain gauge is mounted on the top surface of the DCB upper arm at the location corresponding to the initial crack tip and a second strain gauge was attached near the other end of the sample, see Fig. 1b.

It is worth mentioning here that emphasis of the paper is placed on demonstrating an inverse modelling procedure to determine the fracture toughness by circumventing the frictional effects, rather than rigorously providing the fracture toughness values for a given FRP material system.

3. Inverse modelling approach

The present research utilises a cohesive element-based FE analysis for the inverse modelling procedure to determine the Mode-I interlaminar fracture toughness, G1c. Analytical solutions for WDCB test configuration have been used previously to calculate the fracture energy from the test data. However, the underlying assumptions involved in such approaches based on linear elastic fracture mechanics and beam theories may not be valid in situations of interest. For instance, in the ongoing work by the authors on determining high rate fracture toughness of through-the-thickness reinforced composites, the arms of the specimens are required to be very short to avoid premature failure of the arms. Such a shorter beam arm renders the application of beam theories invalid for calculating the fracture properties. Further, when the fracture process zone is large, linear elastic fracture mechanics-based solutions would not be applicable. Several successful studies exist in the literature that utilise a numerical modelling approach, for example utilising cohesive elements for simulating delamination crack initiation and propagation in composite materials [28–30]. In this work, such an approach is deemed to be appropriate to naturally take into account the dynamic/inertial effects. As a result of the inverse modelling approach, a cohesive law corresponding to the dynamic delamination is obtained, which could then serve directly as an input for the design process of composite structures prone to impact-induced delamination.

The following subsections provide details of the finite element model, the material parameters and the inverse modelling approach to determine the cohesive law characterised by interlaminar cohesive strength and fracture energy.

3.1. Finite element modelling with cohesive elements

A two-dimensional finite element model of the WDCB test is generated using the finite element package Abaqus/Explicit as shown in Fig. 2. The UD FRP beam arms of the DCB are modelled as transversely isotropic linear elastic material with material properties taken from authors' work [27]. The DCB geometry was discretised using 4-noded plane strain elements (CPE4). A layer of 2D cohesive elements of thickness 0.01 mm is inserted between the beam arms to simulate interface delamination. A bilinear traction–separation law [31] characterised by three parameters, namely the cohesive stiffness, the cohesive strength and the fracture energy is utilised to model the initiation and the propagation of the delamination crack. The finite element mesh is ensured to be sufficiently fine such that the number of cohesive elements is adequate in order to properly resolve the cohesive zone. A mesh dependency study was conducted (not reported here for conciseness), with four different mesh sizes given by the characteristic element lengths equal to 0.025, 0.05, 0.075 and 0.1 mm. Convergence of the response was obtained for element lengths of 0.025 and 0.05 mm, following which the element size of 0.05 mm was chosen for further analyses. The steel wedge is modelled as a linear elastic material with isotropic material properties, E = 210 GPa and ν = 0.3. The mass densities of the steel and the composite are taken as 7700 and 1560 kg/m^3 respectively. The loading conditions of the WDCB setup in the SHPB system is simulated through the applied boundary conditions in the FE model as shown in the Fig. 2.

3.2. Comparison metrics

As discussed in the previous sections, a major challenge in processing and interpreting the data obtained in the wedge-driven DCB test lies in modelling the frictional effects between the wedge and the DCB surfaces. The objective of this work is to eliminate this complexity by introducing an alternate form of the load–displacement curve and two other response metrics for comparison in the inverse modelling procedure. Firstly, instead of a conventional load–displacement response, an alternate measure i.e. the strain measured on the top surface

