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DO STANDARD DELAMINATION TESTS RELATE TO PLANAR DELAMINATION GROWTH?

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Abstract: *This paper discusses how standard unidirectional tests are to be related to planar growth, considering that these standard tests contain little to no information on transverse phenomena with respect to physical strain energy applied with loading. A concept is proposed to differentiate between applied work through the strain energy density, and the intrinsic material resistance through the strain energy release rate, to enable development of an overarching physics-based theory to relate standard unidirectional tests to planar delamination grow.*

Keywords: Delamination; Unidirectional; Planar; Physics; Fracture Mechanics

1. Introduction

Delaminations in fibre reinforced laminated composites comprise a damage type in which individual lamina in the laminate separate. This laminar decohesion can be induced by quasi-static, fatigue or (repetitive) impact loading, and is driven predominantly by peel and shear stresses at the interface, characterised as mode I and mode II opening.

Delamination growth in fibre reinforced polymer composites is generally evaluated with experiments that have been standardized for quasi-static load conditions. These tests characterize unidirectional delamination growth in mode I (DCB) [1,2], mode II (ELS [3] or ENF[4]) or mixed mode conditions (MMB) [5]. However, little attention is paid in literature to the applicability of these tests to in-service delamination problems that are generally characterized by planar delamination growth [6].

On top of that, there is only one standard available addressing fatigue delamination, which proposes to correlate for delamination onset the Strain Energy Release Rate (SERR) to a given number of applied load cycles [7]. Despite several attempts, there is yet no standard available to generate so-called fatigue resistance curves, i.e. the delamination growth rate plotted against some sort of similitude parameter based on the SERR concept. Several round robin exercises have been performed both within ASTM [8] and within ESIS-TC4 [9], with a second ESIS-TC4 round robin currently running [10]. The key obstacle to development of standard (fatigue) delamination testing appears the occurrence of fibre bridging in unidirectional tests, whereas the observations with in-service planar delaminations seems to indicate that this is merely a test artefact [11-14].

Hence this study investigated the relation between planar delamination growth, induced by transverse quasi-static and fatigue indentation loading, and these unidirectional delamination tests. To that aim, first planar delamination growth tests performed at EPFL [5], were analysed to identify up to what extent this planar growth could be correlated to the concepts of strain energy release and strain energy density. Secondly, an experimental setup was designed to measure the delamination size through localising the delamination boundary during the transverse indentation loading of planar delamination specimens made of non-transparent carbon fibre reinforced polymer composites. With that set-up, quasi-static and fatigue planar delamination growth experiments were performed, to study the potential correlation between unidirectional standard tests and the performed planar tests. This paper presents the work performed and the experimental results measured, and discussed the applicability of standard unidirectional testing to the planar delamination problem.

2. Energy based concept for the determination of the delamination shape

2.1 Definition of planar delamination

Well-known sources of planar delamination in composite structures are initial laminar disbonds induced during manufacturing [5] or under impact loading [15]. While such initial delamination may not have severe consequences by its own, over time they can grow significantly thereby reducing the strength of the structure, potentially resulting in catastrophic failure.

Planar delaminations may grow in a planar fashion, as illustrated in Figure 1 (a), or they may propagate predominantly in a single transverse direction, as illustrated in Figure 1 (b). This difference appears to be related to the loading mode [16] or magnitude of loading applied, which is known from standard delamination testing to result in different material resistance to delamination growth measured [17]. The resistance expressed in terms of Strain Energy Release Rate (SERR) will vary along the entire planar delamination boundary [18], and potentially may be related to the strain energy locally available at the delamination tip, described using the Strain Energy Density (SED) [19].

