Investigation of interlaminar resistance of angled laminate beams

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Introduction

Delamination occurs in composite laminates when induced interlaminar stresses reach a critical level. Such stresses could become greater around curvatures or bends, causing stress concentrations. It could be compounded if the curved or angled region of the laminates has got creases or wrinkles. Such regions have very complex interlaminar behaviour and could fail prematurely. Thus, a thorough understanding of the interlaminar behaviour in curved laminates is of paramount importance to ensure that large laminate structures with curvatures or bends are designed to be lightweight and cost-effective. As little is known about the effect of crease on the interlaminar performance of the curved laminate structures, in this paper, we will design and manufacture angled laminates with crease and investigate its effect on their interlaminar tension (ILT) and shear (ILS) behaviour.

Specimen design and manufacturing

A carbon/BMI prepreg was used to fabricate angled laminates with a nominal size of 230×250 mm, as shown in Fig. 1. Two types of angled laminates were fabricated, intact or control and creased, all in a symmetric lay-up of $[(0/90°)_F/(\pm45°)_F]_{2/4s}$ with a central angle of 110^0. Intact laminates had either 8 or 16 plies. Creased laminates were made to contain either a 2-ply or 4-ply crease on the convex side. All plies were split into a number of sublaminate stacks with two plies in per stack and were debulked in a vacuum bag. The lamination of control laminates was a simple assembly of the debulked sublaminate stacks into the female mould block. The 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 8-ply laminates was about 2.2 mm, whereas it was about 4.3 mm for 16-ply laminates.

Experimental setup and testing procedures

The crest of the crease in the angled laminates was ground off, as shown in Fig. 2. Every laminate panel was then cut into a number of specimens. Those for compression tests had two holes drilled side by side in the width direction of the flat regions for the gripping purpose. Strain gauges were bonded on the two surfaces of each specimen back to back at the apex in the longitudinal direction.

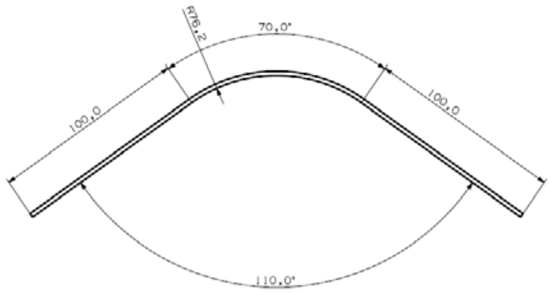

Fig. 1 Dimensions of beam specimen

Fig. 2 Removed crest of a crease

ILT in the angled region was induced through flexure testing via four-point bending. A steel loader constructed from a U-channel section was designed to be almost rigid. ILS in the angled region was created by direct compression through straight arms. The compression loading system was self-aligned under load. Tests for both were conducted at a loading speed of 5 mm/min.

Discussion of ILT test results

Opening moment in flexure tests via four-point bending induces ILT in the angled region. Fig. 3 shows the load-strain responses from both control and creased specimens. It is noticeable that the response was almost linear right up to ultimate failure. While the tensile strain on the concave side of the control specimen shows a slight steepening, the compressive strain(s) on the convex side is linear up to failure. Moreover, the tensile strains were roughly the same as the compressive strain. Following the procedures given in [1], the average ILT stress was calculated to be 5.1 MPa. The corresponding strain at failure of 1.24%. Post-mortem observation of the failed specimens shows ILT-driven delaminations in addition to fibre fracture in the angled region, as shown in Fig. 4. The 4-ply creased specimens show the significant reduction of slope and failure load of about 40%. Delamination was initiated by the crease, as a failed creased specimen is shown in Fig. 5.

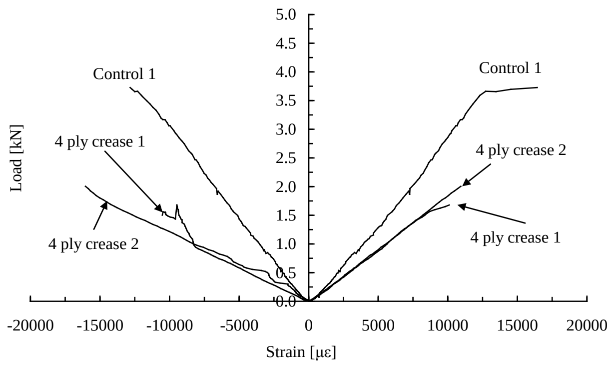

Fig. 3 Load-strain curves for creased and control specimens in flexure tests

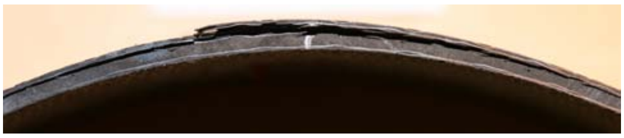

Fig. 4 A failed flexure control specimen

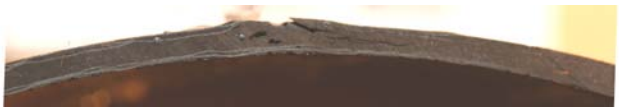

Fig. 5 A failed flexure 4-ply crease specimen

Discussion of ILS test results

Compressive load forms an angle with the two straight arms of an angled specimen. While one load component exerts in-plane compression, the other component induces a closing moment to the angled region. As the closing moment increased with load, unlike the direction tension [2], the contribution of compression resistance to the state of ILS in the angled region seemed limited. In Fig. 6, the strains on the concave side from the control specimen were just fractionally greater than those on the convex side, which was in accordance with the theoretical prediction [2]. The average strain at failure was 1.22%. Post-mortem observation of the failed specimens in Fig. 7 shows ILS-driven delaminations followed by fibre fracture at the apex of the angled region. With the crease in the tensile side of the creased specimens, the creased specimens showed the significant reduction of not only slope but also failure load. The effect of crease on the ILS behaviour was significant. The only half of the failure load was retained due to the presence of four-ply crease. Noticeably, the fact that the strains at failure on the convex side between control and creased specimens were rughly the same suggests that it was delamination that led to the catastropic failure.

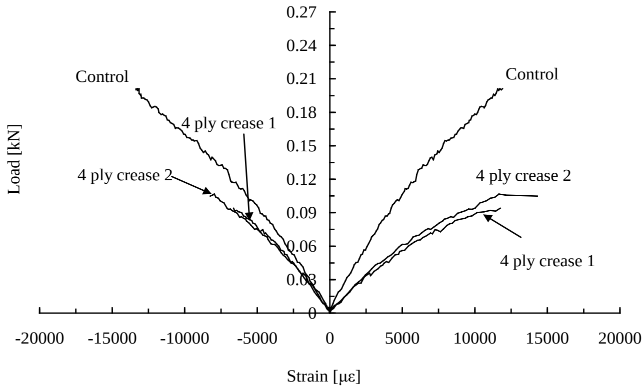

Fig. 6 Load-strain curves for control and creased specimens in compression test

Fig. 7 A failed flexure control specimen

Concluding remarks

ILT behaviour was found to be linear up to failure. Whereas ILS behaviour was complex due to combined stresses, the presence of 4-ply crease in angled laminates caused significant reduction in both strength and modulus.

References

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

[2] Zhou G., Haworth J. and Aspinall B. Study of interlaminar shear and interlaminar tensile behaviour of angled laminate beams, *Proc. of ECCM 14*, Budapest, June 2010.