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Experimental procedure to characterize the mode I dynamic fracture toughness of epoxy resins.

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Abstract

Epoxy resins are widely used in Carbon Fiber Reinforced Polymers (CFRPs) for the aeronautical industry. They must ensure cohesion in most of the structural composite parts incorporated into the modern manufactured aircrafts. So fracture properties of epoxy resins are essential features to resist critical decohesions in case of impact. Surprisingly however, there are few experimental studies dedicated to the dynamic fracture of these thermoset polymers. Therefore, this research aims at developing an experimental procedure to characterize the dynamic fracture toughness of epoxy resins during propagation. Since glassy polymers exhibit viscous fracture, the crack speed \dot{a} is known for influencing the toughness of these materials. Then a strain gage method is proposed to determine the mode I dynamic energy release rate G_{ID} for various crack speeds \dot{a} . Thus an experimental set-up is defined to simultaneously implement strain gage measurement and high speed cinematography. Finally, preliminary results are briefly reported to demonstrate the method validity.

Keywords: *Experimental, Dynamic Toughness, Epoxy Resin, Reinforced Polymer, Cohesive Model.*

1. Introduction

Impact loadings on laminated composite materials may damage the interlaminar phase and initiate the delamination process. This large decohesion critically compromises the integrity of light weight structures made of CFRPs. The material constituting the interlaminar phase must ensure overall cohesion and resist crack propagation. Thermoset epoxy resins are incorporated in most CFRPs since they present good mechanical properties while exhibiting a satisfactory damage tolerance. Moreover, epoxy resins are classically reinforced with embedded thermoplastic nodules that improve their fracture toughness. This material property is characterized by the energy release rate G which stands for the energy per unit area dissipated to form new crack surfaces. For a mode I crack opening, the critical energy release rate G_{IC} refers to the initiation, and the dynamic energy release rate G_{ID} is dedicated to the propagation stage. The experimental determination of G_{ID} is essential to numerically simulate dynamic propagation of a crack in the interlaminar phase with Cohesive Zone Models (CZMs). However, most of the experimental researches on epoxy resins only identify the initiation toughness from quasi-static tests preventing CZMs to finely describe dynamic crack propagation.

As glassy polymers, epoxy resins fracture in a cohesive way according to the viscous crazing process described by Kramer and Berger [1]. The extension of crack surface involves successively alignment, stretching and breakdown of the molecular chains. Each stage of the crazing process influences the fracture toughness. As a consequence, the mode I dynamic energy release rate G_{ID} for epoxy resins is expected to be sensitive to dynamic conditions. In experimental studies on crack propagation in polymethylmethacrylate (PMMA), some authors have reported a strong variation of the fracture toughness with the crack speed parameter \dot{a} [2,3]. Further research on polycarbonate (PC) and PMMA demonstrated that glassy polymers can also exhibit localized heating surrounding a running crack tip [3,4]. This increase in the temperature T_f of the craze zone induces evolution in the material toughness. Therefore, the final purpose of the present research is the definition of an experimental procedure to characterize the dynamic law $G_{ID}(\dot{a}, T_f)$ for epoxy resins. This article focuses on the experimental determination of the mechanical quantities G_{ID} and \dot{a} .

2. Experimental determination of G_{ID}

Linear elastic behavior is assumed in the bulk material because glassy polymers only develop small scale plasticity in the vicinity of the crack tip [3]. A local analysis of the asymptotic mechanical fields is used to measure the mode I dynamic stress intensity factor K_{ID} related to a crack propagating at constant speed \dot{a} . The strain gage technique depicted by Khanna and Shukla [5] is implemented as it fits dynamic loadings. This method consists in bounding a strain gage at a distance y_G close to the crack path (Figure 1) at an angle α verifying the relation Eq. 1 for prevailing plane strain condition,

$$\cos(2\alpha) = -\kappa = -(1 - 2\nu) . \quad (1)$$

The obtuse angle α is then selected according to the Poisson's ratio ν and the distance y_G must be short enough to ensure that the strain gage is located in the singularity dominated zone. In such a case, a peak strain $(\epsilon_{x_2}^G)_p$ is registered when the crack passes below the strain gage, corresponding to $\theta=90^\circ$ (Figures 1 & 2). Then, the two parameter model detailed in Eq. 2 is used to evaluate the mode I dynamic stress intensity factor K_{ID} ,

$$K_{ID} = \mu \cdot (\epsilon_{x_2}^G)_p \cdot \frac{1}{\sqrt{y_G}} \cdot \left[A(\dot{a}, \alpha) + k_d \cdot y_G \cdot B(\dot{a}, \alpha) \right]^{-1} . \quad (2)$$

