Investigation of interlaminar behaviour in angled laminate beams with crease

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Abstract

Carbon/epoxy angled laminate beams with crease were studied for the effect of creasing on their interlaminar tension (ILT) and shear (ILS) behaviour. An angle of the beams was 110^0 with a circular bend radius of 76 mm. The single crease, involving two, three, or four plies, was on the exterior surface at the apex. Both control and creased specimens were evaluated under opening and closing moments. It was shown that for ILT and ILS were induced consistently by and opening and closing moments. It was found that the presence of 4 ply crease affected both ILT and ILS significantly in terms of failure load and stiffness.

1 Introduction

Fibre-reinforced laminated composites have been used extensively to fabricate large structural components with curved regions. The majority of those large laminate structures in use lack reinforcement in the through-the-thickness direction. Delamination could occur not only when induced local interlaminar stresses reach a critical level but also as bends or curvatures in the structures act as stress raisers causing stress concentrations. This could be compounded by the occurrence of manufacturing defects such as crease or wrinkle in the curved regions. Thus the interlaminar behaviour of the curved regions containing crease becomes very complicated and such regions could fail prematurely. Therefore, a thorough understanding of interlaminar behaviour in curved laminates is of paramount importance in [1-8] to ensure that large laminate structures with curved regions are designed to be lightweight and cost-effective but without a compromise of performance. Little is known about the effect of crease on the mechanical performance of the curved laminate structures [1]. In this paper, we will examine the effect of creasing on the interlaminar behaviour of the laminates as well as the effect of laminate thickness on the interlaminar behaviour of the intact laminates.

2 Design and fabrication of creased laminate specimens

To investigate the effect of creasing on interlaminar behaviour of angled laminate beams, two sets of moulds were designed and used to simulate not only a central angle of 110^0 with a circular bend radius of 76.2 mm for the beams, as illustrated in Figure 1, but also a crease at the apex of the angled region with varying severity. Such moulds allowed various creases (i.e.

the number of plies involved in the crease) with the same geometrical profile to be produced on the laminates, as indicated in Figure 2. The orientation of each crease was in the width direction of the beam where either maximum opening or closing moment was expected to occur. The apex of the angled region in control specimens was marked with a through-the-thickness line. The other details of moulds along with their illustrations are shown in [1].

Carbon/BMI CYCOM 5250/G803-40 prepreg with 5-harness satin weave was used for fabricating laminates with a nominal cured ply thickness of 0.275mm. While one intact laminate had 16 plies, the rest of laminates consisted of 8 plies in a symmetric lay-up of $[(0/90°)_F/(\pm45°)_F]_{2s}$. Prepreg sheets were cut to a size of 230×250 mm and were debulked regularly in a vacuum bag with two ply sublaminate stacks. Both male and female mould blocks were coated with release agent Frekote 55. Debulked sublaminate stacks were assembled in the female mould. For creased laminates, debulked plies that were involved in the crease were initially forced in the female block with the aid of a hot air gun and then the remaining sublaminate stacks were placed on the top of the creased plies with a peel ply finish on top. A curing of the laminates in an autoclave under a pressure of 36 psi (0.25 MPa) followed a two-stage curing cycle, i.e. dwelling at 140°C for 80 minutes and curing at 195°C for 200 minutes. The average thickness of the laminates was about 2.2 mm for 8 ply laminates and 4.5 m for 16 ply laminates.