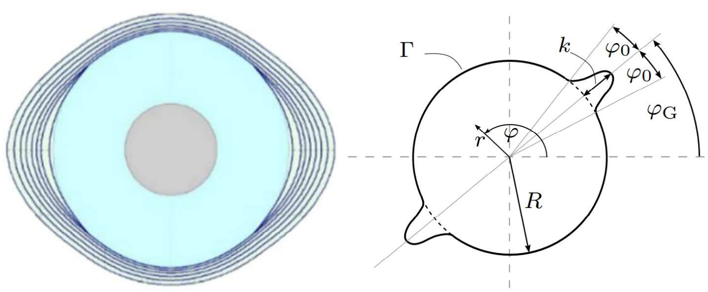

Figure 1. Illustration of planar delamination growth (a) and growth in a single transverse direction (b) [18]

2.2 Relation between strain energy release rate and strain energy density

Traditionally, prediction models developed in a fracture mechanics context relate parameters describing a ‘driving force’ to observed growth. Whereas, crack growth in metallic materials often was described using the Stress Intensity Factor *K*, delamination growth in composites often is described with the SERR *G*. Alternatively, this ‘driving force’ can be described by the SED, as proposed in other literature. However, to make the description of the delamination problem sounds from perspective of Physics, one need not only quantification of the ‘driving force’, but one also needs to quantify the intrinsic resistance of the material to fracture surface formation. Here, the authors propose to follow the concept outlined in [19], where the critical SED required to expand a delamination is considered ‘driving force’, and is related to the measured critical SERR as measure of resistance.

Daneshjoo et al. [19] developed this concept linking the SERR measured in a DCB test (mode I delamination) to the SERR measured in a ENF (mode II delamination) and MMB test, through equating the corresponding SED. This SED S is described by

$$S = D_1 \frac{G_I}{F_I} \tag{1}$$

where G_I is the mode I SERR, F_I is a constant derived from the constituent properties and D_1 is variable depending on the crack growth angle. The critical crack growth angle and the critical SED are determined to be at the point where the SED is at its minimum, which is the point of maximum amount of potential energy density at the crack front.

This relation between maximum potential energy density available at the crack front and the SERR forms the necessary framework to describe planar delamination growth. To illustrate this, consider the analogy with moving a box over the floor: the resistance counteracting the force is not a constant; it initially is constant (static friction) to turn into a dynamic force once the box is moving (dynamic friction).

2.3 Visible transverse delamination effects in planar specimen

In the current test standards (DCB, ENF & MMB) the various delamination modes are kept constant (pure mode I, pure mode II or a constant mix of two modes). In planar delamination growth, the (combination of) delamination modes can vary greatly along the delamination contour due to transverse effects. These effects influence how the planar delamination expands, but they in return are also influenced by the shape of the expanding delamination. The latter is the consequence of stress and strain redistribution campaigning the delamination shape change. This redistribution has an effect on the work applied, which can be observed when plotting the planar specimen compliance against the planar delamination expansion, as illustrated in Fig. 2.

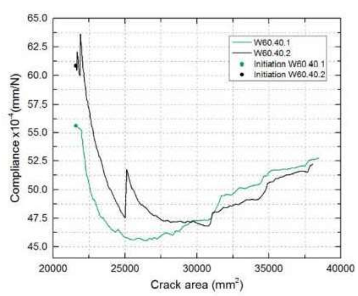

Figure 2. Compliance versus crack area of the composite mat with orthotropic properties [6]

2.4 Measuring planar delamination using the energy framework

While glass fibre reinforced composites are to some extent translucent, enabling the observation of planar delaminations [6], carbon fibre composites are opaque, which inhibits visual observation of internal delaminations. However, assuming that the SED at the delamination tip constitutes the 'driving force', the hypothesis is that through measuring strains on the thin panel surface, delaminations shapes can be visualized. Hence, Digital Image Correlation (DIC) was utilized to measure surface strains, which were transformed into the potential energy density through the classical laminate plate theory. The latter is required,