Dimensionless coefficients (**A**, **B**) are material dependent, function of the crack propagation speed \dot{a} and the angle α . The material parameter μ is the shear modulus. It is worth noting that material parameters in this analysis are quasi-static values. The non-singular coefficient k_d is identified using the characteristic time $\Delta t_{3/4}$ defined in Figure 2 according to the procedure described in Sanford and al. [6]. The mode I dynamic energy release rate G_{ID} is then derived from K_{ID} by the Freund relation [7] which is the dynamic equivalent of the well-known Irwin formula,

$$G_{ID} = f(\dot{a}) \cdot K_{ID}^2 . \quad (3)$$

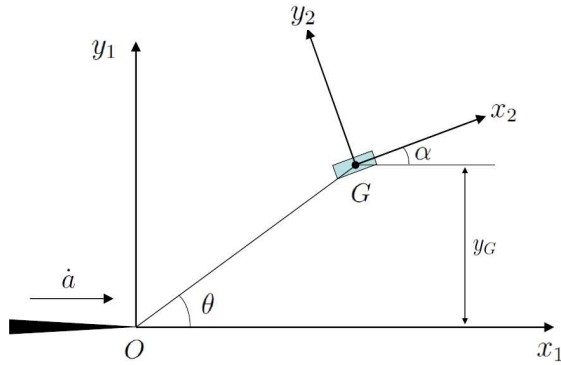


Figure 1 : Description of the strain gage position with respect to the crack tip.

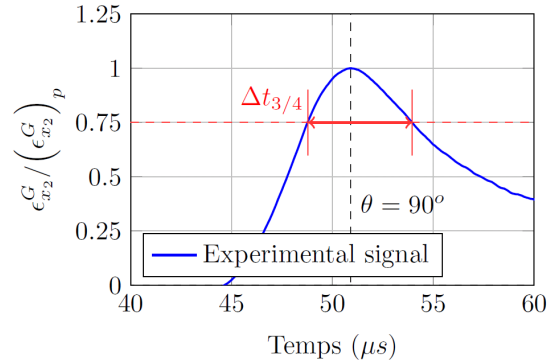


Figure 2 : Peak strain registered by the strain gage oriented at the obtuse angle α verifying Eq. 1.

3. Experimental set-up

A three point bending test was chosen to fracture Single Edge Notched Beam (SENB) specimens (Figure 4). Therefore, thick test samples of pure epoxy resin were manufactured (dimensions: 90mm x 20mm x 8mm). For this purpose, hundreds of plies of epoxy prepreg were successively stacked and several vacuum debulking had to be applied to ensure removal of air trapped during the lay-up operation. Autoclave curing of the laminated plate was performed according to the typical cure cycle specified by the manufacturer for thick structures. This cycle is optimized to eliminate remaining air

inclusions and provide homogeneous plates. So the resulting specimens are suitable to determine the material fracture properties.

The three point bending test presents the advantage of exhibit symmetric fracture with good repeatability. Indeed, a straight propagation is essential to perform valid mechanical analysis exposed previously and anticipate the location of sensors close enough to the crack. For preliminary experiments on SENB epoxy specimens, two strain gages of different grid size were bounded respectively on each side of the crack path in a symmetric way as illustrated in Figure 3. They were fixed on the same axis perpendicular to the crack surface so as to provide G_{ID} for the same time of fracture. The ratio a/w was set to 0.40 to limit influence of the specimen boundaries. In addition, the crack propagation speed \dot{a} was evaluated by high speed cinematography.

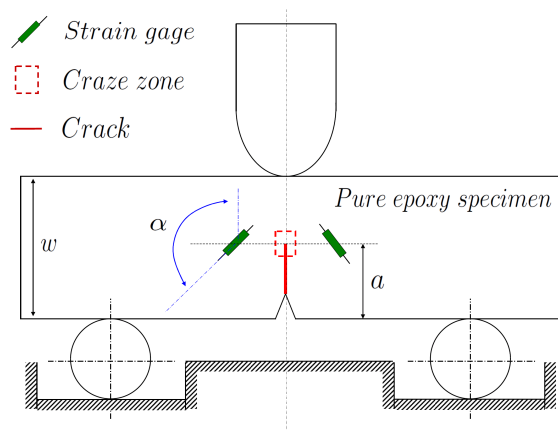


Figure 3 : Diagram of the experimental set-up with specimen instrumented.

