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Characterisation of damage development in single-shear bolted composite joints

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ABSTRACT

Experiments have been performed to study the force-deflection and damage development characteristics of bolted joints in carbon/epoxy composite materials, in the presence of variable bolt-hole clearance. Single-lap, single-bolt joint configurations, sized to induce bearing failure were used. An initial set of tests involved loading joints up to ultimate failure. The primary failure mode was bearing failure. The secondary failure mode was bolt failure for the lower clearance joints, while the larger clearance joints exhibited large displacements without bolt failure. A further series of tests were then performed up to a load level corresponding to the first significant change of slope in the load-deflection curve of the larger clearance joints. These specimens were examined using optical microscopy and SEM to compare the damage in specimens with different levels of clearance. The joints with the largest clearance were found to exhibit the most damage.

Keywords: Bolted Joints, Composites, Clearance, Bearing Failure, Progressive Damage

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1. INTRODUCTION

Mechanical fastening remains the primary means of joining composite components in modern aircraft structures, due in part to the need for disassembly, inspection and repair. Naturally, the introduction of holes has a severe impact on the strength of the

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structure, and the importance of designing efficient bolted joints in composite structures is reflected in the extensive literature that has built up on the subject over the last 30 years. For two excellent reviews of the literature, see [1,2].

Design of bolted joints in composite materials involves a higher level of complexity than that in metals, due to the almost unlimited combinations of composite materials and fibre patterns, and the fact that bolted joints in composites fail at loads that are not predicted by either perfectly elastic or perfectly plastic assumptions. Previous work has characterised the various failure modes and identified the dominant factors and parameters associated with such joints [3,4]. The principal failure modes are shown schematically in Fig. 1. Composite joints in aeronautical applications are designed to fail in bearing or net tension (Fig. 1(a) and 1(d)). Shear-out can generally be avoided by suitable choice of lay-up and edge distance, while pull-through is not common in shear-loaded joints, and fastener failure frequently occurs as a secondary mode after bearing failure has occurred. Bearing failure occurs due to compressive forces acting at the hole boundary and involves crushing of the laminate material in contact with the fastener. Failure occurs progressively with increasing load, so is non-catastrophic. Bearing failure occurs when the ratio of hole diameter to joint width (d/w) is low, or (in multi-bolt joints) when the ratio of by-pass load to bearing load is low. It is strongly affected by lateral constraint (i.e. clamping force due to bolt torque), since lateral constraint prevents the delamination of plies and buckling of fibres.

Analyses of joints to date have frequently been two-dimensional [5-10]. However, in some cases (e.g. single-lap joints or joints with countersunk fasteners) stresses vary significantly through the laminate thickness with highly localised peaks, which initiate failure. The bearing failure mode itself is a three-dimensional phenomenon in which interply normal and shear stresses play a large part [1]. For these reasons, three-dimensional analysis methods are becoming more common [11-15].

To support development of such analysis methods, an experimental programme is being performed to characterise joint behaviour in single-lap, composite joints. To accentuate the three-dimensional variations in the stress distributions, variable bolt-hole clearance is being considered. Both single-bolt and multi-bolt joints will be studied. The objective of this paper is to present data generated during tests involving single-bolt, composite joints with varying bolt-hole clearances, loaded quasi-statically in tension. The single-lap, single-bolt joint is one of the standard configurations for characterisation of mechanically fastened composite joints in MIL-HDBK-17 [16, 17], and in ASTM standard D 5961/D 5961M - 96, Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates [19]. MIL-HDBK-17 states that the single-lap configuration is more representative than the double-lap configuration of most critical aircraft bolted joint applications. Single-lap joints result in significant stress concentrations in the thickness direction and lower bearing strengths than in double-lap joints [17].

The joints in this study were sized to induce bearing failure. Results presented include force-deflection curves as well as analysis of damage using optical microscopy and SEM. The work forms part of the European Commission research programme BOJCAS: Bolted Joints in Composite Aircraft Structures [19].

2. EXPERIMENTAL METHODS

The joint type was single-lap, single bolt with the test procedure and joint geometry based on the ASTM standard D 5961/D 5961 M – 96, [19]. The specimen geometry is shown in Fig. 2. The laminate thickness was at the upper end of the range allowed in the standard (between 3 and 5 mm), while all ratios were in accordance with the standard (e.g. w/d = 6, e/d =3, d/t = 1.6). The relatively large thickness was chosen to maximise the three-dimensional effects introduced to the joint during loading. In order to avoid premature bolt failure and obtain bearing as the primary mode of failure, an 8 mm (nominal) diameter bolt was chosen giving a d/t ratio of 1.6. The remaining specimen dimensions then followed from this ratio.

The carbon fibre/epoxy material used was HTA 6376, manufactured by Hexcel (UK), a current high-strength material used in the aircraft industry. The lay-up for the tests was balanced, symmetric and quasi-isotropic, consisting of forty plies and yielding a nominal laminate thickness of 5.2 mm when cured. The bolts used were titanium alloy aerospace grade fasteners of a protruding head configuration. Their nominal diameter was 8 mm, with an f7 ISO tolerance. A steel nut was also used, together with steel washers at both the head and nut side of the joint.

