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Risø-R-1411(EN)

Fracture mechanics characterisation of medium-size adhesive joint specimens

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March 2004

Abstract

Medium-size specimens (~ 2 m in length), consisting of two glass-fibre beams bonded together by an adhesive layer were tested in four point bending to determine their load carrying capacity. Specimens having different thickness were tested. Except for one specimen, the cracking occurred as cracking along the adhesive layer; initially cracking occurred along the adhesive/laminate interface, but after some crack extension the cracking took place inside the laminate (for one specimen the later part of the cracking occurred unstably along the adhesive/laminate interface). Crack bridging by fibres was observed. The measured applied moment at steady-state crack growth was compared with predictions based on independent mixed mode fracture resistance measurements made on small laboratory specimens. The predicted and measured strength values of the medium-size specimens were found to be in good agreement with each other. Thus, the scaling from small specimens to medium-size specimens was successfully achieved.

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Contents

Preface

This report contains a description of some of the work that was carried out in a project called "Improved design for large wind turbine blades, based on studies of scale-effects (Phase 1)", partially supported by the Danish Energy Authority under the Ministry of Economics and Business Affairs through a EFP2001-fund (journal no. 1363/01-01-0007). The project ran 1½ year from 2001 to 2002. The participants in the project were: The Materials Research Department, Risø National Laboratory (project leader), The Wind Energy Department, Risø National Laboratory, The Department of Mechanical Engineering (Solid Mechanics), The Technical University of Denmark, Department of Mechanical Engineering, Aalborg University, LM Glasfiber A/S and Vestas Wind Systems A/S. It was found to be impossible to acquire students at Aalborg University. As a result, no work was performed there. Instead, more work was carried out at Risø National Laboratory.

This report only contains the results of some fracture mechanical testing of some medium-size specimens. The specimens were manufactured by LM Glasfiber A/S/ and tested at specially developed fixture at the Materials Research Department, Risø National Laboratory. The major results of the entire project can be found in the summary-report, which also contains a list of the publications that came out of the project:

Risø-R-1390(EN)
"Fundamentals for improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report" , Bent F. Sørensen, Erik Jørgensen, Christian P. Debel, Find M. Jensen and Henrik M. Jensen, ISBN 87-550-3176-5; ISBN 87-550-3177-3(Internet) ISSN 0106-2840

1 Introduction

Many large components, such as ships, aircrafts and wind turbine blades are made of composite structures that are joined by adhesive bonds. It is therefore of interest to establish approaches for safe design of adhesively bonded composite structures. Traditionally, two different approaches have been used [Matthews, 1987]: An analysis based on *crack initiation* and an approach based on *crack propagation*. Typically, a criterion for crack initiation is a *maximum stress* criterion, i.e. it is assumed that crack initiation takes place when a stress component reaches a critical value. Crack growth criteria are typically based on linear elastic fracture mechanics. Then, a criterion for crack growth is that crack propagation takes place when the *energy release rate* reaches a critical value, denoted the crack tip fracture energy. However, crack growth in fibre composites is usually complicated by the fact that crack bridging often occurs during crack growth. Crack bridging occurs the form of many single fibres or fibre bundles that connect the crack faces in the crack wake behind the crack tip. The energy uptake associated with crack bridging can be large in comparison with the crack tip fracture energy. It is therefore of interest to develop approaches that can take the effect of fibre bridging into account.

In a parallel study [Sørensen et al., 2003], an experimental method was developed for characterising crack growth in laminates and adhesive joints. The ratio between crack face opening ("mode I") and crack face sliding ("mode II") can be changed arbitrarily. For adhesive joints made of similar materials as the one examined in the present work, the steady-state fracture resistance under mixed mode cracking was determined to be around 2200 J/m^2 [Sørensen et al., 2003]. It is also possible, by a J integral based approach, to deduct effective cohesive laws, i.e. mechanical laws that describe the effect of crack bridging in terms of non-linear stress-separation relationships. The cohesive laws are regarded as being materials laws. The idea is that the cohesive laws can be measured at small laboratory specimens and can be used to predict the strength of larger structures having different geometries.

