Mode-I behavior of adhesively bonded composite joints at high loading rates

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ABSTRACT
This study investigates the high loading rate behavior of adhesively bonded carbon/epoxy composite joints under mode I loading. A computationally guided experimental setup is developed to study the mode-I behavior of composite joints in the range of quasi-static to high loading rates. A double cantilevered beam specimen with wedge insert type loading setup is used to conduct quasi-static and dynamic experiments. For the dynamic loading, a modified split Hopkinson bar is used to load the sample at high rates. The local deformation field is measured using high Spatio-temporal resolution digital image correlation (DIC). From the experiments, the mode-I energy release rate is calculated from the load, crack extension and crack root rotation data measured using load cell and DIC. A decrease in the initiation fracture toughness with increase in loading rate was observed which is attributed to the strain rate dependent behavior of the epoxy-based film adhesive. For both quasi-static and high loading rates, a mixed adhesive-cohesive failure is observed from the fracture surface analysis.

1. Introduction

Adhesively bonded carbon fiber-reinforced epoxy composite joints are widely used in aerospace structures that could be subjected to high energy dynamic impact events [1]. The impact events induce localized, high strain rate deformation that may result in increased likelihood of failure in the composite joints. The mechanical performance may vary greatly under dynamic loading as a result of strain rate dependent material behavior. Strain rate dependence could include adhesive strength, adherent (composite)-adhesive interface properties, and composite properties. Carbon/epoxy composite laminates exhibit loading rate dependent mode-I interlaminar fracture behavior [2]. This is attributed to the activation and transition of different failure mechanisms from quasi-static to high loading rates. The joining of composite laminates using epoxy-based adhesives adds another layer of complexity in elucidating the response of these bonded joints. Therefore, an experimental test method to characterize interlaminar fracture of bonded joints is essential for the design of composite structures and validation of computational models. However, there are limited studies on the behavior of adhesively bonded composite joints at elevated loading rates.

There is no standard test method established for the dynamic interlaminar fracture of composites due to the challenges associated with high loading rates. A comprehensive review on measuring rate-dependent mode-I fracture of composites is reported by May [3]. Thorsson et al. [4] used a wedge insert double cantilever beam (DCB) specimen on a drop weight impact tower to determine the dynamic mode-I response in the loading rate range of 0.01 mm/s to 3600 m/s. Sun and Han [5] and Kusaka et al. [6] used a DCB composite specimen with a wedge-insert fracture in a Split Hopkinson pressure bar (SHPB) system. Most recently Liu et al. [7] used a DCB specimen with a loading block in the specimen for dynamic loading in a SHPB in the range of 10–30 m/s. These studies primarily used post failure investigation for understanding failure modes, however, in-situ measurement is essential to better understand the localized failure initiation and propagation. High spatial and temporal resolution imaging along with digital image correlation (DIC) provide an efficient method to characterize the local strain fields and the failure evolution. In addition, DIC helps in
measuring crack tip opening displacement (CTOD) parameters using images captured during deformation and thus allows estimating the effective energy release rate during bonded joint failure. Therefore, in this study, an experimental method is developed using a combination of Split-Hopkinson bar loading and DIC assisted high spatio-temporal measurement of crack propagation. A numerical analysis-driven experimental design approach is adopted to design the specimen and the test configuration. Using the experimental setup, loading rate dependent fracture behavior of the adhesively bonded joints is investigated and discussed in detail. This study also serves to validate the composite fracture behavior of the adhesively bonded joints at different loading rates. Section 2 describes the numerical finite element (FE) analysis of mode-I experimental design. Experimental setup and experimental observations of the bonded composite joint response at different loading rates are presented in Section 5. Finally, conclusions are presented in Section 5.

2. Analysis-based design of specimen and test configuration

A SHPB with a modified end with a wedge that drives through the sample is considered as shown by the loading configuration in Fig. 1. Due to the complex nature of loading, the effects of wedge angle, pre-crack length (a), friction at the contact point of wedge and specimen, and the usage of transmitted bar versus load cell are numerically investigated. Two wedge angles (60° and 90°) are considered to understand the effect of wedge angle on the loading, and specifically, how the wedge maintains contact with the specimen as the strain wave transfers through the specimen. The wedge is pushed into a symmetric triangular notch present at the left edge of the precrack as shown in Fig. 1. The objective is to obtain the most meaningful loading configuration and diagnostics for the experiment, therefore two types of load measurement at the support end of the sample are investigated in this study. In the first modeling approach, a transmitted bar is modeled, whereas in the second, fixed boundary conditions are used for a load cell. The mode-I specimen is 127 mm long and 25.4 mm wide. In order to determine the appropriate parameters, a “pre-test” finite element model is developed with the objective of guiding the experimental design.