The varying bolt-hole clearances (see Table 1) were obtained by using constant diameter bolts and variable hole diameters. Four reamers of different diameters, machined to a tight H6 tolerance, were used to finish the holes. Since there is a tolerance on both the bolts and the reamers, the clearance values shown in Table 1 are nominal clearances. However, the tight H6 tolerance (0 to +9 μm from nominal diameter) on the reamers ensured that the hole diameters would be very close to nominal. Clearance Cl was intended to be a neat-fit. Clearance C2 represents the upper range of the ISO fitting f7/H10, which is used by at least one European aircraft manufacturer. The f7 fitting for the 8 mm bolts in this study allows a tolerance of -13 μm to -28 μm on the nominal diameter (i.e. the bolt diameter is allowed to vary between 7.972 mm and 7.987 mm). The H10 tolerance on an 8 mm hole allows a tolerance of 0 to +58 μm on the nominal diameter (i.e. the hole diameter is allowed to vary between 8 mm and 8.058 mm). Combining these two tolerances gives a range of allowable bolt-hole clearances of 13 μm to 86 μm for the f7/H10 fitting. Clearance C3 represents, according to DiNicola and Fantle of United Technologies-Sikorsky Aircraft [20], the upper end of clearances found in aerospace primary structures. Clearance C4 is larger than normally found in aerospace structures but was studied to examine an out of tolerance situation (e.g. due to manufacturing defects or in-service undetected damage). A low torque level of 0.5 Nm was applied to the bolts using a calibrated torque wrench. This was to simulate “finger tight” conditions in order to analyse the worst-case scenario of a bolt loosened during fatigue loading from an initial fully torqued condition. In this paper, results from experiments using C1 and C4 clearances are presented.

For consistency in testing (especially for the larger clearance specimens), a mounting jig was designed to locate the bolt in the centre of the hole. The form of the nut and outside diameter of the washer was machined out of the fixture to a tight tolerance (Fig. 3(a)), and assembly began by placing the nut and bottom washer in this hole forming a snug fit (Fig. 3(b)). The laminates were then placed loosely on top, as shown in Fig. 3(c) and 3(d), and a threaded pin of the same diameter (to a very tight tolerance) as the reamer used to finish these particular laminates was inserted through the specimens and screwed into the nut until the joint was tight - see Fig. 3(e). This ensured the correct positioning of the laminates. A plate was then placed on top and the laminates were clamped in position. The pin was then retracted and the bolt plus upper washer inserted and torqued (Fig. 3(f)). The joint was then removed from the fixture.

Testing was performed on a 100 kN RK DARTEC universal straining frame. Hydraulic grips were used to grip the specimens and were capable of being offset, which eliminated the need for tabs on the single-lap specimens. The test setup is shown in Fig. 4. Two Epsilon extensometers were employed to record the extension across the bolted region of the specimens, and to detect joint rotation if present. In addition, two Linear Variable Differential Transformers (LVDTs) were used to measure the precise displacement between the jaws of the machine. This varies somewhat from the displacement measured by the in-built LVDT in the testing machine, and this practice was adopted to allow more direct comparison with finite element models.

An initial set of tests involved loading joints up to ultimate failure. A further series of tests were then performed up to a load level corresponding to the first significant "knee" (sharp change in slope) in the load-deflection curve of the larger clearance joints. These specimens were then examined using optical microscopy and SEM to compare the damage in specimens with different levels of clearance. The specimens were sectioned as shown in Fig. 5. A "plug" of material was first removed as shown and examined. Then a further cut was made in order to analyse the bearing plane, designated ABCD in Fig. 5. Special attention was focused on the shear plane or faying surface (illustrated in Fig. 5) since the highest level of damage was exhibited there.

3. RESULTS AND DISCUSSION

In Test Series A, two joints with small clearance (C1) and two joints with large clearance (C4) were tested up to ultimate failure. The force-deflection curves for this series are shown in Fig. 6(a). The C4 curves exhibit a delay in load take-up of approximately the same size as the clearance (0.24 mm), while the C1 curves do not exhibit any delay. The consistency of this delay indicates that the bolt-centring jig operated successfully (other tests performed without the use of this jig exhibited wide scatter in this delay in C4 tests). Fig. 7 illustrates schematically the likely movement of the initially centred bolt before load take-up in a large clearance joint, which explains the delay in load take-up. Referring again to Fig. 6(a), the two C1 curves exhibit linearity up to approximately 11-12 kN, and thereafter become non-linear, indicating the initiation of bearing failure. Significant stiffness loss, evidenced by a sharp change in slope, occurs at approximately 18-19kN, and further slope changes occur en route to final failure, which was by bolt failure (Fig. 8). The bolts failed at the threads, and the nut side of the assembly flew off at high speed, accompanied by a loud noise and what appeared in the video still to be a spark. Clearly, at failure, the internal energy in the bolt is converted to other energy forms such as kinetic energy, sound and light, in a similar manner to the conversion of kinetic energy to other forms, during some impacts. The spark has obvious implications for joints exposed to fuel vapour but it should be noted that major structural aircraft joints are multi-bolt in nature, with less secondary bending than exhibited here, generally designed to fail in bearing or in some cases net-tension modes (see Fig. 1), not by bolt failure. Bolt failures would only be expected when the structure is subjected to ultimate loads (as opposed to limit loads).