The purpose of this investigation is to determine the strength of adhesive joints of medium size, viz., specimens that have dimensions that are significantly larger than those of the laboratory specimens. The major aim was to investigate, how accurate the strength of the adhesive joints can be predicted from properties determined from smaller laboratory specimens.

2 Experimental Procedures

2.1 Processing of Test Specimens

The geometry of the specimens is shown in Fig. 1. The glass-fibre laminates were processed by LM Glasfiber A/S. The layup was predominating unidirectional fibres oriented parallel to the beam direction, with a surface layer oriented 45 degrees. After curing, two laminates, having uneven lengths, were joined by an adhesive layer. Six specimens were made in total. For all specimens the length of the longest part was 2000 mm, the width, *B*, was 60 mm nominally, and the thickness, *H*, was nominally 60 mm. The length of the shorter laminate was approximately 1380 mm, and the width was also 60 mm. The thickness, *t*, of the adhesive layer was approximately 5 mm. Three thicknesses of the shorter laminate, *h*, were investigated: h = 10 mm, h = 32.5 mm and h = 60 mm.

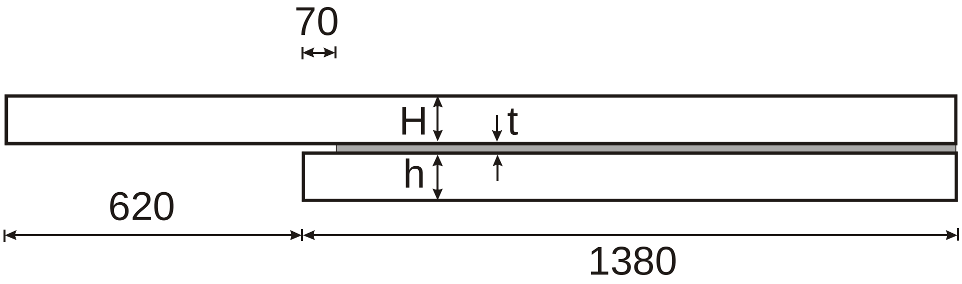

Figure 1. Nominal dimensions (in mm) of the medium-size specimens. (UCSB_emne_1a.cdr)

2.2 Test Procedure

The specimens were tested in four point flexure in a fixture made for the purpose. When cracking takes place at the adhesive layer, the crack tip stress field consists of a mixture of shear and normal stresses; this is a mixed mode specimen. In the following the presence of the adhesive layer is neglected. Then, the energy release rate can be obtained in closed form by the J integral. The result is (plane stress) [Charalambides et al., 1989]:

$$J = 6\frac{M^2}{B^2H^3E}\left\{1-\frac{1}{\left(1+\frac{h}{H}\right)^3}\right\} \quad , \qquad (1)$$

where M is the applied moment and E is the Young's modulus (in the direction of the beam length). With the set-up shown in Fig. 2, $M = P\ell/2$, where P is the applied load (recorded by the load cell) and ℓ is the moment arm. The mode mixity, ψ, defined as $\psi = \tan^{-1}(K_{II}/K_I)$, where K_I and K_{II} are the mode I and mode II stress intensity factors, respectively, is 40.9 degrees for h/H =1, and increasing relatively slowly with decreasing h/H ratio to about 49 degrees for h/H = 0.1 [Charalambides et al., 1989].