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because the measured surface strains need transformation to strains at the plane or interface at which the delamination is. For example, if the delamination is at the centre of the laminate, the strains at the interface of delamination can be determined with

$$\varepsilon_{x0} = \varepsilon_{x,top} - \frac{h}{2}\kappa_x$$
$$\varepsilon_{y0} = \varepsilon_{y,top} - \frac{h}{2}\kappa_y \quad (1)$$
$$\gamma_{xy0} = \gamma_{xy,top} - \frac{h}{2}\kappa_{xy}$$

where the subscript 'top' indicate the measured surface strains. The average potential strain energy density was then determined with

$$u_\rho = \frac{1}{2}\left(A_{11}\varepsilon_{x,0}^2 + 2A_{12}\varepsilon_{x,0}\varepsilon_{y,0} + 2A_{16}\varepsilon_{x,0}\gamma_{xy,0} + A_{22}\varepsilon_{y,0}^2 + 2A_{26}\varepsilon_{y,0}\gamma_{xy,0} + A_{66}\gamma_{xy,0}^2\right) + \frac{1}{2}\left(D_{11}\kappa_x^2 + 2D_{12}\kappa_x\kappa_y + 2D_{16}\kappa_x\kappa_{xy} + D_{22}\kappa_y^2 + 2D_{26}\kappa_y\kappa_{xy} + D_{66}\kappa_{xy}^2\right) \quad (2)$$

which required the constituent properties from the ABD matrix.

3. Experimental observations on planar delamination growth

3.1 Test setup and equipment

A planar delamination test set-up was designed to comply to the following requirements:

- fixture should be sufficiently stiff to limit uptake of strain energy to max 1%,
- fixture can withstand 30 kN without yielding or buckling (twice the max test load),
- fixture should provide clearance to provide sufficient camera field of view.

To this aim a pyramid fixture was designed and manufactured, as illustrated in Fig. 3. In the design of specimen and clamping, it was considered that the panel's positioning allowed to test either pure mode II, or mixed mode I/II loading, analogue to the ELS specimen clamping [3], as schematically illustrated in Fig. 3.

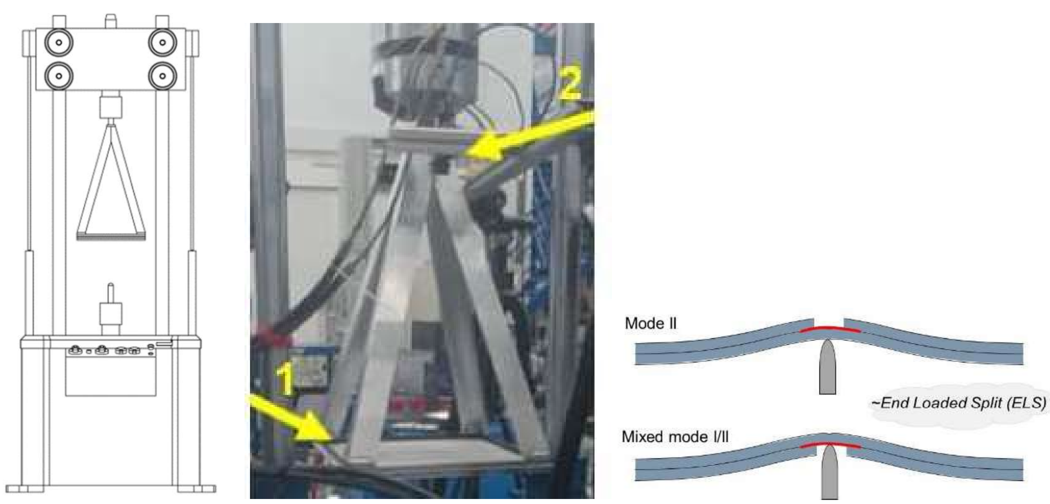

Figure 3. Fixture position in test machine (left), square specimen with speckle pattern (1) clamped in pyramid-shaped fixture, monitored with DIC camera (2); indenter is at actuator side below (centre), concept of tailoring the opening mode through specimen positioning (right)

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3.2 Evaluating the work applied

The loads and cross-head displacements were recorded to quantify the work applied to the panel, which is described by the area underneath the load-displacement curve. Because the load-displacement curve was non-linear (quadratic with an offset), the area underneath the curve between minimum and maximum loading in fatigue was quantified with

$$U_n = P_1(\delta_2 - \delta_1) + \frac{1}{3}(P_2 - P_1)(\delta_2 - \delta_1) \quad (3)$$

3.2 Evaluation of delamination observations

The DIC surface strain measurements were used both to visualize the x/y curvature in the panel, and to formulate a bond state mapping criterion based on the strain energy density (SED). Both analysis techniques complement each other in visualizing the delamination shape, see Fig. 5.

