Enhancement of fracture resistance of composite laminates by the creation of multiple delaminations

Bent F. Sørensen and Stergios Goutianos

Section of Composites and Materials Mechanics, Department of Wind Energy

The Technical University of Denmark

Risø Campus, Frederiksborgvej 399

DK-4000 Roskilde

Denmark

Abstract

Cohesive zone modelling is used to study delamination. A secondary crack can open when the peak traction value of its cohesive law is less than that of the primary crack and the layer between the two interfaces is sufficiently thin.

1. Introduction

The fracture properties of layered polymer matrix composites are highly anisotropic. The fracture energy associated with the growth of a crack in a plane perpendicular to the fibre direction is typically in the orders of 10-100 kJ/m^2], while the fracture energy for growing a crack parallel to the fibre (splitting or delamination) is typically below 0.5 kJ/m^2. As a consequence, failure of composite structures often involves splitting and/or delamination. Failure often starts from geometric discontinuities, such as holes or ply-drops, that induce significant stresses along these weak planes. It is therefore of great practical importance to develop composite materials with enhanced fracture resistance.

One way of enhancing the fracture resistance of weak planes is crack bridging by fibres, e.g. by stitching, knitting, weaving or by the z-pins, which are fibres placed perpendicular to the delamination plane (Mouritz *et al*., 1999; Rugg *et al*., 2002). Another mechanism, which we will explore in the present study, is crack bridging by cross-over bridging, i.e. crack bridging by fibres that are oriented parallel to the cracking plane (Spearing and Evans, 1992; Suo *et al*., 1992; Sørensen and Jacobsen, 1998).

Rask and Sørensen (2012) conducted fracture resistance measurements on adhesively-bonded joints in laminates made of glass fibre composites using the DCB specimen loaded by uneven bending moments (DCB-UBM). The pertinent results will be reviewed in the following. Two different laminate

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configurations, having the same surface layers towards the adhesive, were tested under two moment ratios, symmetric loading (nominal Mode I) and with moment applied to one beam arm only (mixed mode). For symmetric loading (nominal mode I) the crack propagated along the adhesive/laminate interface with significant fibre bridging (cross-over bridging) (see Fig. 1a) resulting in significant rise in the fracture resistance approaching a steady state fracture resistance of about 0.7 kJ/m^2 for both laminate configurations. For mixed mode loading, one laminate developed two cracking planes, one along the adhesive/laminate interface and one inside the laminate (see Fig. 1b) while for the other laminate configuration, three cracks developed, one along the adhesive/laminate interface and two along layer interfaces in the laminate (see Fig. 1c). All crack developed fibre bridging by cross-over bridging. The resulting overall fracture resistance, given in terms of the J integral, calculated from the measured applied moments and beam curvature, are shown as a function of the end-opening in Fig. 2. As mentioned, for the specimens loaded with symmetric moments (mode I), the fracture resistance attained a steady-state value of about 0.7 kJ/m^2, see Fig. 2. The laminate configuration that developed two parallel cracks during mixed mode attained a steady-state fracture resistance of about 1.5 kJ/m^2 while the laminate configuration that developed three crack had a steady state fracture resistance of about 2.1 kJ/m^2. These results indicates that the steady-state fracture resistance of the adhesive joints increases proportionally with the number of cracks. Potentially, this mechanism of multiple cracks offers an approach to multiply the fracture resistance of layered composite materials. A key question is, however, what are the mechanics properties of the interfaces that allows the development of multiple crack? Can the formation of multiple crack be obtained by control of the interfaces between the layers and thus lead to much tougher laminates?

The present paper summarizes results from a model study (Goutianos and Sørensen, 2016) that provides answers to the questions posed above. The analysis concerns a DCB-specimen with two interfaces, a primary crack and a secondary crack. The mechanics of the interfaces will be described in terms of two cohesive laws, one for the primary crack and one for the secondary crack. The study investigates under which conditions the secondary crack will open and propagate along with the primary crack.

