FATIGUE FAILURE OF A COMPOSITE SANDWICH BEAM CONTAINING A CENTRAL NOTCH

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ABSTRACT

Sandwich panel specimens, consisting of glass fabric/epoxy resin skins co-cured to an aluminium honeycomb core, have been tested in four-point flexural fatigue loading. The beams had a through-thickness hole with a diameter equivalent to approximately three cell diameters. There were two regimes of fatigue failure. For higher peak fatigue loads, producing failure in less than 10,000 cycles, failure occurred by the initiation and propagation of fatigue cracks from the hole in the compressive skin of the sandwich panel. For lower peak fatigue loads and longer fatigue lives, failure occurred by the catastrophic propagation of a crack on the tensile face of the beams, with no prior evidence of macroscopic damage. Preliminary microscopic analysis suggests that failure on the compressive face was due to the initiation and growth of a local buckling failure.

1. INTRODUCTION

Composite materials provide excellent in-plane properties of strength and stiffness for low weight, but flexural properties can be improved significantly by using a sandwich construction with the composite materials as the faces bonded to a lightweight core. The faces can be adhesively bonded to the core or, as in the aluminium honeycomb-core material used in this study, the bond between the faces and the core can be formed during co-curing. While sandwich constructions are finding increasing applications in aerospace, sandwich panels have been widely used in marine applications for many years [1].

In general, the quasi-static properties of sandwich panels appear to have received much more attention than the fatigue properties, both for undamaged panels and for panels with introduced defects. In the fatigue investigations, the choice of a wide range of skin materials, core materials and test techniques (usually either three-point or four-point loading) has meant that experimental and theoretical understanding of the behaviour of one type of sandwich panel construction in fatigue may not be applicable to other types of construction, and a range of failure modes have been observed. For example, Belingardi and colleagues [2] tested honeycomb sandwich beams under both quasi-static and fatigue loading (four-point bending), using either initially undamaged beams or with damage introduced before testing (skin/core interface debonding). They found that for initially undamaged beams, failure occurred by local buckling on the compressive face of the beam. For specimens with partially debonded skins, failure occurred due to cell wall fracture at the intersection of the undamaged and damaged material. Various failure modes were found by Harte and colleagues [3] (during the fatigue failure of sandwich panels consisting of aluminium foam cores and aluminium alloy skins) by varying the face and core thicknesses, together with the roller spacings in four-point bending. Failure modes included fatigue failure of the tensile face, indentation fatigue of the foam core, and core shear failure. By contrast, Kulkarni and colleagues [4], testing a sandwich panel consisting of a PVC foam core and glass epoxy skins in three-point bending fatigue, found a sequence of failure which began with a delamination on the compression face, near the core/skin interface, which then propagated to the tensile interface as a core shear crack. The fatigue strength was found to increase with increasing core density, for a similar sequence of failure [5]. Early work on the fatigue behaviour of beams having a honeycomb core (aluminium or paper) with aluminium alloy skins [6], tested in three-point loading, found failure to be by the initiation and growth of fatigue cracks in the aluminium skins.

In this paper, preliminary results are reported on the failure in fatigue of sandwich panel specimens (GFRP skins and an aluminium honeycomb core) containing a through-thickness hole.

2. EXPERIMENTAL METHODS

2.1 Materials

The sandwich panel consisted of woven Glass Fibre Reinforced Plastic (GFRP) faces with a hexagonal aluminium honeycomb core, supplied by Technical Resin Bonders Ltd. The faces consist of two layers of plain woven glass fabric-reinforced epoxy resin which is co-cured to an aluminium honeycomb core (single-wall thickness 0.076 mm) with an average hexagonal cell diameter of 6 mm. The thickness of the honeycomb core was 25.4 mm and the glass/epoxy faces were about 0.5 mm thick. Specimens cut from the panel with a water-cooled diamond blade cutter, had dimensions of 500 mm x 70 mm and the double-wall thickness of the hexagonal honeycomb core was always parallel to the long dimension of the specimens. A defect consisting of a circular through-thickness notch of diameter 15 mm was cut in the centre of the sample.