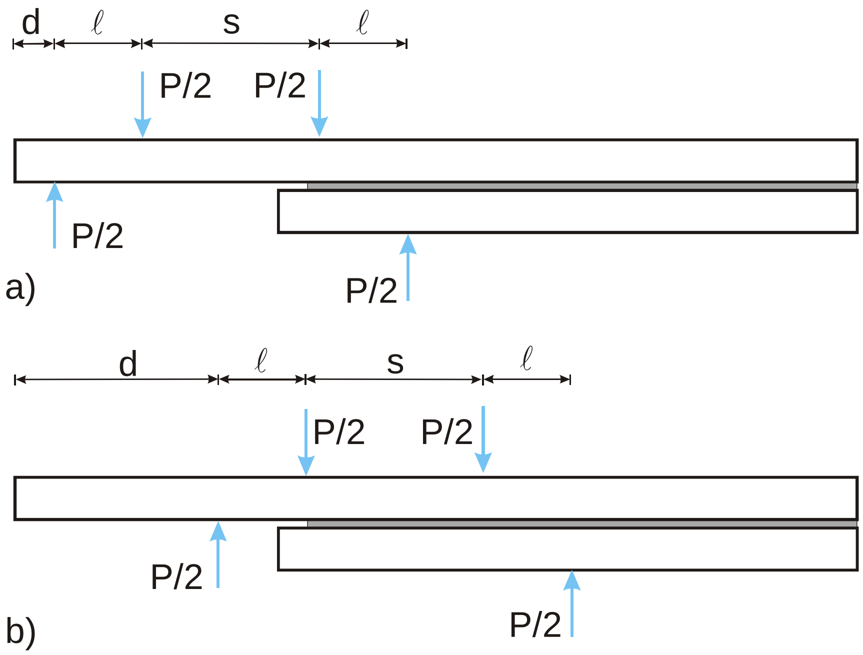

Figure 2. The loading principles for crack initiation (a) and crack propagation (b). (UCSB_emne_1a.cdr)

Prior to the experiments, the dimensions of each specimen were measured by a slide caliper and a ruler. Table 1 summarise the major dimensions. Also, an approximately 10 mm long pre-crack was made in the middle of the adhesive layer by a saw. Marks, 50 mm apart, were made at the side faces of the specimens to facilitate the measurement of crack length during the experiments.

Table 1. Major dimensions of the specimens: H and h are the heights of the beams, respectively, B is the width and t is the thickness of the adhesive layer.

Specimen Name	H (mm)	B (mm)	h (mm)	t (mm)
A	61	60	10.5	4-5.5
B	61.5	59.5	10.35	4.5
C	62	59.5	32.5	4-5
D	61	59.5	32.5	2.7-5
E	61.5	61.5	60	4.5-5.0
F	61.5	59.5	61.5	4.5-5.5

The specimen was tested at a fixture shown in Fig. 3. The fixture consists of two parts. The lower part (an I-beam) was supported at the ends by rods against the ground and the midpoint was supported at lower part of the test machine. The upper part was mounted with a spherical bearing that allows the part to rotate. This ensured that the loading was statically determinate, although the specimen deformed non-symmetrically. The fixture was mounted at an Instron 1511 test machine. The load was measured by a load cell (D30.20, series no. 62) that was connected to an amplifier (D12571A/K52, calibration 1V = 10 kN; calibration value = 1079). The end-opening of the crack, δ_m, was measured by an LVDT (H. F. Jensen, type TCA B/L 5S, no. 20522) connected to an amplifier (current supply: B&O SN16A, at 24 V; 1 V = 1 mm). The LVDT was mounted such that it could rotate freely and thus the measured displacement, δ_m, could not be separated into displacements in the tangential or normal direction, see Fig. 4.

Figure 3. The experimental set-up in the test machine. (Sample E 09.jpg).

During the experiment, data for time, load, and end-opening were recorded (10 Hz) at a PC by the use of a Notebook data acquisition programme. Also, simultaneous values of elapsed time and crack lengths were written down during the experiment, so that the relationship between applied load and crack length could later be reconstructed from the data files.

The test procedure was as follows: First, a specimen was mounted at the fixture. Steel inserts were used at each load point to avoid damage due to concentrated forces. Each test consisted of two parts: (a) crack initiation and (b) crack growth. All experiments were made under a constant cross head speed of 2 or 5 mm/min. During the crack initiation experiment the specimen was positioned as shown in Fig. 2a. The idea was to ensure that the crack did not propagate much upon initiation. If the crack tip passes the inner load point the moment at the crack tip decreases. Consequently, by (1) the energy release rate decrease and the crack growth will be arrested. After crack initiation had been detected, the specimen was unloaded and moved (increasing the distance d, see Fig. 2b). Occasionally, the moment arms ℓ or the distance between the inner loading points was changed. Therefore, to avoid potential errors in the calculation of the moment, the distances d, s and ℓ (see Fig 2b) were always measured prior to a loading.