Referring again to Fig. 6(a), the C4 curves show linearity up to about the same load level, but with a reduced slope. The knee in the curves occurs at a lower load level (14.5 kN). The C4 joints did not exhibit bolt failure, but instead displaced to almost 5 mm, at which point the test was stopped to avoid damaging the attached extensometers. The avoidance of bolt failure in these joints is interesting, and is believed to be due to the fact that larger clearances result in more concentrated loads on the laminate leading to more laminate damage (see below for evidence of this). This means that more energy is absorbed by the laminate, so that less has to be absorbed by plastic deformation of the bolt.

A second test series (Series B) was then carried out in which two C1 and two C4 joints were loaded up to 15 kN, or just above the level at which the C4 joints exhibited first significant stiffness loss in Test Series A. The resulting load-displacement curves are shown in Fig. 6(b). The lower slope of the C4 curves relative to the C1 curves is more evident here, as is some initial non-linearity in the C4 curves just after load take-up. This initial non-linearity is believed to be due to a more gradual build-up of contact area in the C4 joint, which is supported by three-dimensional finite element modelling [13].

The joints in Test Series B were next sectioned and analysed with microscopy and SEM. Visual inspection was first carried out using a digital camera coupled to a single stage microscope. Figs. 9 and 10 show the damaged region of the holes with clearances C1 and C4 respectively. As observed by Ireman for single-lap joints [11], damage was greatest at the shear plane, and Figs. 9 and 10 focus on this plane. Damage in the C1 joint comprised matrix chip out in the resin rich surface layer formed during curing of the laminate adjacent to the peel ply. For clearance C4, damage was more significant involving both fibre fracture and matrix chip-out. This is most likely due to increased bolt rotation in the hole (depicted in Fig. 7(b)) and a smaller contact area (see next paragraph), thereby inducing more localised contact stresses in this region.

Next, a plug of material was cut out and examined, as illustrated in Fig. 5. This provided a clear image of the impression left by the bolt on the surface of the hole, particularly for the C4 joints (Fig. 11). For clearance C1, the contact angle at the shear plane was of the order of $160° - 170°$, and was fairly constant through the thickness. For the C4 clearance, the contact angle was of the order of $130° - 140°$ at the shear plane and reduced markedly though the thickness, resulting in a significantly lower contact area.

After further sectioning, as illustrated in Fig. 5, the bearing plane was examined. The C1 clearance joint shown in Fig. 12 exhibited localised crushing of the surface ($45°$) ply, and some evidence of a delamination and a shear crack running stepwise between plies 4 and 5 from the shear plane. A shear crack also appears between plies 38 and 39, very close to the hole surface. The C4 joint in Fig. 13 also showed localised crushing of the surface ply, and a more obvious delamination and shear crack running stepwise between plies 3 and 4 from the shear plane. The delamination here propagated further away from the bolt–hole contact region and deeper into the bearing plane of the laminate.

Fig. 14(a) shows SEM pictures of damage in the ply adjacent to the shear plane in the C1 clearance joint. The damage comprised matrix chip out in the resin rich surface layer formed during curing of the laminate adjacent to the peel ply, which was already detected using the simple microscopy technique described above. The damage was only the depth of the peel ply and did not breach the first ply of the laminate. Fig. 14(b) shows significant damage around the bearing region at the shear plane for clearance C4. The damage developed fully through the first ply resulting in a region of broken fibres and matrix chip out.

4. CONCLUSIONS

With the use of the bolt-centring jig in the study, larger clearance led to a consistent degree of delay in load take-up. Without such a jig, the delay would have been variable depending on bolt position. This delay has implications for multi-bolt joints in that it would result in transfer of load to other (lower clearance) holes.

Larger clearance also resulted in some initial non-linearity after load take-up and a lower slope in the linear portion of the force-deflection curve. The lower slope is believed to be due to the lower contact area in the larger clearance joints. The lower contact area was confirmed with microscopy after sectioning. This lower slope would exacerbate the above-mentioned transfer of load in multi-bolt joints.

Earlier significant loss of stiffness was observed for the larger clearance joints. This is believed to be due to larger amounts of joint damage at given load levels, due to more concentrated contact loads on the hole. Examination with optical microscopy and SEM showed that the most significant damage occurred at the shear plane of the joint for all clearances, and damage was more extensive for the larger clearance.

Low clearance joints failed by bolt failure, whereas larger clearance joints exhibited large displacements without bolt failure, before the tests were eventually stopped to avoid damage to extensometers. This is believed to be due to larger clearances resulting in more concentrated loads on the laminate and hence more damage. From an energy viewpoint, with the larger clearance, more energy is absorbed by laminate crushing mechanisms, and less by plastic deformation of the bolt.