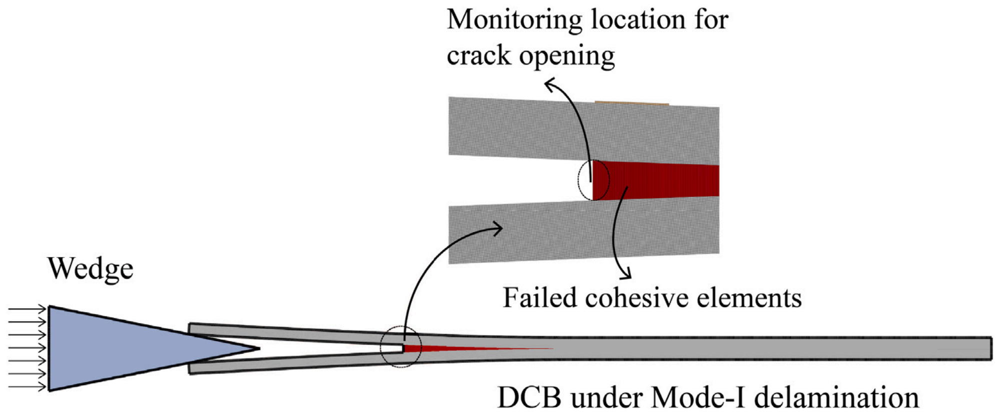


Fig. 2. Finite element model of the WDCB specimen with a layer of cohesive elements. The picture corresponds to the simulated result of the wedge-loaded DCB specimen showing the delamination crack (indicated in red). For one of the comparison metrics, namely the crack opening, the displacements of the nodes of the cohesive element at the initial crack tip location are tracked.

of DCB using a strain gauge and the applied wedge displacement is used. The bending strain measured at the location in the DCB arm corresponding to the initial crack tip (see Fig. 1) can be used directly to correlate with the load applied at the WDCB contact point through beam theory, if necessary. It is worth mentioning that this load will be different from the load measured directly from the test, as the latter includes the frictional force in addition to the force required to fracture the specimen. The other two metrics are the crack length *vs* wedge displacement and the crack opening (at initial crack tip location, see Fig. 2) *vs* the wedge displacement histories. The objective of the inverse modelling procedure is to determine the interface cohesive parameters with which the simulation results match well with the experimental data in terms of the three metrics described above. Among the three cohesive parameters, the cohesive stiffness parameter is set to a sufficiently high value to avoid any artificial compliance without inducing any numerical issues. Thus, the procedure aims to determine the other two cohesive parameters, the cohesive strength and the fracture energy. To this end, the following procedure is adopted:

(i) Guess values for the cohesive strength and the fracture energy are chosen and the simulation is conducted,
(ii) the resulting three metrics are then compared with the experimental data and
(iii) the process is repeated until the metrics obtained from the simulations match with the experimental results.

After convergence is obtained for the three metrics, the corresponding interface properties are then established as the cohesive strength and the fracture energy of the composite interface.

4. Results and discussion

4.1. Experimental results

In the experiments, two tests were conducted using SHPB along with the detailed data acquisition and measurements involving high speed imaging, DIC and strain gauges as discussed in Section 2. For the purpose of demonstrating the methodology, these tests are considered sufficient as there is a repeatability in the test data. The results of the experiments are plotted in terms of the strain–displacement response, crack opening and crack length history as shown in Fig. 3. The strain–displacement curve can be related to the traditional load–displacement curve in a standard DCB test. The initial region in the curve until the peak strain can be considered to be elastic, as evidenced by near-zero crack opening and crack length. Post the peak strain, it is clear that ‘softening’ occurs in the strain–displacement curve, reflected in the corresponding increase in the crack length as well as the crack opening. The average (dotted line) of the two experimental responses are then used as the set of comparison metrics in order to extract the cohesive interface properties.