To verify the delamination shape through the use of DIC surface strain measurement and CLT transformation, two additional non-destructive measurement techniques were utilized:

- Lock-in thermography
- Ultrasonic C-scanning

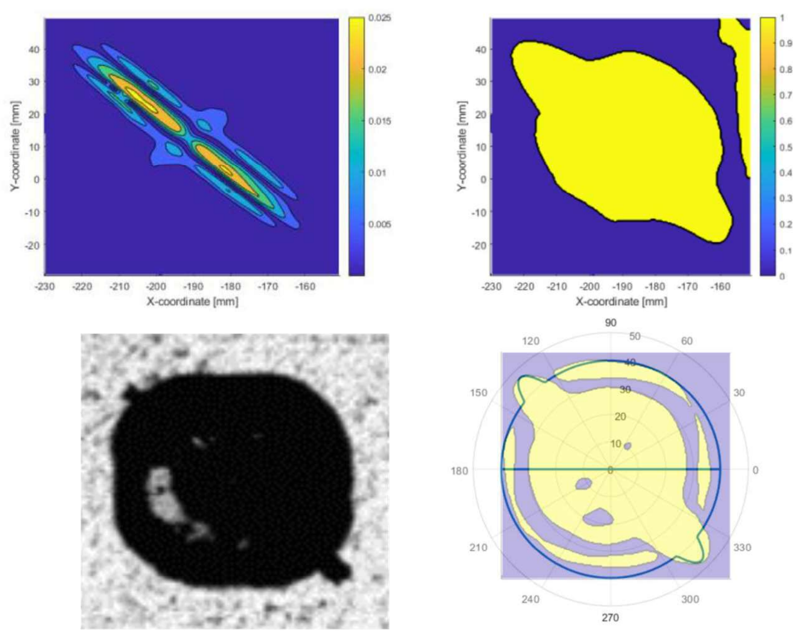
of which a C-scan is provided in Fig. 5 to illustrate the similarity in the observed delamination shapes.

To quantify the area of the measured delamination shapes, a shape function proposed by Köllner [18] was used

$$A_{del} = \pi R_p^2 + \frac{1}{4}k\phi_0(8R_p + 3k) \quad (4)$$

of which Fig. 5 illustrates through an overlay with the bond state map the fit.

(a) (b)



(c) (d)

Figure 5. Comparison between the xy-curvature map (a), the bond state map (b), the corresponding C-scan result (c), and the overlay with the shape function (d).

3.3 Notable observations

With planar embedded delaminations two modes of delamination growth can occur: planar and transverse growth. Whereas literature solely spotted these two delamination modes separately, in this study both of these modes occurred in the same experiment, but in separate phases. In the initial phase of the test, the delamination area growth is increasing rapidly, as shown in Fig. 6 (a). Due the nonlinear relationship between delamination radius and area, the rapid areal increase occurs with a diminishing rate of radius increase. Once portions of the delamination contour are at their local delamination threshold, the delamination increase converges to the portion of the delamination front experiencing the least resistance. This transverse growth has a different relation to the panel’s compliance increase, which results in substantially less energy dissipated with transverse growth, see Fig. 6 (b).