Bolt failures in the low clearance joints involved a sudden release of internal energy, with the bolt fragment being ejected at high velocity, accompanied by a loud noise and what appeared on the video still to be a spark. Clearly, such a spark could have implications for joints exposed to fuel vapour. However, it should be noted that the joint in this paper is not a realistic structural joint and is only used for generation of basic joint design data according to the MIL-HDBK-17 and ASTM standards [16, 18]. The high degree of secondary bending in this joint (which is a major factor in the mode of bolt failure exhibited here) is not representative of aircraft joints. Major structural aircraft joints are multi-bolt, designed to fail by bearing or sometimes net-tension, not bolt failure.

Future work will involve microscopic analysis at other load levels for study of damage progression, and also study of clearances C2 and C3, as well as joints with countersunk bolts. In addition, multi-bolt joints with variable clearances will be examined to see the effects on load distribution, and overall joint stiffness and strength. The results will be used to validate three-dimensional finite element models being developed for single and multi-bolt joints.

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Table 1 Meaning of clearance codes in this study

Hole Clearance Code	**Nominal Bolt-Hole Clearance (μm)**
C1	0
C2	80
C3	160
C4	240

Figure Captions

Figure 1 Failure modes of composite bolted joints (a) Tension (b) Shear-out (c) Cleavage (d) Bearing (e) Fastener Pull-Through (f) Fastener Failure

Figure 2 Geometry of test specimens

Figure 3 Steps for centring bolt in hole
(a) Jig profile (b) Fit Nut and washer in tight-fit hole (c) Add first laminate (d) Add second laminate (e) Insert threaded pin of same diameter as hole (f) Clamp laminates (clamp not shown), insert bolt and washer

Figure 4 Test setup of joint tests, showing extensometers and LVDTs

Figure 5 Sectioning of specimens for microscopy

Figure 6 Force-deflection curves – note: C1_1 means C1 clearance, Test 1, etc.
(a) Test series A – loading to ultimate failure (b) Test series B – loading to 15kN

Figure 7 Schematic of bolt movement for clearance C4 (a) Pre-Test (b) After load take-up

Figure 8 Video stills just before and after final failure of the C1 joints in Test Series A – note what appear to be sparks emitted on bolt failure

Figure 9 Damage in surface ply of the shear plane of C1 hole after Loading to 15kN

Figure 10 Damage in surface ply of the shear plane of C4 hole after loading to 15kN

Figure 11 Contact area for holes with clearance C1 and C4 (a) C1 clearance (b) C4 clearance

Figure 12 Bearing plane of laminate in joint with clearance C1

Figure 13 Bearing plane of laminate in joint with clearance C4

Figure 14 SEM images of sectioned holes after loading to 15kN (a) Joint with C1 clearance (b) Joint with C4 clearance