A quasi-isotropic layup [45/90/-45/0]_s commonly used in aerospace structures is considered for the composite laminate sample. Each ply is 0.1828 mm thick and the adhesive is 0.2032 mm thick. A ply-level finite element model with one solid element per ply along the thickness is employed. The carbon/epoxy composite material (IM7/8552) behavior is captured with a progressive damage material model MAT 162 [8] in LS-DYNA using the properties shown in Tables 1 and 2. The MAT 162 material model is capable of modeling damage initiation and evolution due to fiber tension/shear, fiber compression, fiber crush, matrix transverse compression, intralaminar and interlaminar failure modes. Additionally, the model accounts for strain rate dependent stiffness and strength. For a detailed description of the material model

![Fig. 1. Schematic of the experimental setup with load cell/transmitter bar with the two wedge geometry used in the modelling.](image-url)
the reader is referred to Ref. [9]. The adhesive is modeled as an isotropic elastic-plastic material (MAT 003 in LS-DYNA) using the data for FM 300–2 [10] film adhesive. Adhesive failure is not modeled. Both the adhesive and the composite plies are modeled using single integration point eight-noded solid elements with hourglass control type 4. The adhesive-composite interface and composite-composite interfaces are modeled using cohesive contact tiebreak to model delamination using the properties shown in Table 3. Due to the lack of experimental results, strain rate dependencies for the composite-composite interface, adhesive-composite interface, and adhesive behavior are not considered. The properties of the composite laminates and the interface between the composite plies are obtained from the previous phase of this project as part of the NASA Advanced Composites Consortium (ACC) [11] and open literature. The fracture toughness between the adhesive and composite is assumed to be higher than the fracture toughness between the composite plies [12]. The Hopkinson bar of 1-inch diameter is modeled as an isotropic elastic material using aluminum material properties and the explicit analysis is performed for 5 m/s, 7.5 m/s, 10 m/s and 15 m/s striker bar impacts. A coefficient of friction of 0.005 is used for friction between the wedge and the composite. The sensitivity of the coefficient of friction is also explored.

2.1. Load cell versus transmitted bar and effect of wedge geometry

Fig. 2a shows the incident and transmitter bar signal at the center of the bar predicted for a striker impact velocity of 10 m/s in the 60° wedge impact simulation. It shows that the transmitted signals are very weak due to high impedance mismatch between the sample and the bar. Measurement of such a low strain signal in the experiments using strain gage is difficult, therefore, a load cell at the support end is selected for further numerical studies and for the experiments to obtain a reliable force measurement. The pre-test prediction results (not shown) also indicate no significant difference in the contact forces at the specimen and the wedge for load cell or transmitted bar design configurations. A striker bar length of 609.6 mm is chosen so that such specimen failure is achieved during the first pulse. The pulse loading duration predicted is approximately 230 µs and the specimen characteristic time (time taken for the longitudinal wave to travel to travel along the length of the specimen) is 20 µs. Time zero corresponds to the time of the striker bar impact. Load introduction to the specimen through wedge contact begins around 380 µs.

Fig. 2b shows a typical total vertical force (2P) time history for the forces predicted at the contact between the wedge and the specimen, and at the fixed end of the specimen for a 10 m/s impact using a 60° wedge and a = 10 m. It is seen that the peak loads and the load trends are similar at the specimen-wedge contact and at the load cell end under dynamic loading.

To assess the influence of wedge geometry, two wedge angles 60° and 90° are studied with a 20 mm precrack at 5 m/s impact. For both wedge angles, delamination between the first ply (45°) and second ply (90°) is predicted as the primary failure mode. Fig. 2c shows the fracture energy dissipated in mode-I and mode-II for the two wedge angles. The 90° wedge loading results in increased mode-II content of fracture energy dissipated in the interface between the plies. The mode-II content of fracture energy in the 90° wedge is close to 30% of the mode-I fracture energy. Whereas in the 60° wedge, the mode-II component is less than 10% of the mode-I component. Since the final goal of this experimental configuration is to validate the mode-I failure, the 60° end wedge is selected.