2. Model

2.1 Problem description

The problem is depicted in Fig. 3. A DCB specimens with beam height *H*, width *B* and length *L* is loaded with pure bending moments, M_1 and M_2, applied to the ends of the cantilever beams. The fracture characteristics of the primary cracking plane ($x_1 > 0$; $x_2 = 0$) is modelled by a cohesive law, where the key parameters are the peak cohesive traction $\hat{\sigma}_n^1$ and the fracture energy $J_{n,ss}^1$. The potential fracture plane of the secondary crack is placed a distance *h* below the primary crack ($x_2 = -h$). The cohesive law parameter of the secondary crack is denoted $\hat{\sigma}_n^2$ and $J_{n,ss}^2$, respectively. In case the crack propagates along the primary crack only, the fracture resistance will correspond to the area under the traction-separation law of the primary crack. This follows from a J integral analysis taken around the active

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cohesive zone (Goutianos and Sørensen, 2016). In case the secondary crack opens, there will be a positive contribution from the forward cohesive zone (right hand crack tip) of the secondary crack, but there may be a negative contribution from the left unless it remains closed (Goutianos and Sørensen, 2016).

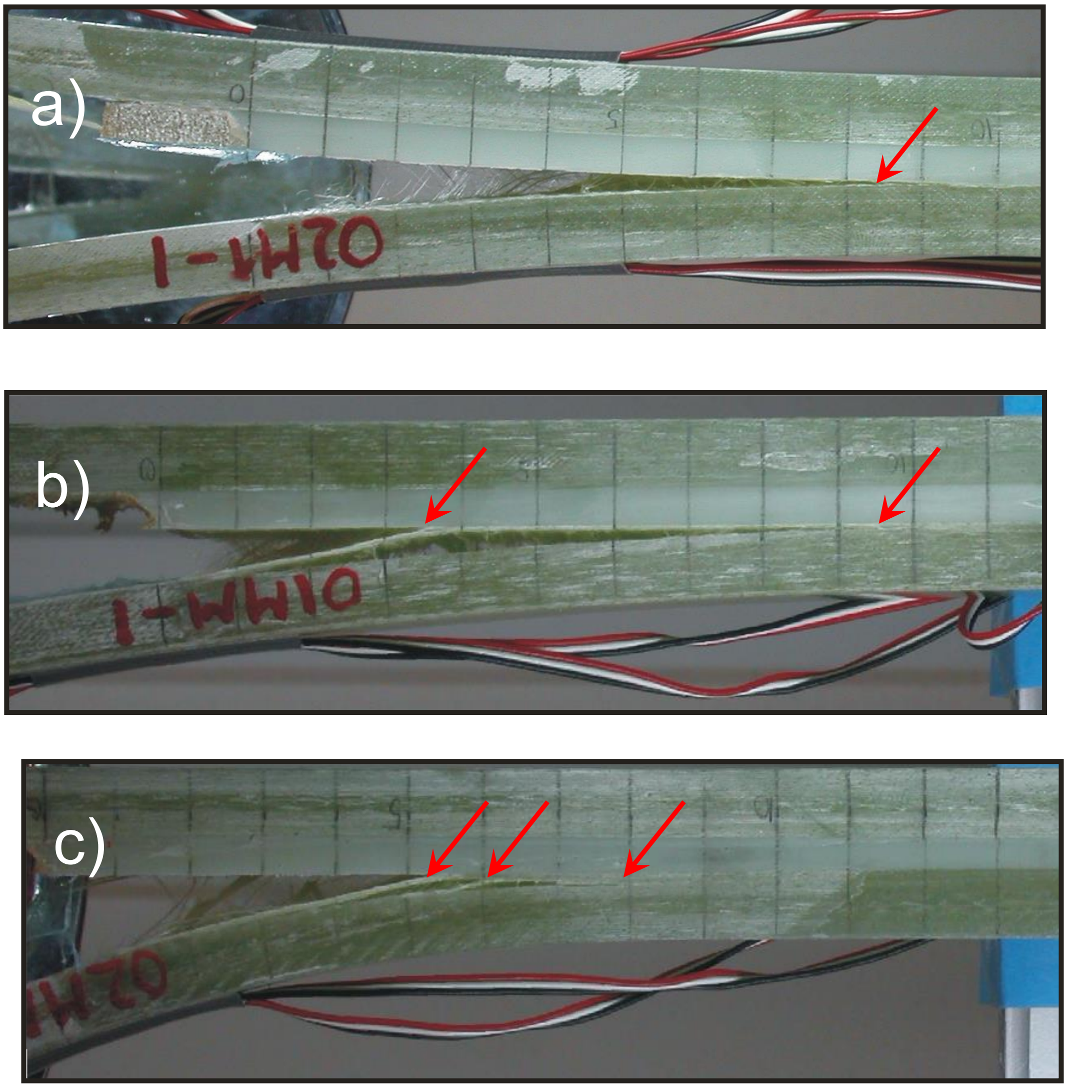

Figure 1: Observation of fracture process zones in adhesively bonded joints; crack tips are indicated by red arrows. (a) Example of propagation of a single crack with a fibre bridging zone observed for symmetrical loading. (b) Two cracks and (b) three cracks propagating under mixed mode loading (after Rask and Sørensen, 2012).

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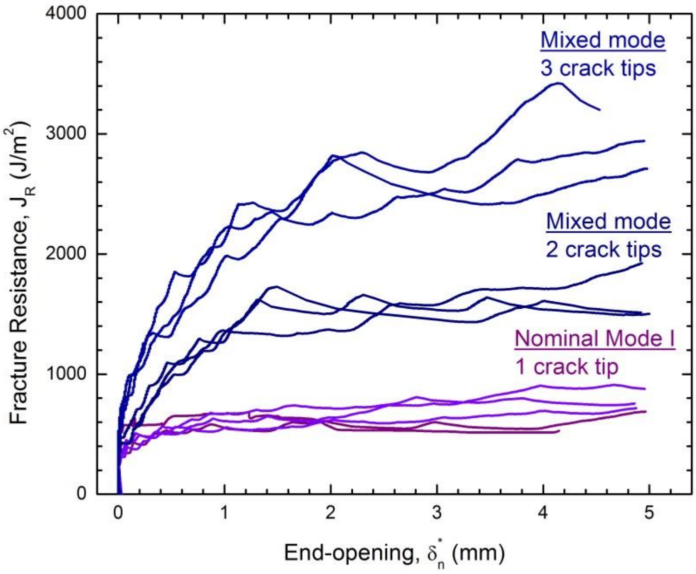

Figure 2: Measured fracture resistance as a function of measured end-openings for specimens experiencing respectively one, two and three cracks. (After Rask and Sørensen, 2012).

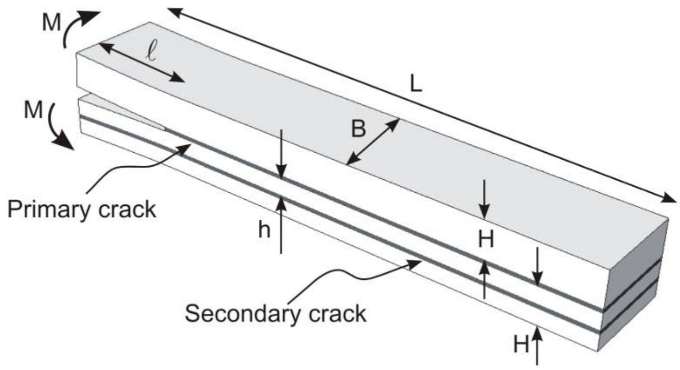

Figure 3: Sketch of the problem - a DCB specimen loaded with uneven bending moments, where one of the beams has two potential fracture planes: One along the specimen mid-plane (the primary crack) and one a distance *h* below the midplane (the secondary crack). (From Goutianos and Sørensen, 2016).