2.2 Testing

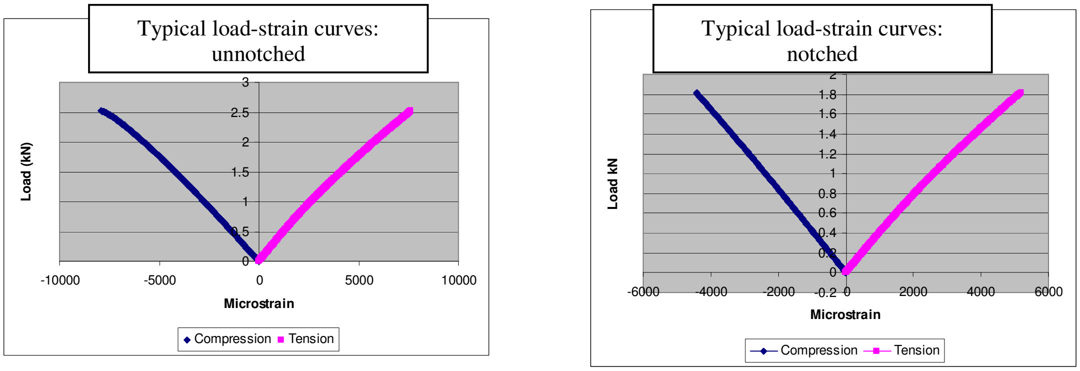
Four-point bend tests under quasi-static or fatigue loading were carried out with an inner roller spacing of 215 mm, and outer rollers 430 mm apart. To prevent damage at the rollers, four protective steel plates with dimensions 70 mm x 12 mm x 2 mm were bonded using DP490 adhesive to the specimens at the position of the rollers. The rollers also included shoulders to prevent sideways movement during testing. In addition, a 7 mm diameter pin extended from one of the outer rollers through a hole in one protective steel plate, and through a pre-drilled hole in both faces of the sandwich panel, to prevent lateral movement of the specimen during fatigue cycling. All tests, both quasi-static testing and fatigue testing were carried out using an Instron 1341 computer-controlled servohydraulic fatigue machine. The specimens were instrumented with two strain gauges to measure longitudinal strain, one on the tensile face and the other on the compressive face. For specimens without holes, the strain gauges were positioned on both faces at the centre of the specimens; for specimens with holes, the strain gauges were located mid-way between the hole and the inner roller. Fatigue tests were carried out at a frequency of 2 Hz. A camera was mounted on a tripod near to the fatigue machine to record the development of damage. Microscopic investigations included burning away the matrix of the composite faces in order to investigate damage in the glass fabric layers.

3. RESULTS and DISCUSSION

3.1 Quasi-static testing

Typical load-strain curves for the unnotched specimens are shown in Figure 1(a). The figure shows the load plotted against the longitudinal strains measured on the compressive and tensile faces. In general, these curves were non-linear above about 1000 με. Above about 3000 με, the strain measured on the tensile face was slightly higher than on the compressive face, with a strain to failure on the tensile face of 8000±400 με and on the compressive face, 7600±100 με, for an average load to failure of 2.55±0.09 kN. Under quasi-static loading, a catastrophic failure occurred on the compressive face, anywhere within the region of constant bending moment between the inner rollers. The fracture line extended roughly parallel to the width direction of the specimen, with an overlapping of the face material occurring at the fracture line.

The notched specimen also failed by local buckling, but this time the fracture always propagated through the notch and was presumably initiated by local buckling [7]. Typical load–strain curves for notched specimens are shown in figure 1(b). The mean failure strain (and standard error) measured for the notched specimens were 5700±400 με (tensile face), 5400±200 με (compressive face) with a failure load of 1.95±0.06 kN. Interestingly, the notched failure load is 24% lower than the unnotched failure load which is very close to the reduction in the net-section cross-sectional area due to the hole (21%), suggesting that the sandwich panel is only very slightly notch-sensitive for this diameter of hole. The face material at the fracture line again overlapped after failure.