2.2. Pre-crack length and effect of contact friction

The model is also used to evaluate the influence of the precrack length on crack growth. Using the 60° wedge, two precrack lengths are considered: 20 mm and 10 mm at 5 m/s and 10 m/s impacts. In general, longer crack growth is predicted for a shorter precrack compared to a longer precrack during the first incident pulse. For example, the shorter precrack resulted in 20 mm crack growth compared to the 8 mm crack growth for the longer precrack (a = 20 mm). Fig. 3a shows predicted resultant contact force-time history comparison. Crack initiation occurs just after reaching peak load for both cases. Peak load rises very quickly and is higher in magnitude for 10 mm precrack length compared to the 20 mm precrack. However, crack growth occurs for a longer time for the shorter precrack length compared to the longer precrack length. These results suggest that a shorter precrack is preferred for the specimen design as it provides longer crack growth offering the possibility of allowing more time to capture crack growth during experiments. In all these pre-test prediction studies, delamination between the first ply (45°) and second ply (90°) is predicted as the dominant deformation mechanism. The peak loads increase with an increase in the striker bar impact velocity as shown in Fig. 3b. Fig. 3c shows the influence of friction between aluminum wedge and the carbon/epoxy composite specimen for a 10 m/s impact. The peak contact force for a coefficient friction of 0.20 is about 10% higher than the peak force for a friction coefficient of 0.005. However, there is no significant difference in the overall deformation mechanics between the two coefficients of friction. Based on these numerical pre-test studies, a 60° wedge, load cell at the specimen support, and a 10 mm precrack are selected for the experimental studies.

3. Materials and methods

3.1. Specimen geometry and experimental methods

The composite laminate specimens used in this study were composed of a total of 32 plies with 16 plies for each adherend. Specimen design and the dimensions of the sample used in the study is shown in Fig. 4a. The length of the pre-crack was around 10.0 mm and the length of the adhesive layer was 114.3 mm. The overall dimension of the sample was 127 mm × 25.4 mm with a total thickness of 6.35 mm. All specimens were fabricated from IM7/8552 unidirectional tape with a nominal ply thickness of 0.183 mm FM309-1 epoxy-based film adhesive was used to secondary co-bond the laminates. The FM309-1 has a similar composition as FM300-2 which was used for the FE analysis. The thickness of the adhesive layer was 0.152 mm. A Polytetrafluoroethylene (PTFE) insert was used to make the pre-crack in the samples ahead of the adhesive as shown in Fig. 4a. Also, the angle of the notch that is manufactured on the sample was 90°. Mode-I experiments were carried out in a modified SHPB setup. A schematic and an image of the dynamic experimental setup is shown in Fig. 4b. The incident bar is made of a precisely machined aluminum bar of 1830 mm and 25.4 mm diameter. Note that the tip of the incident bar was designed with a wedge angle of 60° to slide into the groove at the tip of the sample as shown in Fig. 4b. Two strain gages were attached to the incident bar to measure the incident and reflected strain signals in the bar. Impactor velocity was independently measured using two laser diodes/receiver assembly that was placed near the impact end. In order to measure the load, a load cell of capacity 22.24 kN was attached at the support end of the sample using a specially designed adapter. This load cell was connected to the signal conditioner in order to amplify the signal obtained from the load cell, and the signal conditioner is connected to the oscilloscope to record the

<table>
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<th>Property</th>
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<th>Composite-Composite</th>
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load data during experiments. To capture the image during dynamic loading of the sample, an ultrahigh speed camera, Shimadzu model HPV-X2, was used. The camera is capable of capturing images at the highest framing rate of 5 million frames/second with a constant resolution of 400 × 250 pixels². In this study, considering the rate of loading, a framing rate varying from 1-5 million frames/second was used. To obtain the local deformation features near the crack tip, a high magnification imaging setup was required. Therefore, a high magnification long distance microscope from Navitar was attached to the camera as shown in Fig. 4b. Considering the field of view requirement and the spatial resolution for the measurement, the magnification factor of 16 μm/pixel was used in this study. The field of view achieved with the imaging setup was close to 6.4 × 4.0 mm², see Fig. 4a. The illumination of the sample was provided with a flashlight from Photogenic. The camera was triggered from the oscilloscope and an appropriate delay was set in the camera to record the crack initiation and propagation in the sample. The flash lamp was triggered by the camera. The speckling of the sample was done using the toner powder. First a thin layer of the white paint was sprayed on the sample using an airbrush, next toner powder was deposited on the paint by spraying before the drying of the paint. The speckle pattern obtained for the current experiment is shown in Fig. 4a. For the quasi-static experiments, the images of the deforming specimen were acquired using a 5 MP Grasshopper CCD camera from FLIR at a rate of 5 images per second and at a full-field resolution of 2448 × 2048 pixels². Image rate was synchronized with the load-cell data during experiments. This ensures simultaneous imaging of the microstructural evolution of the crack tip propagation and local displacement evolution with respect to loading. Also, this verifies if the crack simultaneously initiates across the width of the sample. Uniform lighting was provided by high intensity white LED lights.