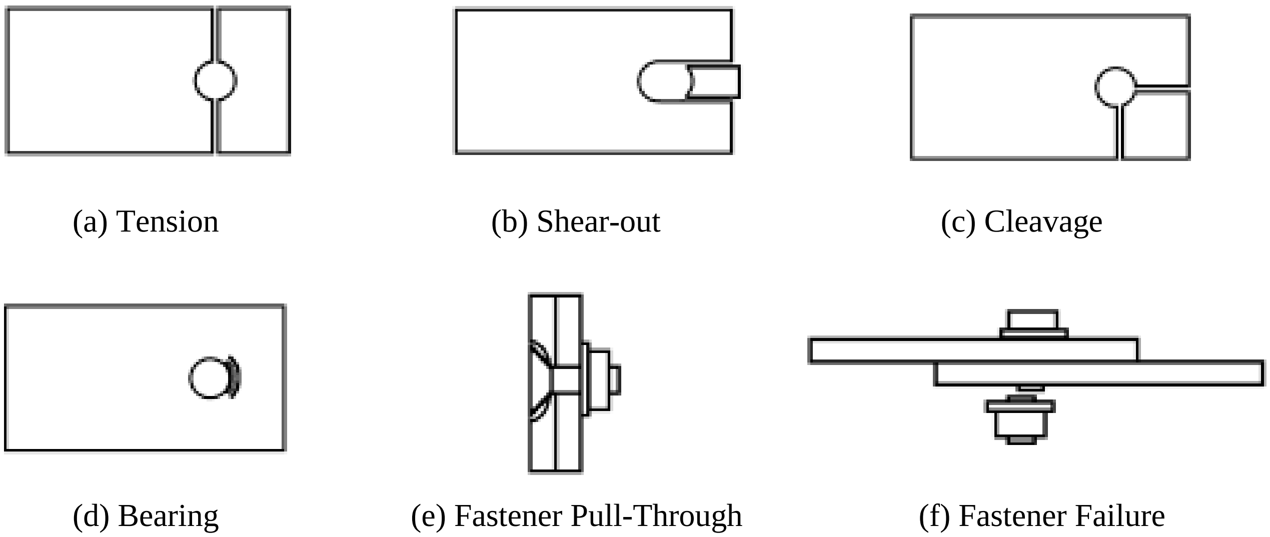

Figure 1 Failure modes of composite bolted joints

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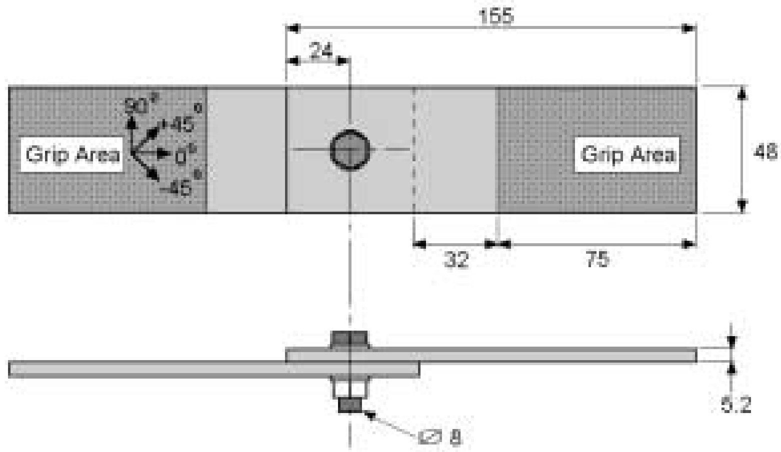
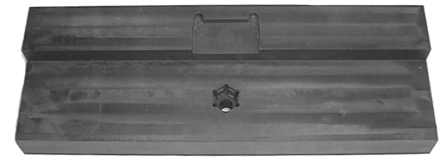
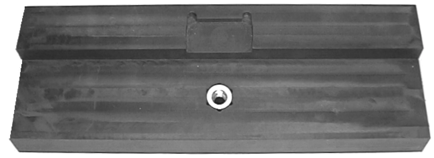


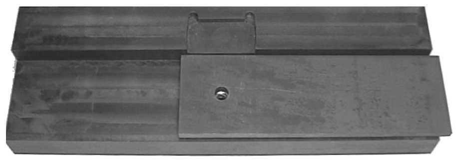
Figure 2 Geometry of test specimens



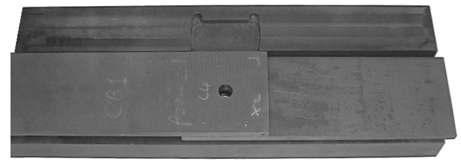
(a) Jig profile



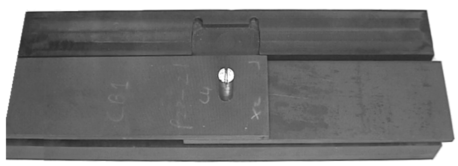
(b) Fit nut and washer in tight-fit hole



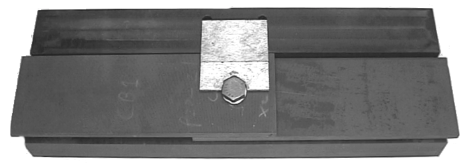
(c) Add first laminate



(d) Add second laminate



(e) Insert threaded pin of same diameter as hole



(f) Clamp laminates (clamp not shown), insert bolt and washer

Figure 3 Steps for centring bolt in hole

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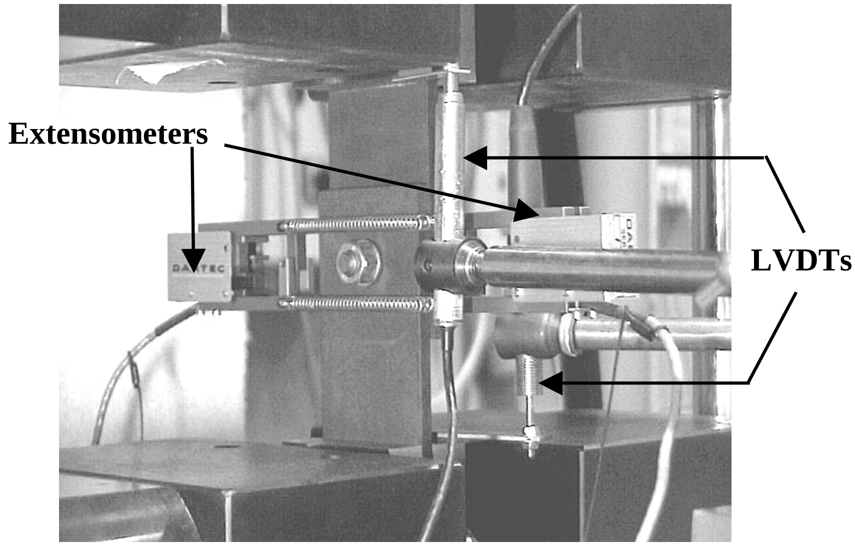