4.2. Simulation results: Fracture properties

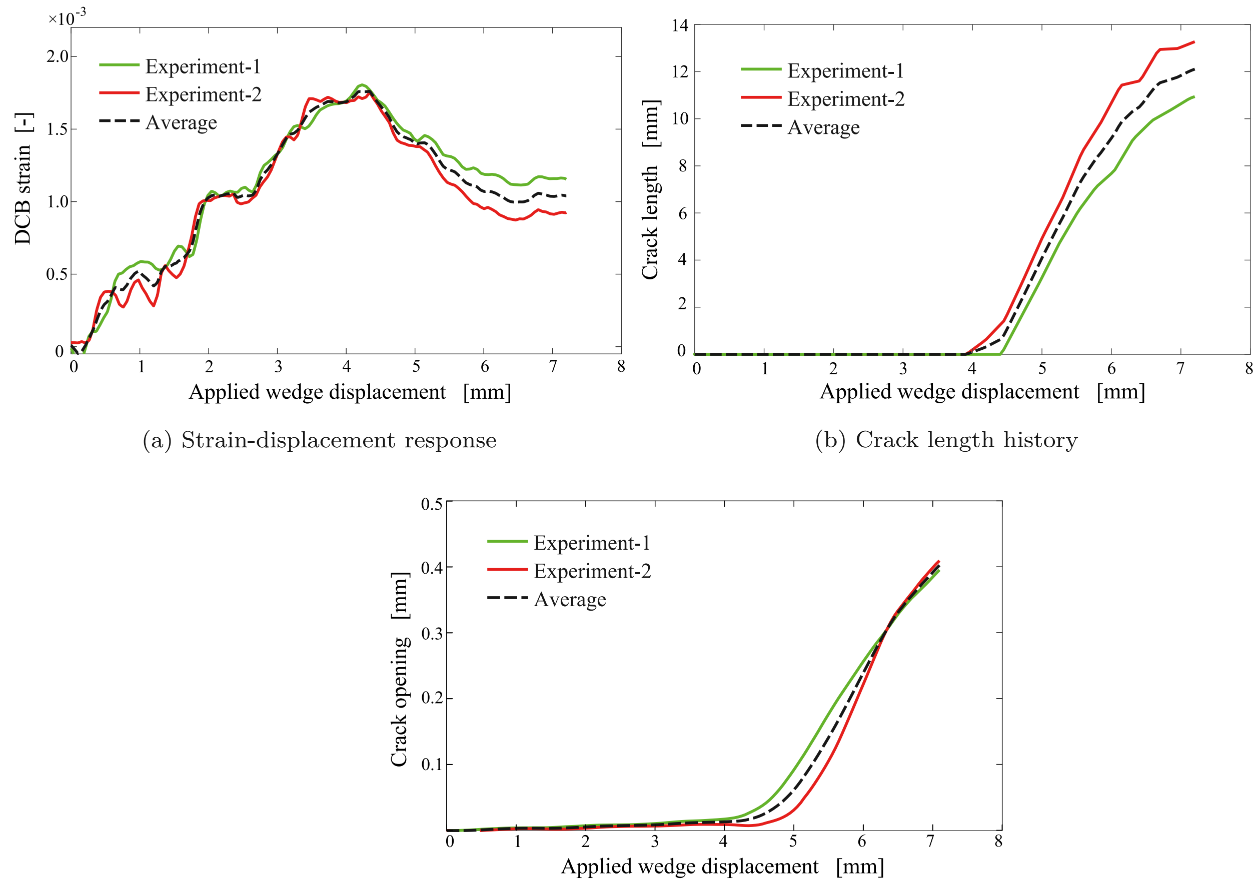
The inverse modelling procedure discussed above is followed to conduct a series of simulations to identify the best match for the interface properties by using the three metrics. Through several iterative simulations, the converged interface properties are obtained. In order to highlight the procedure and explain the effect of the cohesive strength and the fracture energy, the results of the simulations corresponding to three chosen values for each interface parameter (i.e., the cohesive strength and the fracture energy) are discussed in the following sections.

4.2.1. Strain–displacement response

The results of the simulations in terms of the strain–displacement response are summarised in Figs. 4(a) and 4(b), showing the effect of the cohesive strength and the fracture energy on the response respectively.