Images acquired during loading were then imported into the correlation software Vic-2D (Correlated Solutions, Inc.) for post-processing. In this software, subset and step sizes of 33 pixels and 3 pixels were used, respectively. The strain filter size was selected to be 15. Note that selecting these image correlation parameters was based on an extensive optimization process, details of which are beyond the scope of this work, but can be found in Refs. [14].

3.2. Data extraction and analysis

The energy release rate, \( G \), is the rate of change of potential energy with respect to the crack extension area. Assuming linear elastic fracture mechanics and geometrical linearity, the energy release rate can be defined as,

\[
G = \frac{P^2}{2b} \frac{dC}{da}
\]  

(1)

where \( P \) is the applied load, \( b \) is the width of the specimen, \( C \) is the compliance of the specimen and \( a \) is the length of the crack. Hogberg et al. [15] developed a closed form equation using modified beam theory assumption to calculate the total energy release from the load data and crack root rotation as follows,

\[
J = (1 - \nu_1 \nu_2) \frac{12}{E_b h^2} \frac{P}{h} (\theta_1 - \theta_2)
\]  

(2)

where \( P \) is the opening load, \( \nu \) is the Poisson’s ratio, \( a \) is the crack length, \( E \) is the longitudinal elastic modulus of the composite adherend which is 58.0 GPa in this study, \( h \) is the adherent thickness, and \( \theta_1 \) and \( \theta_2 \) are the in-plane rotation above and below the crack tip, also termed as crack tip root rotation. The crack tip rotation is the relative rotation of the arms about its centroidal axes as a result of shear force and nonrigid clamping.
of the DCB arm at the crack tip [16]. It was shown that the crack tip root rotation is affected by both bending moment and shear forces at the crack tip. This quantity can be estimated from the displacement field measured using the digital image correlation.

Fig. 5 shows the forces acting on the specimen due to the wedge loading. The loading is assumed to be symmetric about the center axis. A resultant force \( R \) is applied by the wedge on each adherend at an angle \( \theta \). The angle is dependent on the point of contact between the specimen and the wedge due to the radius of the actual physical wedge geometry '\( r \)' as seen in Fig. 5 (magnified image of the contact point). The resultant can be decomposed to the horizontal force \( H \) and vertical force \( P \). The load propagates through the specimen and the horizontal force at the

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**Fig. 4.** a) Schematic and the image of the edge of the sample with crack, also dimensions of the sample, field of view (FOV) and speckles for both quasi-static and dynamic experiments are shown, b) schematic and image of the dynamic loading and imaging setup.

**Fig. 5.** Free body diagram of forces acting on the composite specimen and close up showing the angle of contact, \( r = 0.6 \) mm, \( y = 0.42 \) mm.
load cell is denoted by $F_{LC}$. Using finite element models, the relation between the load cell force and the vertical opening force $P$ (used later in fracture toughness calculations) is determined. The angle $\theta$ at failure (mode I fracture energy initiation) is determined as $\sim 45^\circ$ from the FE models based on the radius $(r)$ of the actual physical wedge, and the vertical distance between the center of the wedge and the specimen $y$, as shown in Fig. 5. The FE models are run for the dynamic and quasi-static loading rates with fixed boundary conditions at the load cell side. For quasi-static loading, the specimen is in equilibrium. Based on the forces predicted in the model, the horizontal force at the load cell $F_{LC}$ is equal to the horizontal force at the wedge-specimen interface.

$$F_{LC} = 2H = 2R^2\cos(\theta) = \frac{2P}{\tan(\theta)}$$

(3)

For $\theta = 45^\circ$, $P = 0.5F_{LC}$

(4)

Under dynamic loading rates, the horizontal forces at the fixed end are predicted to be larger than the horizontal loads at the wedge-specimen interface, $F_{LC} > 2H$. This is attributed to the stress wave reflections occurring at the fixed end of the specimen. Based on the forces predicted in the model, it is observed that the vertical force $P$ is approximately half of the load cell force $P \approx 0.5F_{LC}$.