Figure 4 Test setup of lap shear tests, showing extensometers and LVDTs

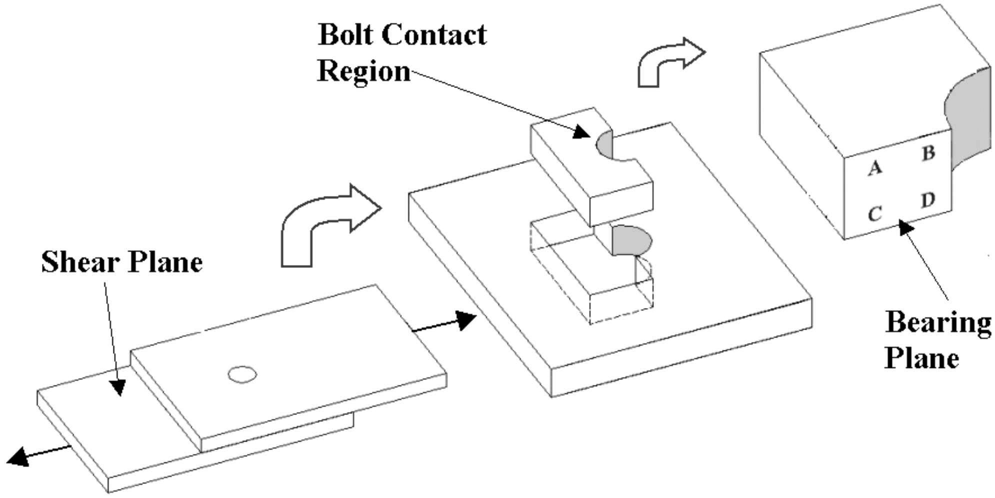
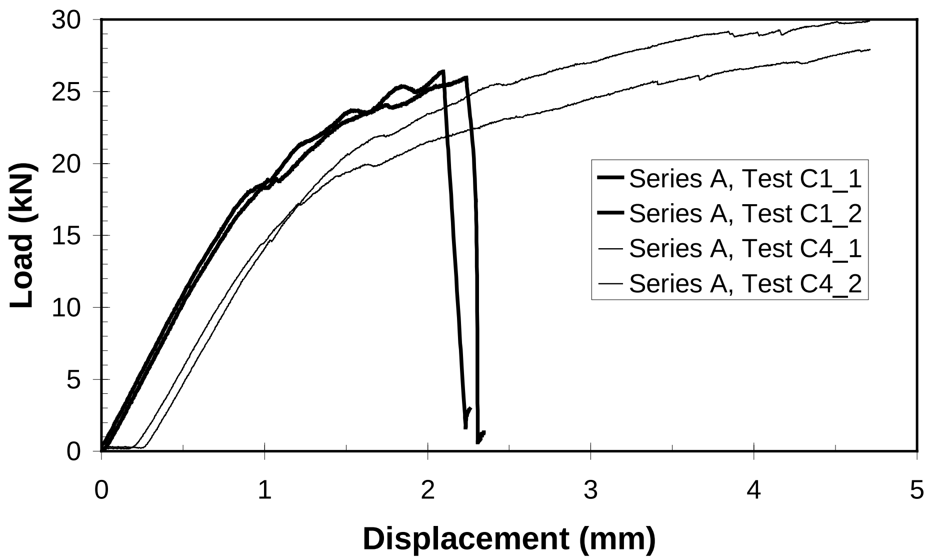
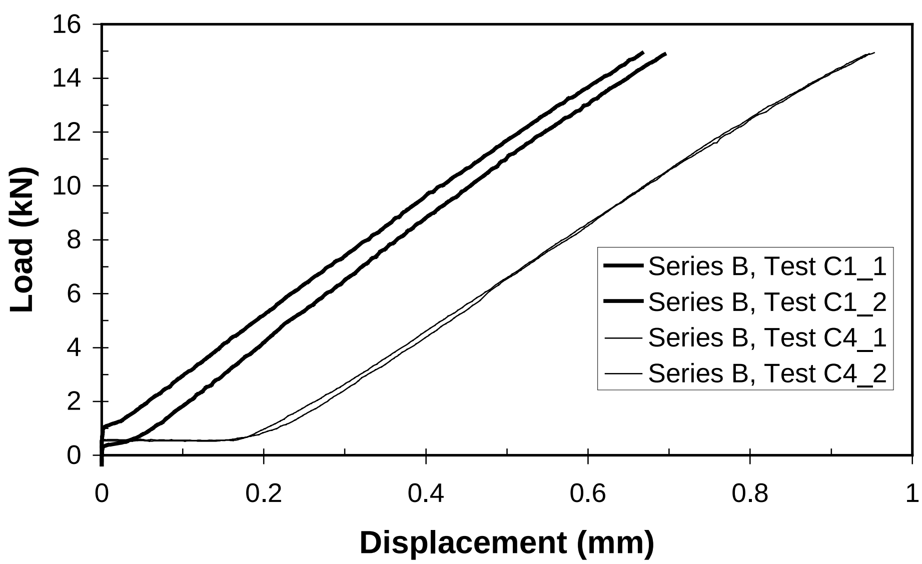


Figure 5 Sectioning of specimens for microscopy

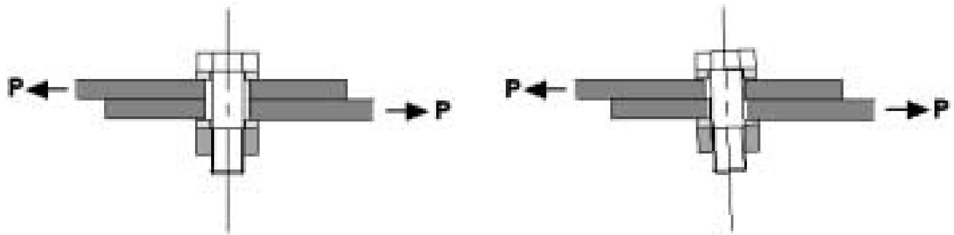


(a) Test series A – loading to ultimate failure



(b) Test series B – loading to 15kN

Figure 6 Force-deflection curves – note: C1_1 means C1 clearance, Test 1, etc.