The overall fracture resistance was calculated from the applied moments (plane strain) as follows (Sørensen *et al.*, 2006):

$$J_R = (1-\nu_{13}\nu_{31})\frac{21\left(M_1^2+M_2^2\right)-6M_1M_2}{4B^2H^3E_{11}} \qquad for\,|M_1| \le M_2 \tag{1}$$

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where M_1 and M_2 are the moments applied to the beam ends (taken positive in the anti-clockwise direction), ν_{13} and ν_{31} are the major and minor Poisson's ratio's, B is the specimen width, H is the beam height and E_{11} is the Young's modulus in the x_1-direction. This result comes from a J integral analysis where the integration path was taken along the external boundaries of the specimen.

2.2 Numerical model

The problem was analysed as a 2D plane strain problem using the commercial finite element code Abaqus version 6.11 in explicit mode. The model consisted of four-node and three-node 2D plane stress solid elements (reduced integration) and uncoupled, user-defined 2D cohesive elements. The simulations were conducted incremental. Rotations, not moments, were prescribed to increase monotonically in order to ensure stable solutions. Results will be presented in terms of the J integral value, calculated using equations (1), as a function of the normal opening displacement of the original crack tip ($x_1 = 0$), denoted Δ_n.

3. Numerical results

Results presented in the following were obtained for cohesive laws having the same fracture energy but different peak traction (and thus different critical separation) values. Fig. 4 shows examples of R-curves obtained using the finite element analysis. For one example ($h/H = 0.1$), the secondary crack remains nearly closed as the primary crack propagates. The value of J_R increases to a steady-state value that is a bit higher than $J^1_{n,ss}$. For the second example($h/H = 0.01$), the secondary crack opens fully as the primary crack advances. The resulting steady-state fracture resistance reaches a value that is close to the sum of $J^1_{n,ss}$ and $J^2_{n,ss}$, indicating that the presence of the secondary crack has led to a higher apparent steady-state fracture resistance than for a single crack.

Next, Fig. 5 shows the predicted steady-state fracture resistance as a function of the ratio between the peak traction values of the cohesive laws of secondary and primary cohesive zones respectively. Results are shown for a variety of value of the distances between the two cracking planes, *h*. It is seen that the steady-state fracture resistance reaches a value of about 1.8 - 1.9 times the fracture energy of the primary crack for a broad range of parameters. This near-doubling is possible when the peak traction value of the secondary crack is equal to or less than the peak traction value of the primary crack. However, it is only possible when the layer thickness, *h*, is small, $h/H < 0.05$.

4. Discussion

The results of our study shows that it is possible to obtain enhanced steady-state fracture resistance by the formation of a secondary crack providing that two conditions are fulfilled: 1) The peak traction value of the interface below the surface layer (the plane of the potential secondary crack) is identical or lower

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to that of the primary crack. 2) The thickness of the layer should be sufficiently thin so that the normal traction σ_{22} (operating across both cohesive zones) is almost the same for the two fracture process zones. Thus, if the layer is sufficiently thin, the formation of a secondary crack should be possible in a laminate that has identical fracture properties between the layers.

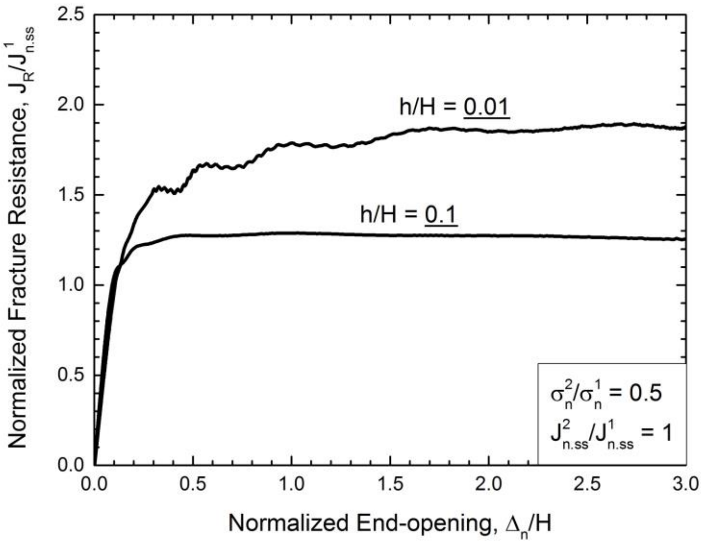

Figure 4: Examples of predicted R-curves: The fracture resistance is plotted as a function of the end-opening. (After Goutianos and Sørensen, 2016).