(a) (b)

Figure 1: Typical load-strain curves to failure in quasi-static loading for (a) unnotched and (b) notched specimens

3.2 Fatigue testing

The fatigue test results are shown as normalised S-N curves in figure 2, where the peak fatigue load has been normalised by the average quasi-static failure load. The fatigue test results divide into two regions. Region 1 refers to the higher peak fatigue loads, which correspond to peak fatigue loads above 70% of the quasi-static failure load. In this regime, all of the specimens failed by the development of cracks which initiated on the compressive face of the specimens from the notches; these cracks grew stably as fatigue cracks and grew across the remaining ligament width on each side of the hole until catastrophic failure occurred. For a peak fatigue load which was 90% of the quasi-static failure load, the number of cycles to failure varied between 65 cycles and 930 cycles. At 75% of the quasi-static failure load, the number of cycles to failure varied between 260 and 6100.

In Region 2, i.e. for peak fatigue loads equal to 70% or less of the peak quasi-static failure load, the number of cycles to failure was considerably higher. For example, for a peak fatigue load 70% of the quasi-static failure load, the number of cycles to failure varied between 22,500 and 31,000; for 60%, the number was between 17,500 and 75,000. Furthermore, in Region 2, failure of the sandwich panels occurred on the tension face of the sandwich panel, suddenly and catastrophically, without any obvious evidence of damage prior to catastrophic failure.

Figure 3 shows examples of the failed specimens in Region 1 (figure 3(a); compressive face), and Region 2 (figure 3(b); tensile face).

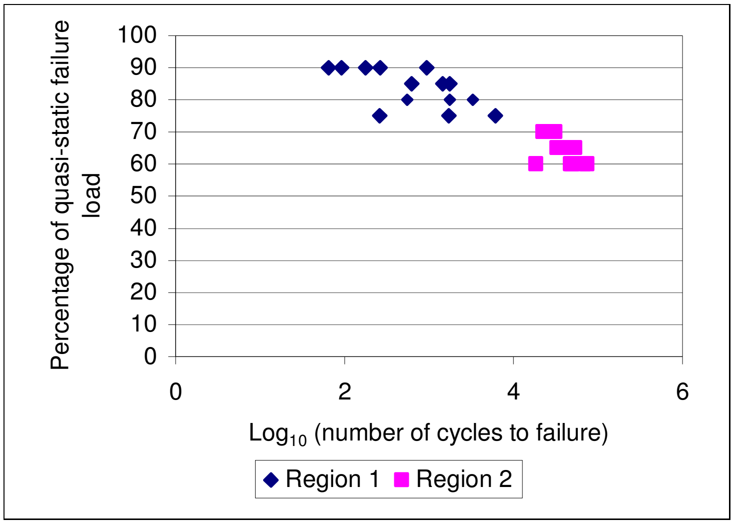
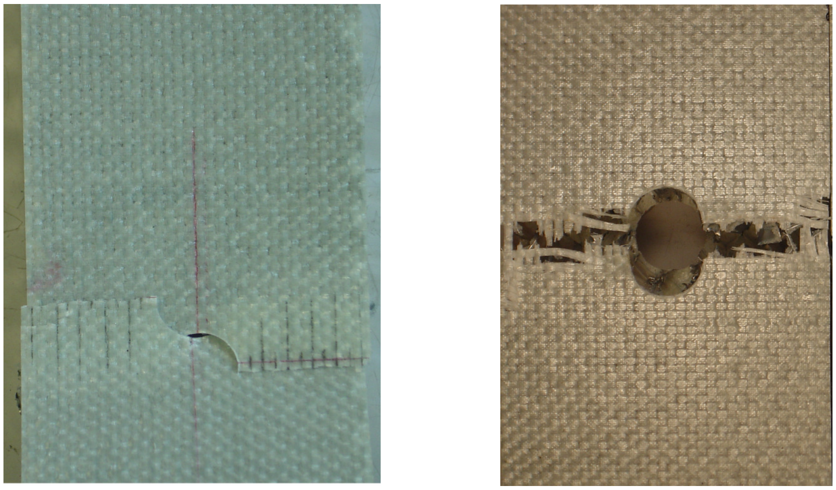