The load cell can provide the total load $(2P)$ acting on the sample and the other quantities except crack root rotations are known. The use of DIC in this study allows the measurement of crack tip rotation during the entire duration of the loading of the sample as shown by Rajan et al. and Gorman et al. in quasi-static loading of similar loading conditions [16, 17]. This is done by the spectral decomposition of the deformation gradient obtained from the DIC displacement field. In this study, the average values of the crack tip rotation above and below the crack tip were used for the total energy release rate calculation. After the initiation of the crack, the tip location needs to be tracked to obtain the crack tip rotation and to calculate the total displacement from the DIC. In order to do that the crack tip was located by using the strain localization ahead of the crack tip and this is discussed later. In order to compare the total energy release rate estimation from Eq. (2), the fracture energy was also estimated using the equation that is derived based on the Timoshenko beam theory [18].

$$J = (1 - \nu_1) \frac{AP^2}{2EP} \left( \frac{3\xi^2}{R^2} + \frac{1}{R} \right)$$

(5)

It can be seen that the first term in Eq. (5) is same as the Eq. (2) which gives the energy contribution from bending moment to the energy release rate, whereas, the second term gives the shear contribution to the total fracture energy during crack initiation and propagation.

### 4. Results and discussion

#### 4.1. Loading symmetry and crack root rotation

The dynamic loading of the sample is performed using an SHPB as discussed in the experimental section. In the wedge insert type loading of the composite samples, the symmetry of the loading is important to precisely estimate the fracture toughness of the adhesive bonds. Loading symmetry can be investigated by measuring the lateral displacement (opening displacement) above and below the crack tip. Contour plot of the full-field lateral displacement for 8.24 m/s is shown in Fig. 6a which shows relatively symmetric opening displacement. To quantify the difference in the lateral displacement at the top and bottom arm of the DCB specimen, the lateral displacement at points $A_1$ and $A_2$ (see Fig. 6a), above and below the crack vs. time is plotted in Fig. 6b. Also, the difference in the absolute value of lateral displacement is plotted to show the difference in the symmetry in loading. The lateral displacement at both points is close and the difference in the displacement remains low until the initiation of the crack at $23-25 \mu m$. After the crack initiation, the difference in the displacement ($A_1 + A_2$) gradually increases, however, the difference in the displacement stays below $3 \mu m$ which gives a percentage relative difference in lateral displacement close to 13% at the peak load.

The correction to the energy release rate due to the non-symmetric bending and shearing at the crack tip is estimated using the crack tip root rotation. The net crack root rotation ($\theta_1 - \theta_2$) for the quasi-static experiment and the dynamic experiments until the initiation of the crack tip are shown in Fig. 6c. Time zero corresponds to initiation of the loading. Root rotation for the quasi-static experiment is within $3 \mu rad$ until initiation, whereas under dynamic loading, it is 4 times higher than the quasi-static loading which indicates that the crack root rotation correction in the fracture toughness will be higher in the dynamic loading conditions compared to quasi-static loading. Also, the crack root rotation is relatively close in all higher loading rate experiments at the crack tip.

#### 4.2. Load vs CTOD and microscale crack propagation

The representative load (2P)-CTOD curve for two quasi-static experiments and dynamic experiments of varying impact velocities are shown in Fig. 7a and Fig. 7b (both assuming $P = 0.5F_{LC}$). In the quasi-static experiments, the load-CTOD curve shows a linear response at the beginning of the loading, followed by a sudden drop in the load at an applied load close to 1.59 kN (2P). Microstructural images captured during quasi-static loading show that at 1.59 kN, the crack initiates and propagates through the adhesive causing cohesive type initiation of the crack, then it is deflected to the interface resulting in interface failure.
between adhesive and the composite ply. The crazing of the epoxy adhesive causes significant whitening of the epoxy due to high plastic deformation of the adhesive. The two representative experiments under quasi-static loading show that the fracture initiates consistently at the same load. When the specimen is subjected to dynamic loading, a distinct load-CTOD response was observed. Initially, the load-CTOD has a response very similar to the quasi-static loading. After the crack initiation, the load-CTOD exhibits a nonlinear response as shown in Fig. 7b. The crack initiation occurs at 1.02, 0.90 and 0.83 kN for impact velocities 8.24, 10.20 and 14.60 m/s, respectively, which is close to half of the crack initiation load in the quasi-static loading condition. The microstructural evolution of the crack shows a very similar behavior as seen in the quasi-static loading. Crack is initiated in the adhesive and then deflected to the interface between the adhesive and the composite ply. Note that the crack does not constantly stay in the adhesive material or interface, instead, the crack propagation causes mixed cohesive and adhesive type failure in the sample. It can be clearly seen in the fracture surface, the initiation is predominantly cohesive, however as the crack advances a mixed type failure is visible (Fig. 7c). This type of oscillation is governed by the ratio of critical energy release rate of the adhesive material and the interface (between the adhesive material and composite ply) [19].