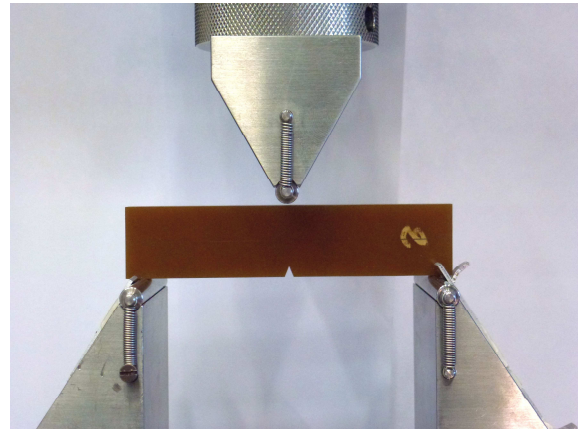


Figure 4 : Picture of the experimental set-up without instrumentation.

4. Preliminary results

Preliminary experiments exhibited quasi-brittle fractures and the crack propagated in a straight direction, verifying essential assumptions of the mechanical analysis. Moreover, the peak strain due to the singularity dominated zone was actually recorded when the crack tip passed below the gage.

For the particular experiment summarized in Table 1, the distance to the crack path and the grid length varied with the considered sensor configuration. However the shapes of the normalized peak strain signals represented in Figure 5 are quite identical, except for the time $\Delta t_{3/4}$ which is greater for gage 2 since it increases with the distance y_G . This demonstrates that the singular strain field was similarly captured on each side of the crack path in both tested strain gage configurations with limited influence of the gage size on the characteristic time $\Delta t_{3/4}$.

In addition, each recorded signal was post processed following the procedure described previously to identify the dynamic stress intensity factor K_{ID} and the dynamic energy release rate G_{ID} normalized with the corresponding initiation values K_{IC} and G_{IC} . Although strain gage configurations were different, the mechanical analysis gives very similar values reported in Table 1. These converging results in the determination of K_{ID} and G_{ID} prove that the two parameter model depicted in Eq. 2 is able to describe the singularity strain field around the crack tip with sufficient accuracy for this experimental set-up using one of the tested strain gage configurations. Finally, the proposed procedure is validated for strain gage of grid length under 0.60mm, bounded at a distance closer to 1.50mm from the crack path.

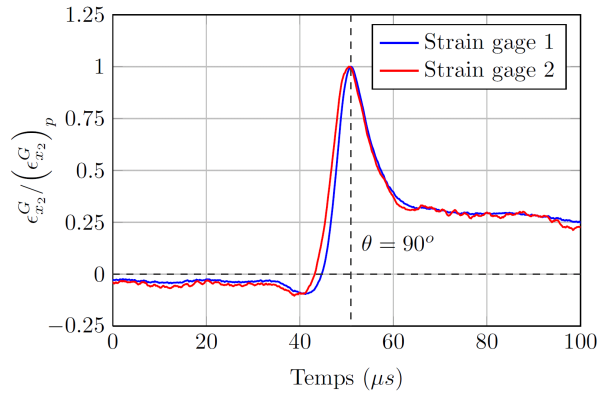


Figure 5 : Strain gage signals recorded for the same experiment with a/w set to 0,40.

Table 1 : Experimental results referring to signals reported in Figure 5.

	Gage 1	Gage 2
Gage length	0.38 mm	0.60 mm
\dot{a}	255 m/s	
y_G	1.29 mm	1.50 mm
$\Delta t_{3/4}$	5.2 μ s	5.7 μ s
K_{ID}/K_{IC}	0.88	0.91
G_{ID}/G_{IC}	0.62	0.66

5. Conclusion

In this research, an experimental procedure was developed to characterize the dynamic fracture toughness of epoxy resins. A strain gage technique associated to high speed cinematography was detailed for simultaneous measurements of the mode I dynamic energy release rate G_{ID} and the crack propagation speed \dot{a} during fracture. Preliminary experimental results concerning the determination of G_{ID} were reported for different strain gage configurations. Experiments exhibited straight propagation paths and the analysis of the respective peak strain signals gave very similar results. These converging G_{ID} values validated the proposed procedure for the tested strain gage configurations.

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