Figure 2: S-N curve for the failure of the fatigue failure of the sandwich panels showing Region 1 (failure on compressive face) and Region 2 (failure on tensile face).

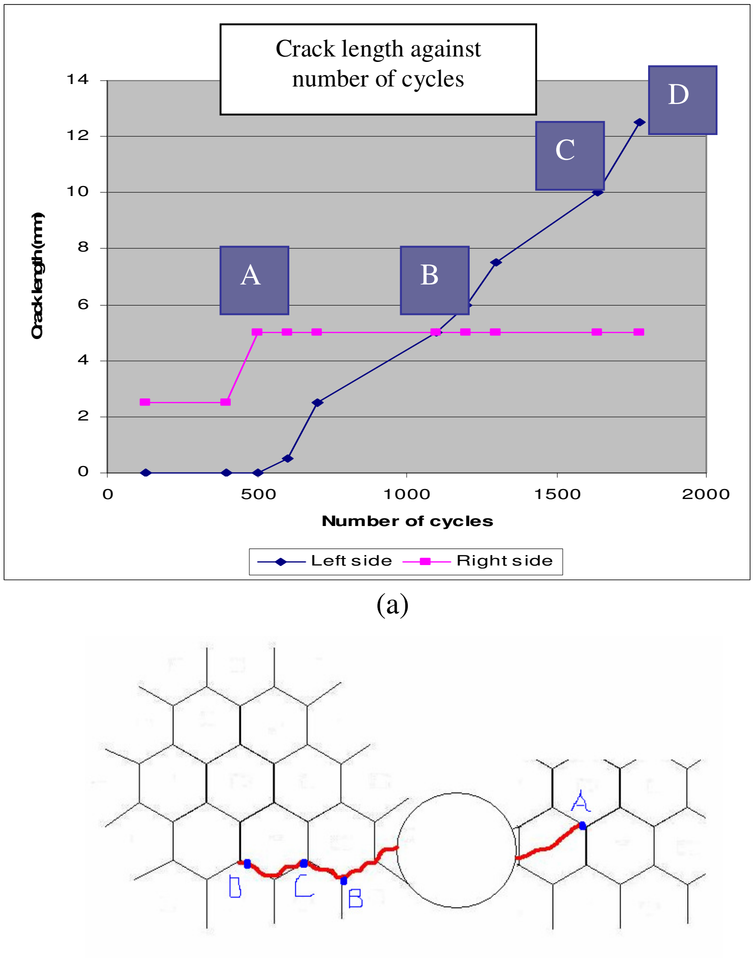


(a) (b)

Figure 3: (a) Compressive face of specimen after fatigue failure (Region 1). (b) Tensile face of specimen after fatigue failure (Region 2). The specimens are 70 mm wide.

3.3 Damage observations on failure in the compressive face (Region 1) due to fatigue loading

Failure of the beams with peak fatigue loads above 70% of the quasi-static failure load occurred in two stages: slow growth of fatigue cracks initiating from the notch, followed by catastrophic failure. Figure 4 shows an example of the increase in the length of cracks in a specimen tested with a peak fatigue load 80% of the quasi-static strength. As figure 4(a) shows, the crack on the left side of the notch initiated after about 500 cycles and grew slowly, to a length of about 5 mm after 1100 cycles (point B in figure 4(b)), and then continued to grow slowly to point D over the next 700 cycles. By contrast, the crack on the right side of the notch grew to a length of 5 mm (point A) after about 500 cycles, but then did not grow further. The specimen failed when the combined length of the cracks, together with the 15 mm diameter initial notch, was about 33 mm. The paths of the crack growth in relation to the underlying core structure are shown in figure 4(b). These paths can be determined because the GFRP skins are sufficiently transparent for the honeycomb core to be seen using high intensity transmitted light.