4.3. Local strain field and crack tip velocity

In order to find the crack tip location, crack tip velocity, the local lateral strain field is calculated using DIC. The contour plot of the local strain field at different loading times for the quasi-static and dynamic loading is plotted in Fig. 8. When crack initiates, a sudden drop in the lateral strain is expected in the adhered and this is used to identify the crack initiation. Crack tip location is identified by finding the jump in the lateral strain along the bond line in the material. The uncertainty in the crack tip location measurement is within 5%. It can be seen from the 14.60 m/s impact experiment, the speckle image at t = 10 μs, without the strain field overlay, shows the crack tip location and corresponding local strain field. The tip location is very close to the end of the strain...
localization as a result of high local deformation near the crack tip. It is clear from the local strain contour, the distance travelled by the crack tip at a given time $t$, for instance $t = 10 \mu s$ increases with increase in impact velocity.

The crack tip location is tracked for all the experiments to estimate the average crack tip velocity. Crack tip location vs. time for the quasi-static loading and three different impact velocities are plotted in Fig. 9a, and the trend is relatively linear. In the quasi-static loading the time scale is in seconds, see Fig. 9a. A linear fit to the crack tip location vs time is shown and the slope of the curve gives the crack tip velocity. For the quasi-static loading, the average crack tip velocity is close to $8 \times 10^{-4} \text{ m/s}$, whereas in higher strain rate experiments the crack tip velocities are 270, 300 and 500 m/s for impact velocities 8.24, 10.20 and 14.60 m/s, respectively. The average crack tip velocities and its standard deviation from repeated experiments are plotted in Fig. 9b. The crack tip velocities are $248 \pm 38 \text{ m/s}$, $351 \pm 58 \text{ m/s}$, and $466 \pm 35 \text{ m/s}$ for impact velocities $7.5 \pm 0.58$, $10.2 \pm 0.91$, and $14.7 \pm 0.30 \text{ m/s}$, respectively. In addition, the crack tip velocity shows a relatively linear scaling with the impact velocities considered in the study.

4.4. Energy release rate at different loading rates

The energy release rate calculated from the quasi-static experiments using eq. (2) and eq. (5) (Timoshenko beam theory based) is shown in Fig. 10a. Comparing both the energy release rate, it can be seen that using Timoshenko beam theory based eq. (5), the initiation fracture energy estimated to be approximately 23% lower compared to the eq. (2) where the correction of the root rotation is performed by measuring
the root rotation directly from the experiments. After, the crack initiation, the crack root rotation at the tip remains relatively constant, therefore the difference in the peak fracture energy for both the methods remains small within 10%. Note that, in this study, the fracture energy is discussed based on Eq. (2). The fracture energy at initiation of the crack for quasi-static loading is estimated to be 860 J/m². After the crack initiation, the resistance to crack propagation may be attributed to the mixed adhesive cohesive failure and it reaches a peak fracture toughness of 1150 J/m². The measured toughness compares well with the reported fracture toughness of 1050 J/m² for the FM 309–1 adhesive [25]. This shows the robustness and accuracy of the wedge insert type loading, and the analysis of the data by using the conventional DCB mode I energy release rate equation and correction using the crack root rotation. Qualitatively, a similar crack growth resistance was observed during the dynamic crack propagation in 8.24 m/s impact, see Fig. 10b. The average initiation fracture toughness for higher loading rate is 625 J/m² which is 27% smaller than the initiation fracture toughness measured under quasi-static loading.