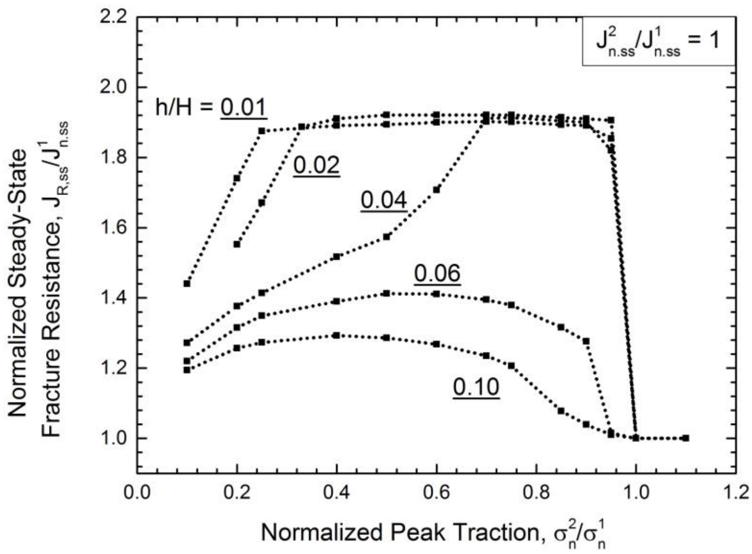

Figure 5: Predicted values of the steady-state fracture resistance plotted as a function of the ratio between the peak traction value of the secondary and primary crack respectively for various values of the distances between the cracking plane, *h*. (After Goutianos and Sørensen, 2016).

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One perspective is to enhance the load-carrying capabilities and damage tolerance of adhesively-bonded joints by surface preparation of the surface to be bonded, so that the peak traction value of the adhesive/laminate interface exceeds that of the peak traction of the interface between the surface layer in the laminate. Results from a study by Kusano *et al*. (2013) suggest that this should be possible. For an adhesively-bonded joint where the adhesive was applied to a surface straight after removal of a peel-ply (i.e. no additional surface treatment), the cracking was found to occur by a single crack along the adhesive/laminate interface with no visible fibre bridging. The associated fracture energy was about 0.11-0.14 kJ/m^2. For similar specimens where the surfaces to be bonded were plasma-treated by a gliding arch, most specimens developed an additional secondary crack with large scale bridging inside the laminate. Those specimens developed a large fracture resistance enhancement (beyond 0.5 kJ/m^2). The peak traction values were not measured in the study of Kusano *et al.* (2013), and thus it cannot be assessed if the development of the secondary crack can be attributed to an increase in the peak traction value of the primary crack. However, images taken during the experiments show a small amount of crack bridging of the primary crack of plasma-treated specimens, indicating that the fracture properties and thus likely the peak traction value, of the primary crack had been increased. This supports the idea that proper control of surfaces to be bonded can be used to create adhesively-bonded joints that develop multiple cracks and thus obtain significant toughness enhancement by this mechanisms.

Finally, it is worth noting that in the experimental study of Rask and Sørensen (2012), the formation of secondary cracking was observed under mixed mode loading only. This indicates that the formation of a secondary crack is more likely under mixed mode loading than under symmetric loading. Further model studies should be conducted to explore the formation of secondary cracking under mixed mode.

5. Conclusions

The major result from the analysis of a cracked specimen containing two parallel cracks with fracture properties described in terms of different cohesive laws are as follows:

The overall steady-state fracture resistance will be close to the sum of the fracture energy of the two cracks if the right hand secondary crack opens, but the left hand side crack tip remains closed. The secondary crack will open when the peak traction value of the its cohesive law is equal to or less than that of the primary crack, and the thickness of the layer between the two interfaces is sufficiently small. This offers the possibility of creating joints and laminates with high steady-state fracture resistance by proper design of the mechanical properties of interfaces between layers.

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