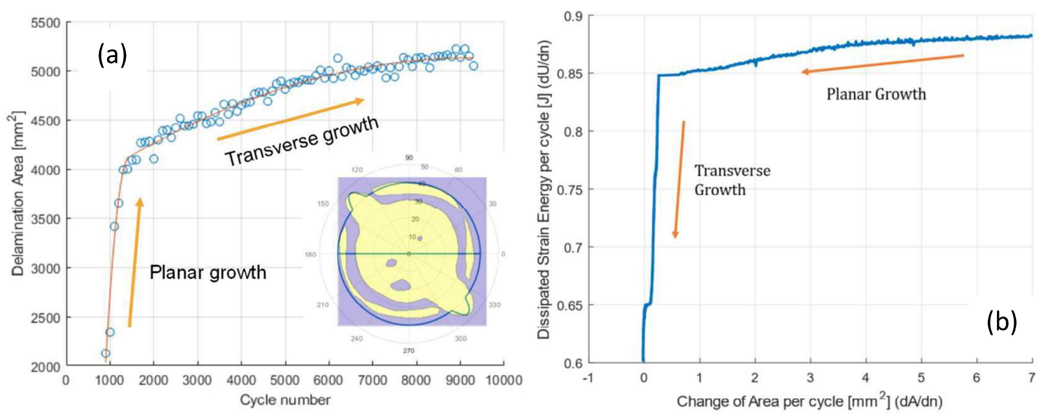


Figure 6. Fatigue delamination area growth curve exhibiting a transition from planar to transverse growth (a) and the dissipated strain energy associated to the areal growth (b)

4. Discussion on observations and the implications on current delamination framework

The planar delamination growth experiments [20] illustrate that when sufficient strain energy (work) is applied to the panel, the entire contour of delamination experience loading beyond the local threshold. The delamination grows in a planar fashion, experiencing local resistance related to fibre orientations relative to its growth direction. This variation in local resistance reveals itself by an overall change in areal delamination growth rate dA/dN, as shown in Fig. 6 (b). This variation in resistance in growth direction relative to the local fibre orientations, has been demonstrated in 1D experiments by Yao et al. [21,22]. Once local portions of the delamination contour reach their local delamination threshold, the extension becomes less planar, up to the extent that only very locally delamination increase is observed. This transverse growth occurs then only in the direction with the least resistance, which is known for low da/dN in fatigue to be less than at higher da/dN [17], and is associated here to planar growth. This explains the rapid decrease with energy dissipation, once only transverse growth is observed, see Fig. 6(b).

This variation along the entire delamination contour imposes some difficulty in prediction [23], because of the interplay between the local driving strain energy, influenced by the actual delamination shape, and the local resistance, related to the respective fibre orientations. The latter can be affected by fibre bridging [6], despite generally considered an artefact of standard 1D DCB testing. However, insufficient evidence exists to draw firm conclusions, particularly, because in planar testing the effect of fibre bridging cannot be dissected well from the effect of in-plane stretching [6].

The different variation in strain energy density locally at the delamination contour relative to the variation in intrinsic local delamination resistance illustrates that a simple scaling law, i.e. Paris-type relation, based on one SERR parameter only is insufficient to describe planar delamination growth.

Hence concepts in which the driving work is characterised with SED, while the resistance is quantified in the physical SERR should be further developed in order to use 1D standard test data to predict planar delamination growth.

5. Conclusion

The current study illustrates that at the moment insufficient evidence exists in literature to apply standardized 1D tests results to planar 2D delaminations predictions, because

- 1D samples exhibit phenomena that yet have not been studied well for planar delaminations, like fibre bridging
- 1D samples lack transverse phenomena observed in planar delaminations
- 1D samples have one specific interface configuration (eg. 0°//0°), while planar delaminations in their circumference experience multiple fibre orientations with their intrinsic resistance and delamination features.

In addition, most methods only use simple scaling laws that relate growth to loading parameters allegedly describing similitude, which from perspective of physics is questionable. Instead, the base theory for delamination prediction should separate the applied loading from the intrinsic material resistance, through the use of respectively strain energy density and strain energy release. This would explain the observed different intrinsic delamination resistance in fatigue delamination growth, when transitioning from planar to transverse growth at low delamination growth rates.

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