Note that, the calculation of the energy release rate in this study assumes the contribution of the kinetic energy is negligible. This assumption is valid for the quasi-static loading conditions since the crack tip velocities are very small. In order to check the validity of this assumption in the dynamic loading conditions, the kinetic energy contribution of the fracture energy is calculated by using [20],

\[ J_{KE} = \frac{1}{2} \rho h V^2 \]  

where \( \rho = 1600 \) kg/m³, \( V \) is the velocity of the opening which was measured to be close to 7.5 m/s for the impact velocity 8.24 m/s. The kinetic energy contribution is close to 0.025 kJ/m² and it is negligible compared to the estimated fracture toughness in the dynamic experiments, see Fig. 10b.

The crack growth resistance with crack growth is plotted for three higher rate experiments conducted in this study, see Fig. 11a. After crack initiation, the crack growth resistance increases and this could be due to the mixed adhesive cohesive failure during crack propagation in the material, as shown in Fig. 7c. Few points are noteworthy, at low impact velocities 8.24 and 10.2 m/s, experiments show a local stable region of crack propagation at crack extension close to 2 and 3 mm respectively. The peak fracture toughness for the quasi-static experiment is 1150 J/m² as discussed previously, as the rate increases, the peak toughness also increases as shown in Fig. 11a.

In order to see the trend in the loading rate effect on the fracture toughness, the initiation fracture energy is plotted against the loading rate. It is clear that the increase in loading rate reduces the initiation fracture toughness and it reaches nearly a plateau after a loading rate of \( 2.3 \times 10^7 \) J/m².s. The average initiation toughness for high loading rate experiments is between 400 and 600 J/m² for all the loading rates considered in this study, see Fig. 11b. The initiation fracture toughness is 30–53% lower compared to the quasi-static initiation fracture toughness. This is primarily explained previously by the decrease in the plastic zone size due to the stiffening of the adhesive at higher strain rates. A smaller process zone as a result of rate-dependent stiffening of the adhesives causes a drop-in initiation fracture toughness [21]. In this study, the adhesive is an epoxy-based material, and it is well known that epoxy is strain rate dependent in nature. Also, the high shear rate experiments reported in Ref. [22] for FM 300–2 with similar composition as of FM 309-1 showed an increase in ultimate shear strength (~13%) when the shearing rate increased by 2800 times, whereas in the present study the loading rate in 8.24 m/s is \( 2.3 \times 10^7 \) J/m².s and corresponding strain rate...
in the adhesive will be high. In light of this, to measure the size of the process zone, the von Mises local strain is calculated ahead of the crack tip following [23]. The variation of the local von Mises strain along axial distance 'X' from the crack tip for the quasi-static and 14.6 m/s experiments is plotted in Fig. 11c. It can be clearly seen that the strain near to the crack tip is high and it reduces nearly to zero along the axial coordinate. Interestingly, the process zone size in the quasi-static loading is close to 1.8 mm whereas for the 14.6 m/s impact experiments the process zone size is close to 1.0 mm, see Fig. 11c. Therefore, it may be concluded that the reduction in the initiation fracture toughness is associated with a smaller process zone developed at the crack tip in high rate loading conditions as a result of stiffened response of the FM 309–1.

5. Conclusions

In this study, an experimental setup is developed based on numerical simulation to measure the mode-I type loading behavior of adhesively bonded joint under different strain rates. The total energy release rate is calculated using the load and the crack root rotation measured directly from the experiments. This energy release rate measured was compared with the Timoshenko-beam-theory-based energy release rate calculations and showed that the Timoshenko-beam-theory under predicts the energy release rate. It was seen that the initiation mode –I fracture toughness of the adhesive bond (FM 309–1) considered in this study was 860 J/m² with average peak fracture toughness close to 1150 J/m² which is close to the previously reported fracture toughness of the FM 309–1. As the loading rate increases the initiation fracture toughness dropped to 30–53% of the quasi-static initiation fracture toughness. This is mainly attributed to the rate dependent stiffening of the adhesive that causes a reduction in the process zone size which leads to reduction in the initiation fracture toughness.

CRediT authorship contribution statement

Suraj Ravindran: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft. Subramani Sockalingam: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Supervision, Writing - original draft, Funding acquisition. Karan Kodagali: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft. Addis Kidane: Conceptualization, Methodology, Supervision, Funding acquisition. Michael A. Sutton: Conceptualization, Methodology, Funding acquisition. Brian Justusson: Conceptualization, Methodology, Writing - review & editing. Jenna Pang: Methodology, Project administration, Writing - review & editing.

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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