Regarding the effect of cohesive strength, several values of the cohesive strength, σ_c ranging from 25 MPa to 150 MPa with increments of 25 MPa were considered for simulations. The strain–displacement response corresponding to three selected values of cohesive strength, σ_c = 50, 75 and 100 MPa is plotted in Fig. 4(a). The fracture energy for the simulations is taken as G_c = 0.2 N/mm. It is observed that the cohesive strength has a minor influence on the response. This is expected as the cohesive strength becomes a numerical parameter at the structural scale, particularly when the fracture process zone length is smaller as compared to the specimen scale. However, the cohesive strength cannot be assigned very small or very large values as the former would introduce artificially large process zone, while the latter would induce numerical issues (a very fine mesh would be necessary in such case). From the results reported in the figure for three different values of the cohesive strength σ_c, a value of 75 MPa is chosen as the cohesive strength of the interface as it matches well with the experimental response and any further increase in the cohesive strength does not alter the response noticeably.

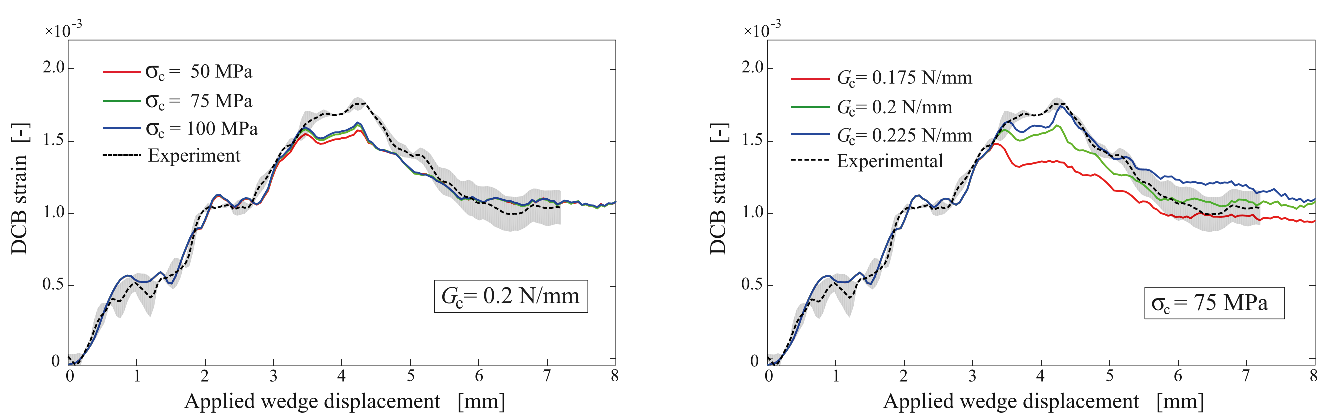
To show the effect of fracture energy, the responses corresponding to three chosen values given by G_c = 0.175, 0.2 and 0.225 N/mm are shown in Fig. 4(b). The cohesive strength of the interface elements is fixed as σ_c = 75 MPa. Unlike cohesive strength, the fracture energy strongly influences the response as observed from Fig. 4(b). From the results, it can be observed that the response corresponding to G_c = 0.2 N/mm matches very well with the experiment on an average.



(a) Strain-displacement response (b) Crack length history

(c) Crack opening history

Fig. 3. Experimental results of the WDCB specimen tests showing the evolution of (a) bending strain, (b) crack length and (c) crack opening, as a function of wedge displacement.