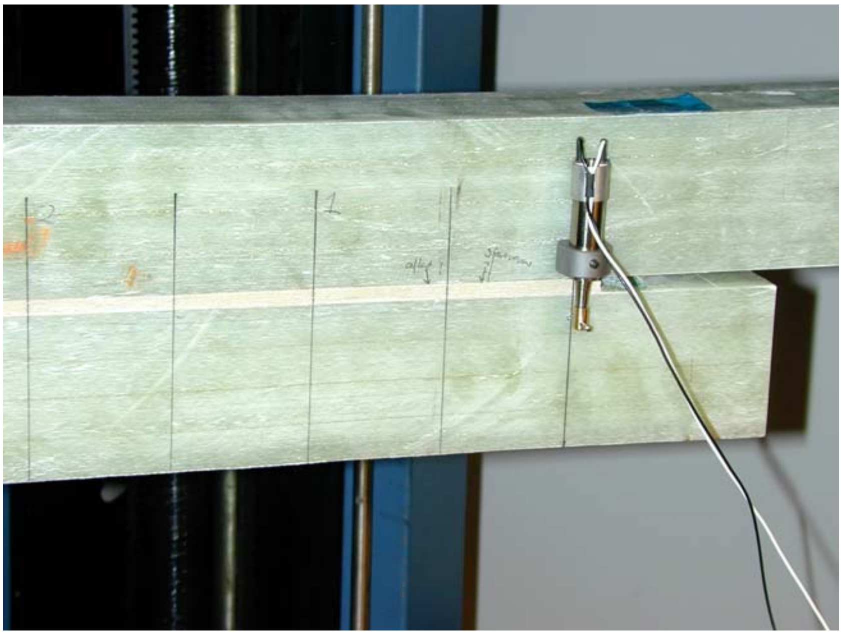

Fig. 4. An LVDT records the crack opening displacement of the initial pre-crack. (Sample_F_last_2333.jpg)

The crack growth experiments (type (b) experiments) were conducted differently for the two specimens of each type (same *h*/*H*). For one specimen, the specimen was partially unloaded approximately five times, after a crack growth of approximately 50 mm, 100 mm, 150 mm, 200 mm and 300 mm. For the other specimen, the loading was monotonically; no unloading was performed until the crack tip reached the inner support (after approximately 900 mm crack growth). In cases where rapid crack growth occurred (i.e., the crack jumped a long distance > 50 mm) the rapid crack growth distance was marked at side of the specimen.

3 Results and Discussion

In all experiments a crack initiated from the pre-cut notch, but immediately grew out to the interface between the adhesive and the laminate of the long beam. This was expected; a crack loaded such that a mixture of mode II and mode I exist at the crack tip seeks to propagate in the direction to become a mode I crack [Thouless and Evans, 1990]. Observations revealed that the first crack extension took place along the adhesive/laminate interface. Thereafter, separation took place in the external lamina (oriented 45 degrees with respect to the longitudinal direction of the beam) of the laminate, see Fig. 5. Then, extensive fibre bridging occurred. The crack propagation usually occurred stably. However, rapid crack jumps did occur and were marked up at the side of the specimen.