(a) Pre-test (b) After load take-up

Figure 7 Schematic of bolt movement for clearance C4

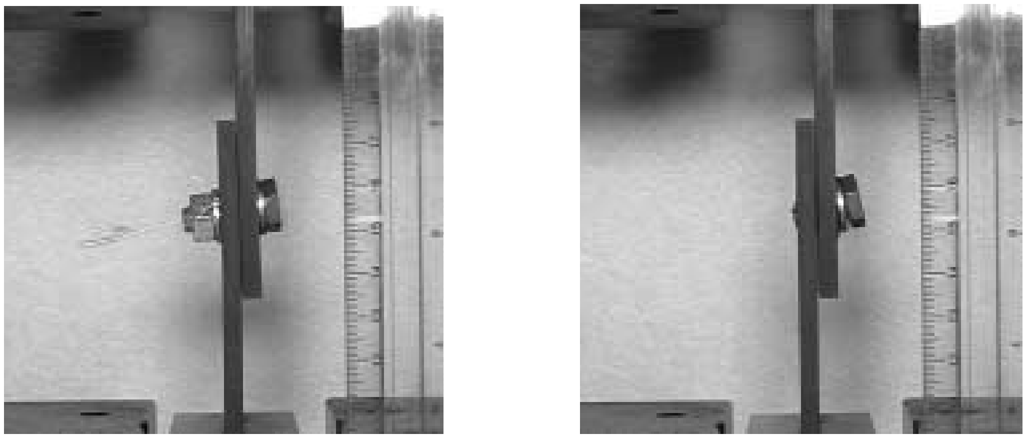


Figure 8 Video stills just before and after final failure of the C1 joints in Test Series A – note what appear to be sparks emitted on bolt failure

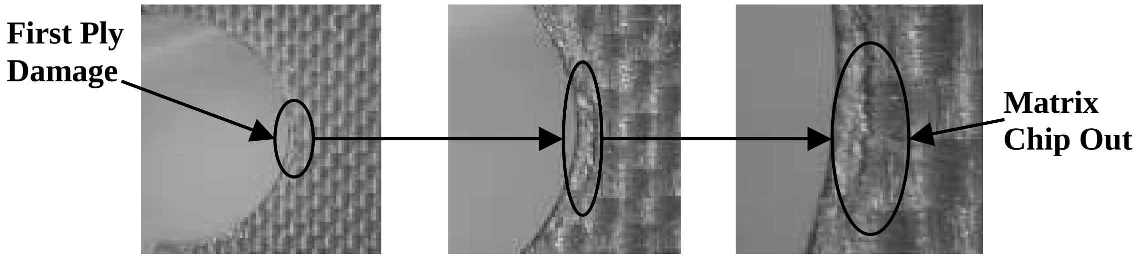


Figure 9 Damage in surface ply of the shear plane of C1 hole after loading to 15kN

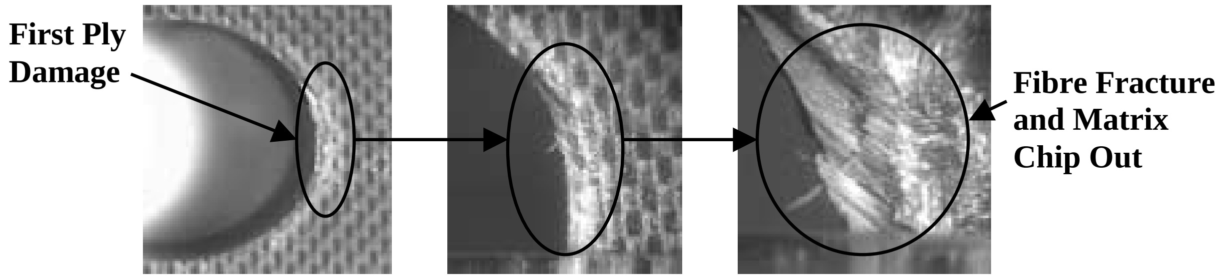
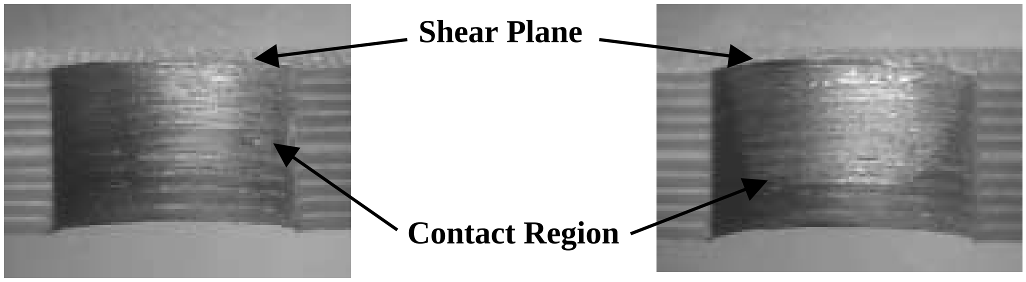