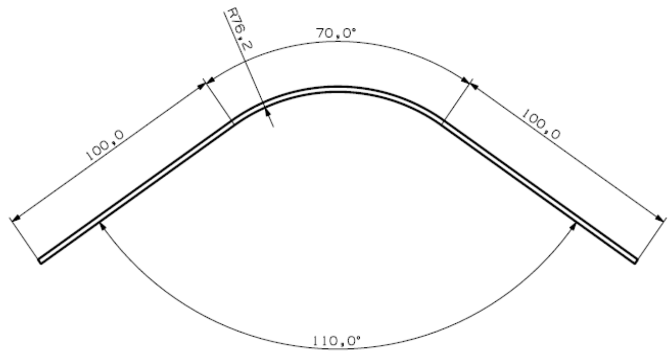

Figure 1: Dimensions of beam specimen

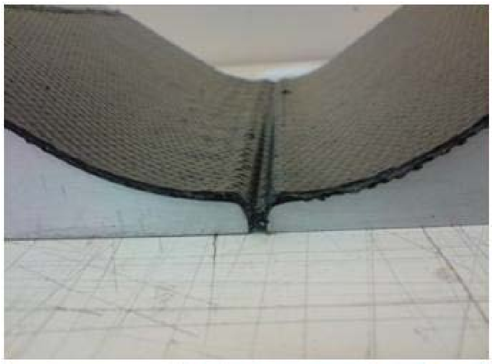

Figure 2: Creased plies in moulding block

3 Experimental setup and testing procedures

The laminates with the creases had the crests of the creases ground off using a tungsten carbide cutter. Then, laminate panels were cut into six (each 40 mm wide) or eight (each 30 mm wide) beam specimens, with a water-cooled diamond-coated blade. Those for ILS tests via compression had two holes drilled side by side in the width direction of the flat regions for the gripping purpose, using a tungsten carbide drill. Finally two single element strain gauges were bonded on the two surfaces of each specimen back to back at the apex in the longitudinal direction. Moreover, whereas no attempt was made to fill up void under the creased plies, the remaining non-creased plies remained flat after cure.

Testing fixtures for producing opening moment were achieved via flexure in four-point bending, as shown in Figure 3. Both loading and support contact cylinders used in this test had a diameter of 6.4 mm. Testing fixtures for producing closing moment consisted of two mechanisms linked by a hinge. One mechanism gripped the ends of two straight arms of each angled specimen and the other was connected to the testing machine, as shown in Figure 4. The whole fixture was allowed to rotate and self-align to force the clamped ends together during testing. The other details of moulds along with their illustrations are given in [1]. All flexure and compression tests were conducted at a loading speed of 5 mm/min.

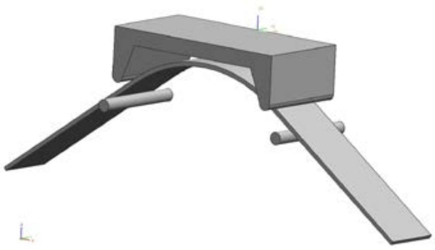

Figure 3: Illustration of tension flexure test setup

Figure 4: Illustrations of compression test setup

4 Discussion of results

4.1 ILT test results

Opening moment in flexure tests via four-point bending was to induce ILT in the curved region of specimens. Figure 5 shows the load-strain response of 8 ply control specimens. It is noticeable that the response was almost linear right up to ultimate failure where the tensile strains on the concave side levelled off. Moreover, the tensile strains were roughly the same as the compressive strains on the convex side. This indicates that a state of stress around the apex was close to pure bending. Therefore, the state of ILT became critical, as bending resistance was much greater. Following the procedure given in [8], the average ILT stress was calculated to be 5.1 MPa. Failure was almost catastrophic. Post-mortem observation of failed specimens shows ILT delaminations in addition to fibre fracture, as shown in Figure 6.