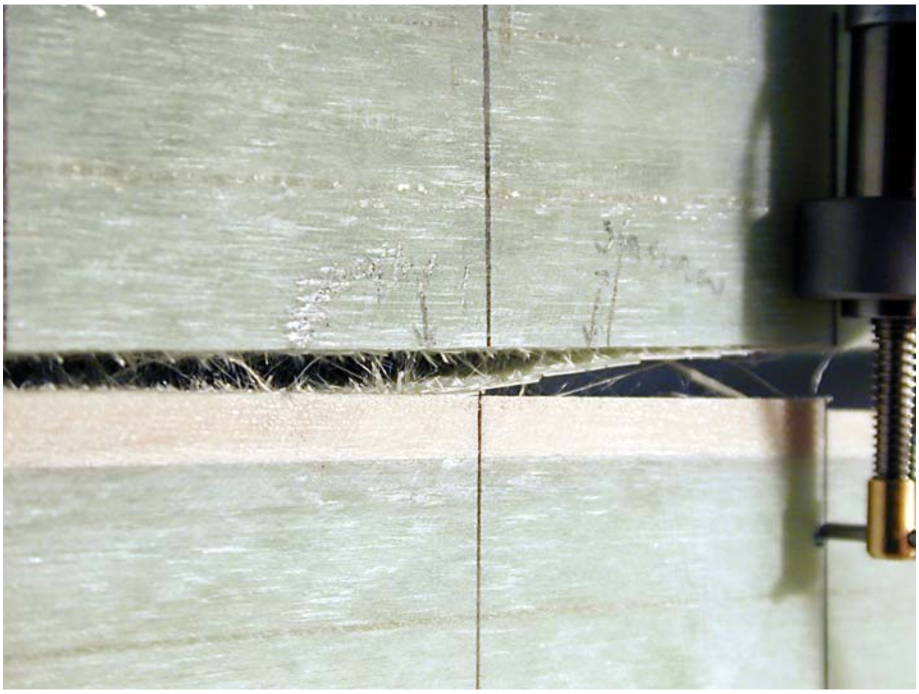

Figure 5. Cracking along the adhesive/laminate interface and inside the laminate (crack length ≈ 353 mm). (Sample_F_last_2774.jpg)

For unknown reasons, specimen C behaved differently from the other. After some stable crack growth inside the external lamina (approximately 250 mm), the crack jumped back to the adhesive/laminate interface; then the crack immediately grew along the interface and did not arrest until the crack tip reached the inner loading point (a crack extension of about 900 mm). The fracture surface that had formed so rapidly was completely free of fibres. This suggests that the interface itself had a lower fracture energy than the one of the laminate experiencing fibre bridging. At the one side of the specimen, echelon cracks were visible in the adhesive layer (Fig. 6). At the other side, the crack had propagated smoothly along the adhesive/laminate interface.

For the specimens having small h/H, it was observed that, for long crack lengths, a significant part of the crack was closed near the crack tip, indication pure mode II cracking, as shown in Fig. 7.

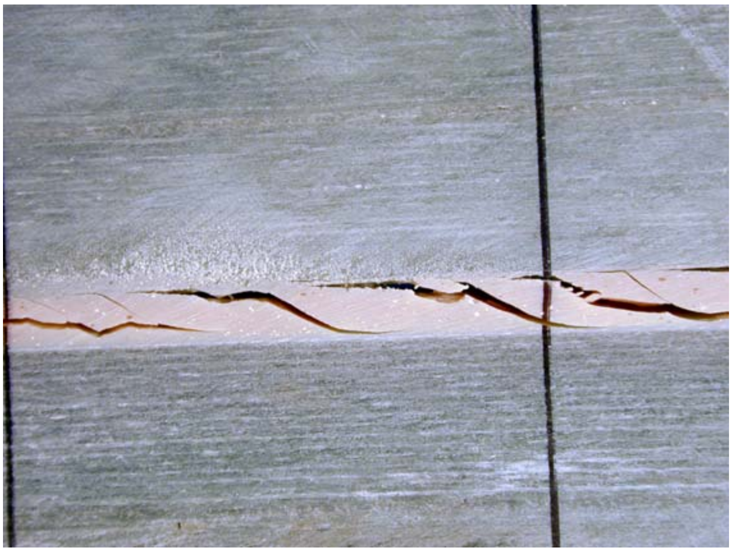

Figure 6. So called echelon cracks in the adhesive layer of specimen C, that experienced rapid cracking along the adhesive/laminate interface. (Sample_C 004.jpg)