(a)

(b)

Figure 4: (a) Growth of cracks on the left and right sides of a hole for a beam fatigue loaded with a peak load 80% of the quasi-static failure load. (b) Path of crack growth relative to the aluminium honeycomb core.

Sectioning the specimens perpendicular to the direction of the crack growth in the compressive skins, suggested that the fatigue cracks grew as tow buckling failures which propagated during fatigue cycling. Figure 5 shows the result of a burn-off test on the compressive skin of a specimen, showing the inner layer of the two-layer fabric of the skin after the initiation and growth of a fatigue crack; the hole is on the left of the image. It can be seen that the crack has fractured about 8 tows as it propagated a distance of about 18 mm across the width of the specimen from the hole. It appears that the growth of the fatigue damage on the compressive face of the sandwich beam from the hole is similar to the microbuckling initiation and growth seen in notched CFRP laminates [8].

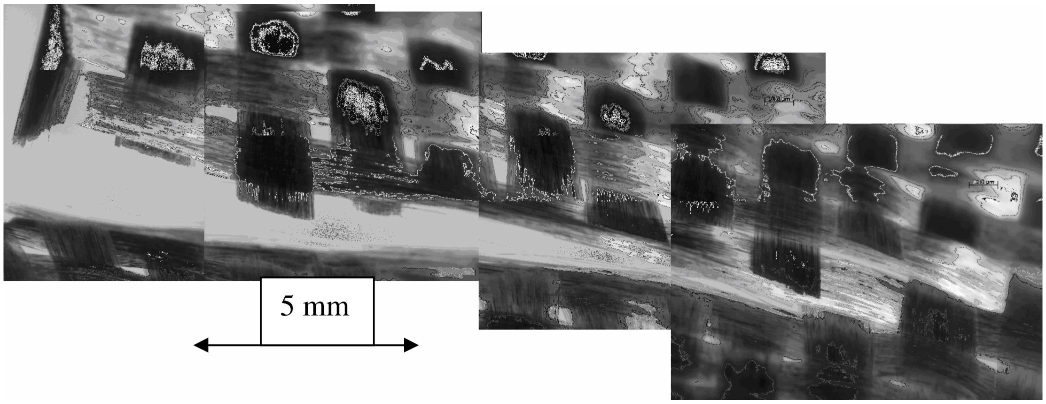


Figure 5: Tow fractures in a layer of woven-glass fabric on the compressive face of a beam as a consequence of crack propagation in fatigue.

4. CONCLUSIONS

Specimens from a sandwich panel having glass fabric reinforced epoxy resin skins co-cured to an aluminium honeycomb core, and with through-thickness holes, have been tested under quasi-static and fatigue loading in four-point bending. The quasi-static strength measurements indicate that the beams are only slightly notch sensitive to the presence of a 15 mm through-thickness hole (equivalent to about three cell diameters).

For the fatigue tests on specimens containing holes, peak fatigue loads between 60% and 90% of the mean quasi-static failure load have been used and two regimes of failure have been identified. For tests with peak fatigue loads greater than or equal to 75% of the quasi-static failure load, failure occured by the initiation and propagation of cracks from the edges of the holes on the compressive face of the beam. The fatigue cracks appear to propagate as local buckling failures. For peak fatigue loads less than or equal to 70% of the quasi-static failure load, failure occurred catastrophically, and without any obvious indication of prior damage, on the tensile face of the beam.

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