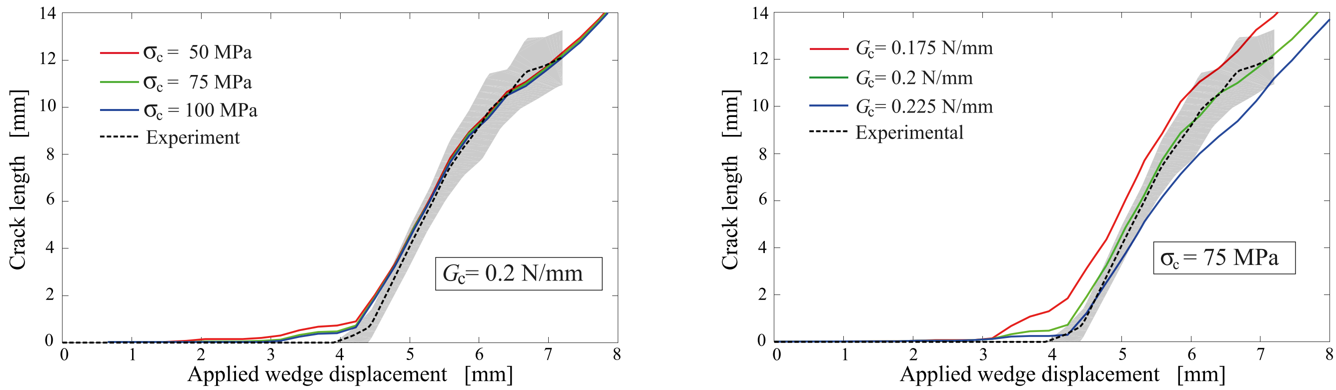


(a) Effect of cohesive strength (b) Effect of fracture energy

Fig. 4. Strain–displacement response of the WDCB specimen for various values of cohesive strength and fracture energy.

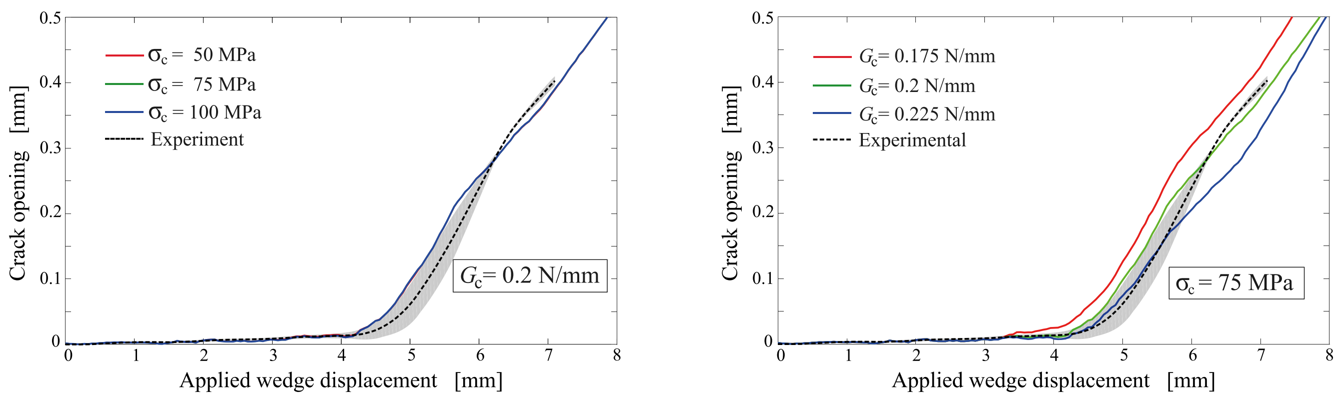
4.2.2. Crack length–displacement history

The second metric, namely the crack length is determined from the simulations by using the number of failed cohesive elements in the interface layer. The results are plotted in Figs. 5(a) and 5(b) for the chosen values of the cohesive strength and the fracture energy. From this plot and the strain–displacement response in Figs. 4(a) and 4(b), one can observe that the crack initiation occurs approximately when the strain ("load") reaches its peak, following which the crack length increases monotonically with further loading. It is evident from the plot that the numerical and the experimentally observed crack length histories are in good agreement for the value of the cohesive strength, σ_c = 75 MPa and the fracture energy, G_c = 0.2 N/mm. The rate of increase in the crack length is found to be approximately constant, thus indicating a steady delamination crack growth. Moreover, the calculated crack propagation velocity of 35 m/s obtained from simulations is in good agreement with experiments.