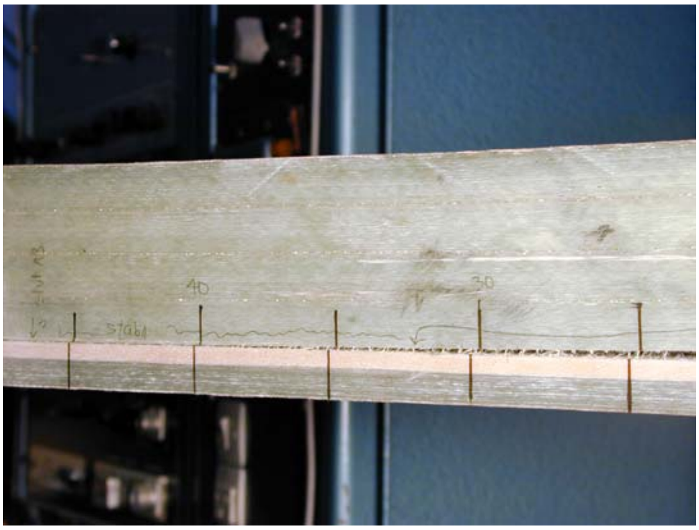

Figure 7. Photo of specimen having a small h/H (specimen A). The crack is closed (pure mode II) beyond a distance of ≈450 mm away from the notch. The crack tip is approximately 900 mm from the notch. Fibre bridging is clearly seen. (Limsamling 01.jpg)

This is most likely an effect of fibre bridging. The stresses from the bridging fibres retard the crack opening. The bridging stresses are likely to cause most bending in the thinner beams (smaller h) that have smaller bending stiffnesses. It is tempting to speculate that the stresses from the bridging fibres were sufficient to bend the beam so much that crack opening was precluded. Modelling, accounting for the fibre bridging, is necessary to clarify this point. However, the observations suggest, that when large scale bridging occurs the crack tip mode mixity may change with increasing crack length, although the specimen appears to be a steady-state specimen.

Examples of measured data, moment, M, as a function of crack opening, δ_m, is shown in Fig. 8. The moment is shown as a function of the end-opening for a monotonic test and a test with several unloading and reloading cycles. The two curves follow each other reasonably well. They attain a steady-state value of about 3.5 kNm after a crack opening of about 2 mm. Note, that the unloading-reloading curves show increasing hysteresis with increasing end-opening (corresponding to a longer crack). The hysteresis may be attributed to frictional contact between the crack faces or broken fibres.

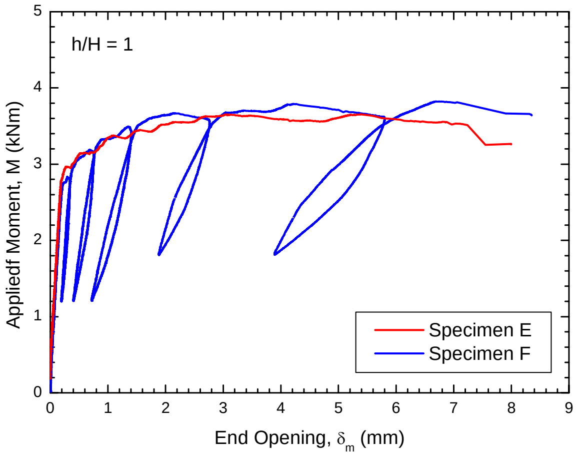

Figure 8. Example of relationship between applied moment and crack opening under monotonic loading and partial unloading (h/H = 1). (E_2_F_2_.opj)

The measured moments (at the point of cracking) is shown as a function of crack length in Fig. 9 (only data after crack initiation is present in the figure). The figure shows that the required moment increases to a steady-state value. The steady-state values of the applied moment depend on the thickness ratio, h/H. Specimens having a smaller h/H value require a higher moment to generate crack growth.