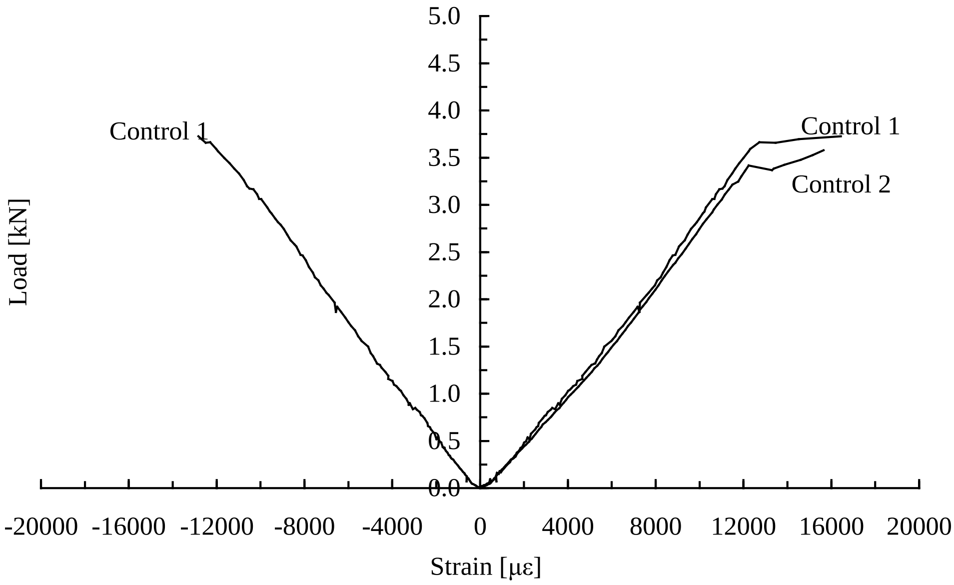

Figure 5: Load-strain curves for control specimens in flexure tests

Figure 6: Interlaminar tensile failure of an 8 ply control specimen

For 16 ply control specimens, their load-displacement responses are shown in Figure 7 along with the group of 8 ply control specimens. Their overall response chracteristics are almost identical. Failure was also catastrophic, with ILT delaminations in a failed specimen being shown in Figure 8.

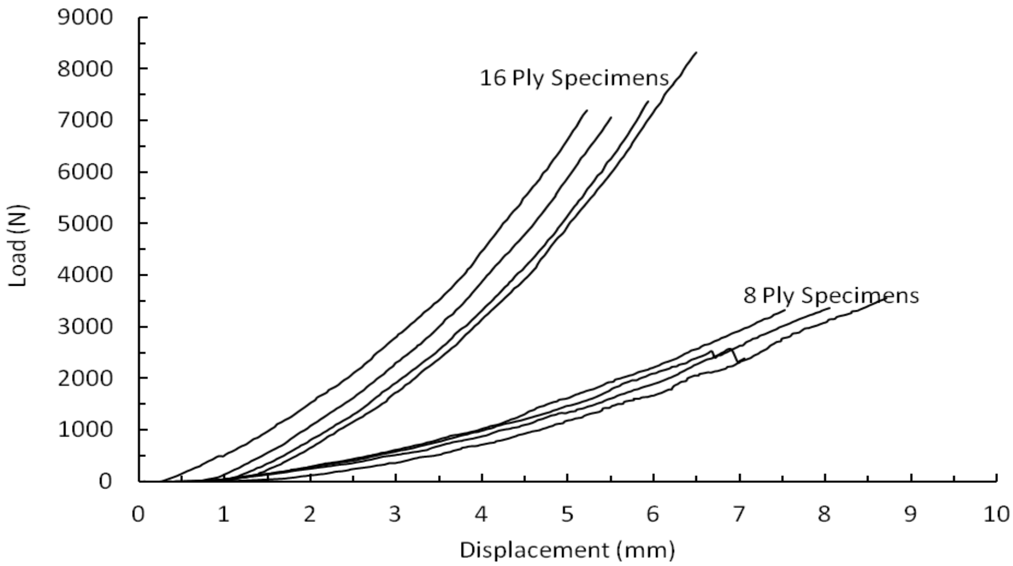

Figure 7: Load-displacement responses for control specimens of both 8 ply and 16 ply in flexure

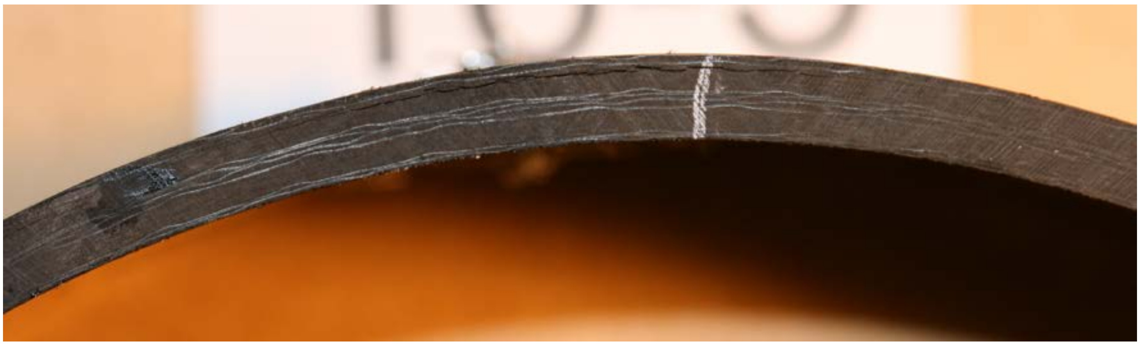

Figure 8: Interlaminar tensile failure of a 16 ply control specimen

Figure 9 shows a comparison of load-strain responses of both control and 4 ply creased specimens. The effect of creasing in the specimens has caused the significant reduction of not only stiffness but also failure load. The loss of the failure load due to the presence of 4 ply crease was more than 40%. A failed creased specimen is shown in Figure 10. In addition, the slopes of load-displacement curves from both control and creased specimens as shown in Figure 11 do not seem to show much defference.