(a) Effect of cohesive strength   (b) Effect of fracture energy

Fig. 5. Crack length–displacement history of the WDCB specimen for various values of cohesive strength and fracture energy.



(a) Effect of cohesive strength   (b) Effect of fracture energy

Fig. 6. Crack opening–displacement response of the WDCB specimen for various values of cohesive strength and fracture energy.

4.2.3. Crack opening–displacement history

Crack opening displacement history is the third parameter that is considered as a comparison metric. From both the experiments and the simulations, crack opening is monitored at the location corresponding to the initial crack tip, see Fig. 2. The results of the crack opening is plotted in Figs. 6(a) and 6(b) for the chosen values of the cohesive parameters. The opening at the initial crack tip remains zero until the crack starts propagating and the strain reaches the peak, as seen from the strain and the crack length histories. It can be observed again that the values of the cohesive strength and the fracture energy equal to 75 MPa and 0.2 N/mm respectively result in a response that matches well with the experimentally observed crack opening history.

From the results, the crack opening rate can be calculated (slope of crack opening-time history) and is approximately equal to 0.25 m/s with a good match obtained between the experiments and the simulation. It is worth mentioning that the above-determined crack opening rate and the crack propagation velocity can serve as the rate parameter for rate-dependent cohesive fracture mechanics models, similar to the parameter ‘strain rate’ in rate-dependent continuum damage mechanics models.

Upon considering the three metrics and their comparison between the simulated values and the experimentally measured values, it can be concluded that the dynamic delamination behaviour of IM7/8552 composite material can be characterised by a bilinear cohesive law with the cohesive strength, σ_c = 75 MPa and the delamination fracture energy, G_c = 0.2 N/mm. Further, by approximating the crack opening and the crack growth as linear in Figs. 5 and 6 and given the near constant wedge velocity of 10 m/s in Fig. 1c, the crack opening rate and the crack propagation velocity were approximately determined to be 0.25 m/s and 35 m/s respectively.

5. Conclusions

An effective methodology to determine dynamic delamination properties of fibre reinforced composites is proposed using an integrated experimental–numerical approach. Wedge-driven DCB tests were conducted using Split-Hopkinson Pressure Bar to simulate delamination at high loading rates. Finite element-based fracture analysis using cohesive elements were utilised to simulate the experiments.

A three metric-based inverse modelling approach is adopted to quantify the interface material parameters using cohesive elements. Importantly, it has been shown that reliable values for the interface properties of the composite can be obtained without taking into account of the frictional effects between the wedge and the DCB arms, an inherent challenge in WDCB tests. It is observed that the cohesive strength has a minimal influence on all the three metrics and it becomes a numerical parameter that can be assigned a value over a range in which it does not alter the response significantly. Fracture energy is the dominant material parameter that affects the response and hence a reliable property to characterise delamination in composite materials. From the results, the dynamic fracture energy of the IM7/8552 composite interface is determined as 0.2 N/mm.

Further research is directed towards employing the method to determine the fracture properties of the through-thickness reinforced composites under high loading rates. As the current approach does not rely on beam theories or any simplified equations to determine toughness, reliable values of fracture properties can be extracted. In addition, as the analysis and design of composite structures against delamination often involves cohesive zone-based approaches, the set of cohesive interface parameters extracted using the proposed approach becomes a natural choice for characterising delamination in composites.

CRediT authorship contribution statement

Sathiskumar A. Ponnusami: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Hao Cui:** Experimentation, Data analysis, Writing – review & editing. **Borja Erice:** Validation, Writing – review & editing. **Maria Lißner:** Writing – review & editing. **Mehtab Pathan:** Simulations, Writing – reviewing. **Nik Petrinic:** Supervision, Resources, Writing – reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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