The effect of h/H can be rationalised by assuming that the steady-state fracture energy, J_{ss}, is the same for all specimens (as mentioned above, the mode mixity, ψ, is approximately the same for $h/H = 0.1$ and $h/H = 1$). Then, by (1) the critical moment at steady-state cracking, M_c, can be predicted to be

$$\frac{M_c}{B\sqrt{J_{ss}H^3E}} = \frac{1}{\sqrt{6}\sqrt{1-\frac{1}{\left(1+h/H\right)^3}}}. \tag{2}$$

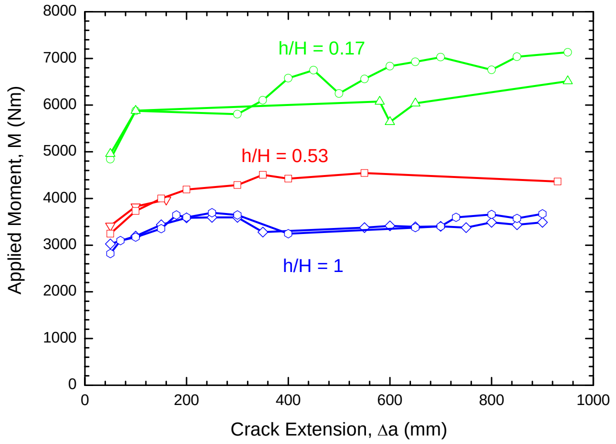

Figure 9. Measured moment-at-crack-growth as a function of crack extension. (Moment_Da_1a.opj)

A prediction of a normalised M_c is shown as a solid curve in Fig. 10, where J_{ss} = 2200 J/m^2 (assumed, for simplicity, to be constant within the mode mixity range) and E = 34 GPa. Recall, that this value of the fracture energy is determined at the *independently* small laboratory specimens [Sørensen et al., 2003]. The experimental data points, normalised according to (2), are also shown. There is a good agreement between predicted and measured values. The trend of h/H, decreasing normalised moment with increasing h/H, is predicted correctly. No attempts are made at this stage to predict the applied moment before the steady-state is reached. This will require a full numerical model, which include the cohesive laws. This is outside the scope of this investigation.

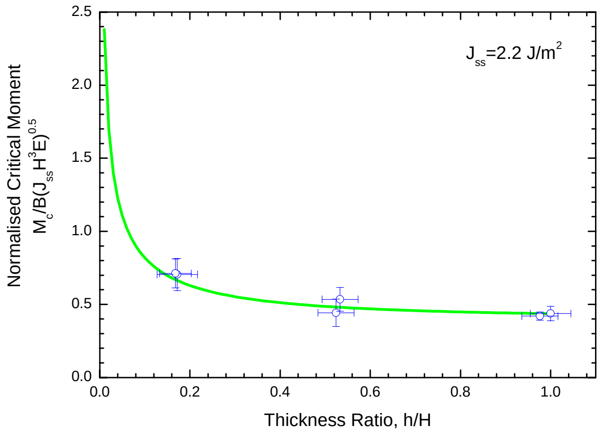

Figure 10. Predicted (solid line) and measured values (points) of applied moment at crack growth as a function of thickness ratio, h/H. (UCSB_thickness_1e.opj)

4 Summary and Conclusions

The fracture characteristics of medium-size adhesive joint specimens were measured experimentally. Except for one specimen, cracking took place just inside the external lamina of the laminate; for one specimen most of the cracking occurred (unstably) along the adhesive/laminate interface. The experiments suggest that under mixed mode conditions, cracking is most likely to occur inside the laminate although the fracture energy there may be significantly higher (due to fibre bridging) than along the adhesive/laminate interface. Independent measurements of fracture resistance of smaller laboratory specimens were used to predict the strength of the medium-size specimens, through a fracture mechanical model. The predicted load carrying capacity of the medium-size specimens were in good agreement with the measurements. The model, given by equations (1) and (2), was capable of predicting scale effects (effects of increasing the thickness ratio h/H), predicting that the normalised moment should decrease with increasing h/H.

Acknowledgements

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Abstract (max. 2000 characters)

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Descriptors INIS/EDB

ADHESION; BENDING; COMPOSITE MATERIALS; CRACK PROPAGATION; FIBERGLASS; FRACTURE MECHANICS; JOINTS; MECHANICAL TESTS; STRUCTURAL BEAMS;