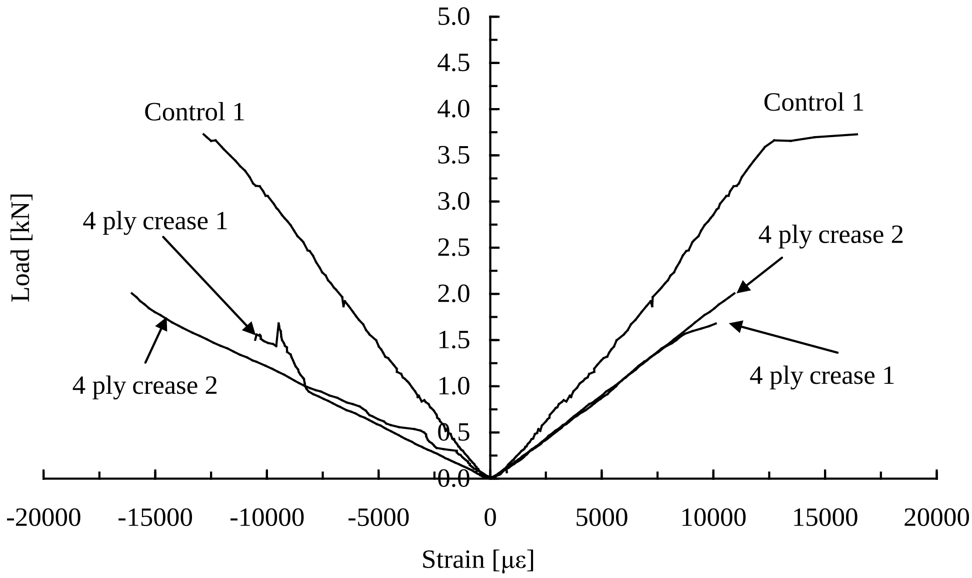

Figure 9: Load-strain curves for 8 ply creased and control specimens in flexure

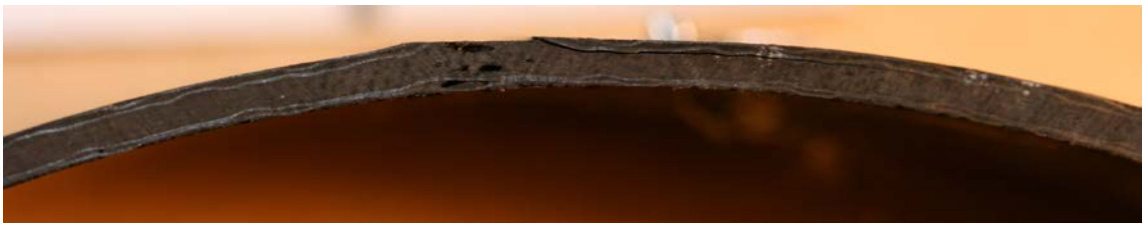

Figure 10: Interlaminar tensile failure of an 8 ply specimen with a 4 ply crease

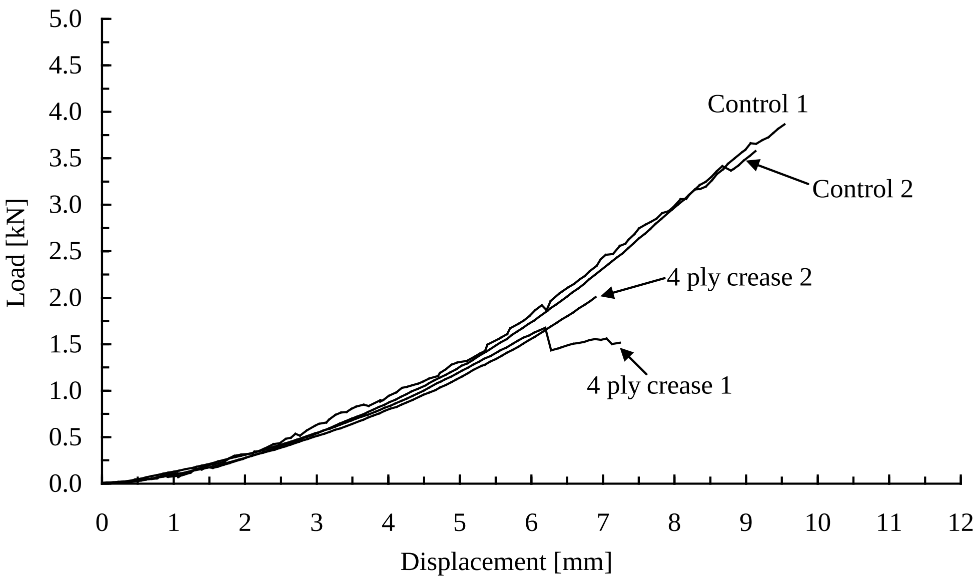

Figure 11: Load-displacement curves for control and creased specimens in flexure

4.2 ILS test results

Closing moment in compression tests was to induce ILS in the curved region of specimens. Figure 12 shows the load-strain responses of control specimens with closing moment. The responses were slightly nonlinear and the strains on the concave side were just fractionally greater than those on the convex side. It is unclear whether the observed nonlinearity reflected the behaviour of the angled region or potential bending of the straight arms. The corresponding average strain at failure was around 1.25%. As the curvature of the angled region increased with load, the average peak load of only 0.21 kN was low. Post-mortem observation of the failed specimens in Figure 13 shows interlaminar shear-driven delaminations followed by fibre fracture at the apex of the angled region.

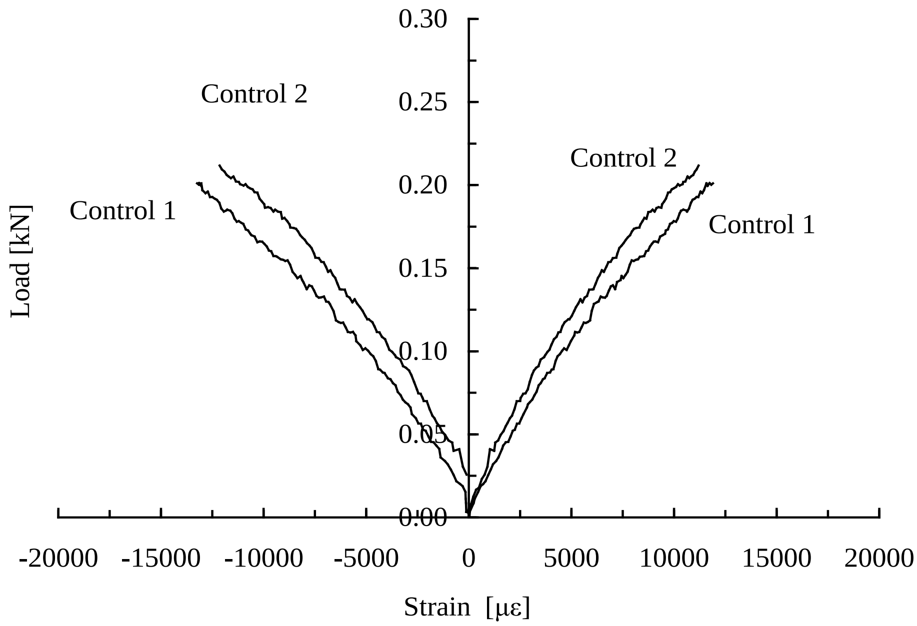

Figure 12: Load-strain curves of control specimens from closing moment tests

Figure 13: Interlaminar shear failure of an 8 ply control specimen

Doubling the thickness of 8 ply control specimens enhanced the perforamnce of 16 ply control specimens in terms of load and stiffness, as shown in Figure 14 via the examples of two groups of tests. However, nonlinearity in the load-displacement responses of 16 ply control specimens is still observed. This seems to suggest that this observed nonlinearity from the thicker specimens was most likely to be caused by a closing of the angled regions. A typical failed specimen is shown in Figure 15.

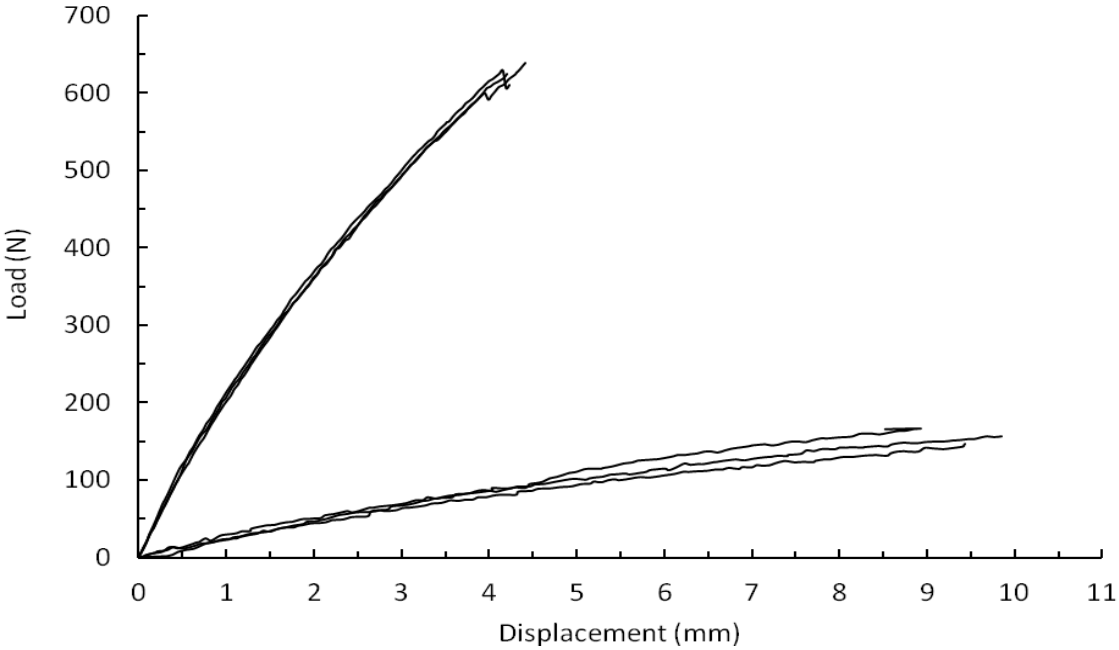

Figure 14: Load-displacement responses for control specimens of both 8 ply and 16 ply in flexure

Figure 15: Interlaminar shear failure of an 8 ply specimen with a 4 ply crease

As a 4 ply crease in the tensile side of the specimens was subjected to closing moment, it could be even more vunerable. Figure 16 shows a comparison of load-strain responses between control and creased specimens. The creased specimens show the significant reduction of not only stiffness but also failure load. The effect of creasing on the ILS behaviour seemed significant. The only half of the failure load was retained due to the presence of 4 ply crease. A typical failed creased specimen is shown in Figure 17.

5 Concluding remarks

The effect of creasing in 8 ply angled laminate beams has been investigated through both ILT and ILS. Interlaminar tension was induced through opening moment, whereas interlaminar shear was induced closing moment. ILT and ILS behaviour was complex, as it was dominated by substantial nonlinearity in both cases. This was examined further by using thicker intact beams. The nature of nonlinearity in their load-displacement or load-strain responses was attributed to the direct response of the angled regions. The presence of 4 ply crease in angled laminates caused the significant degradation in both strength and stiffness.

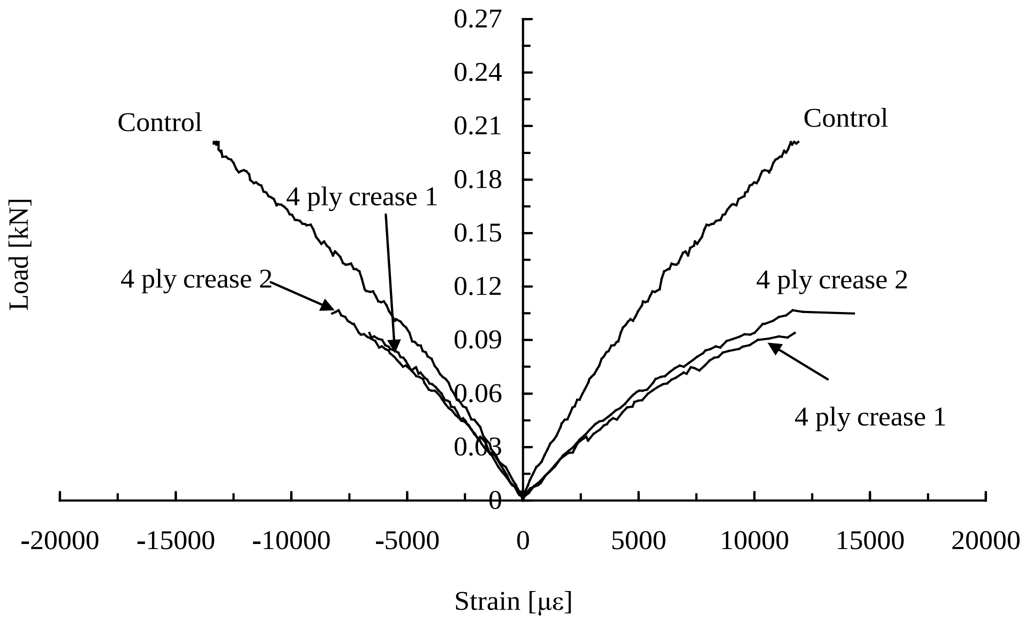

Figure 16: Load-strain curves for control and creased specimens from closing moment tests

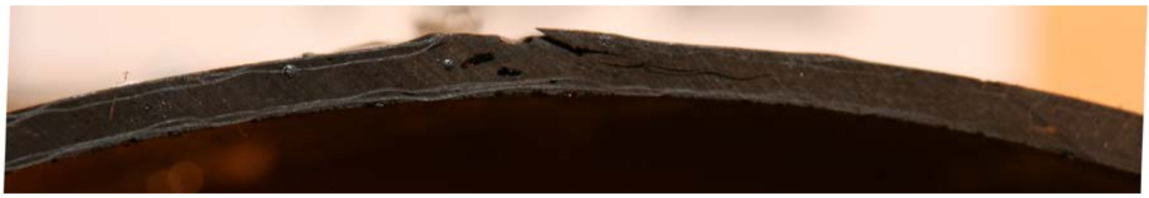

Figure 17: Interlaminar shear failure of an 8 ply specimen with a 4 ply crease

References

[1] Zhou G., Aspinall B., Nash P. *Study of interlaminar tensile and interlaminar shear behaviour of angled laminate beams* in "Proceedings of 14th ECCM", Hungary (2010).

[2] Kedward K.T., Wilson R.S., McClean S.K. Flexure of simply curved composite shapes. *Composites*, **20**, 527-536 (1989).

[3] Hiel C.C., Sumich M., Chappell D.P. A curved beam test specimen for determining the interlaminar tensile strength of a laminated composite. *Journal of Composite Materials*, **25**, 854-868 (1991).

[4] Martin R.H. Delamination failure in a unidirectional curved composite laminate. In *Composite Materials: Testing and Design ASTM STP* **1120**, 365-383 (1993).

[5] Shivakumar K.N., Allen H.G., Avva VS. Interlaminar tension strength of graphite/epoxy composite laminates. *AIAA Journal*, **32**, 1478-1484 (1994).

[6] Cui W., Liu T., Len J., Ruo R. Interlaminar tensile strength measurement of woven glass/polyester laminates using 4-point curved beam specimen. *Composites Part A*, **27**, 1097-1105 (1996).

[7] Jackson W.C., Ifju P.G. Through the thickness tensile strength of textile composites. In *Composite Materials: Testing and Design ASTM STP* **1274**, 219-238 (1996).

[8] Layne A.M., Carlsson L.A. Test method for measuring strength of a curved sandwich beam. *Experimental Mechanics*, **42**, 194-199 (2002).

[9] Anon. *Standard test method for measuring the curved beam strength of a fiber-reinforced polymer-matrix composite*. ASTM Standard D 6415/D6415M-06.