Figure 10 Damage in surface ply of the shear plane of C4 hole after loading to 15kN



(a) C1 clearance

(b) C4 clearance

Figure 11 Contact area for holes with clearance C1 and C4

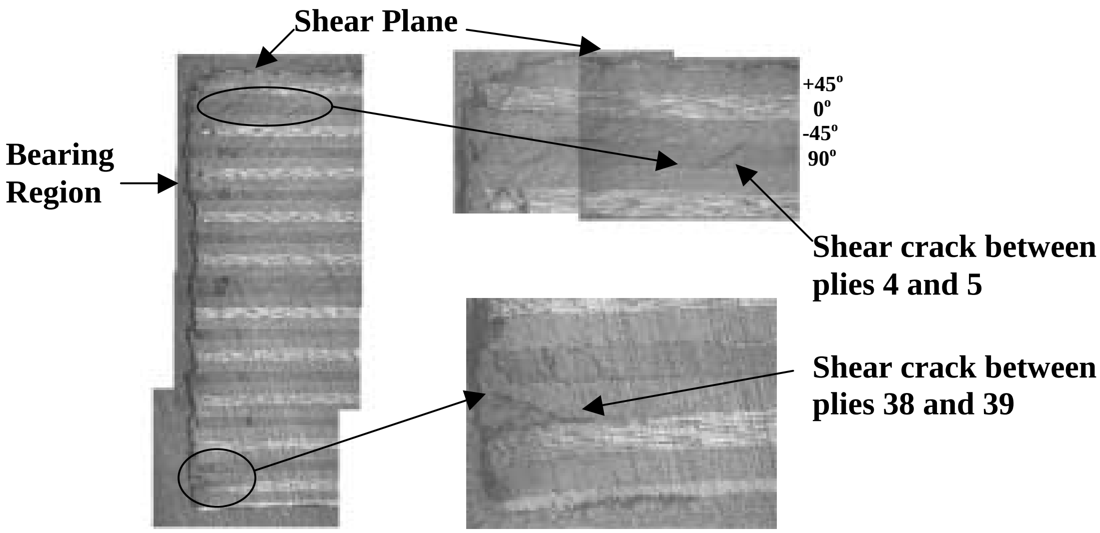


Figure 12 Bearing plane of laminate in joint with clearance C1

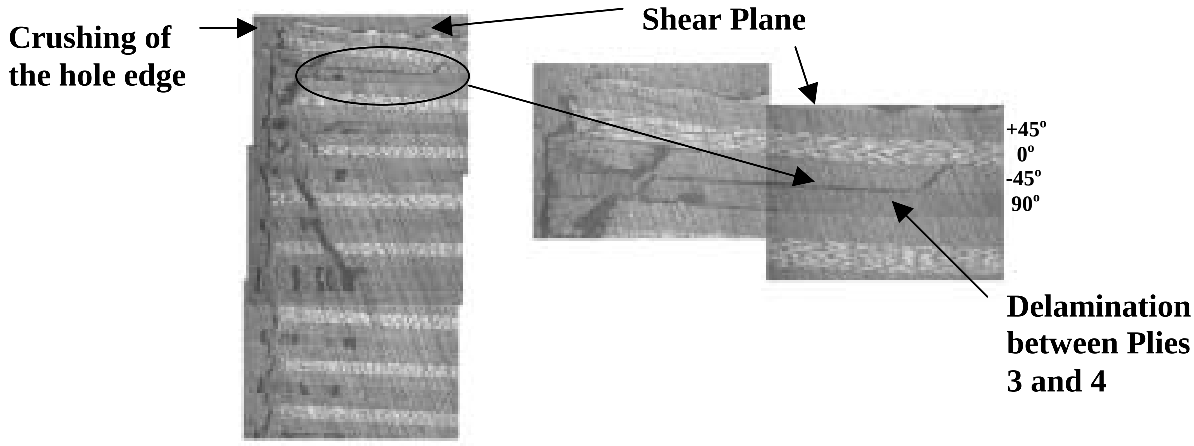
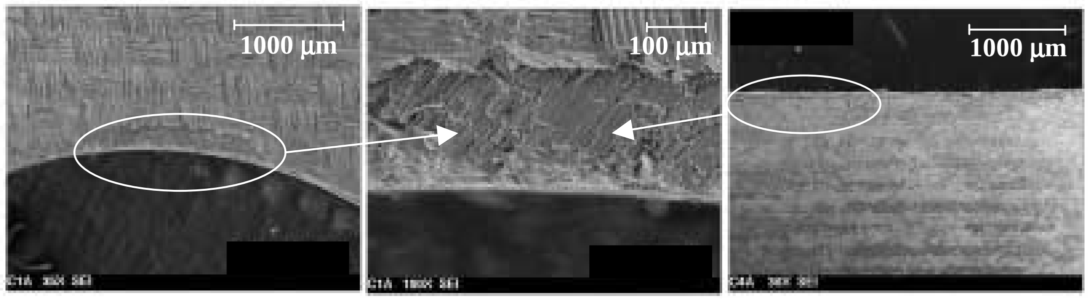
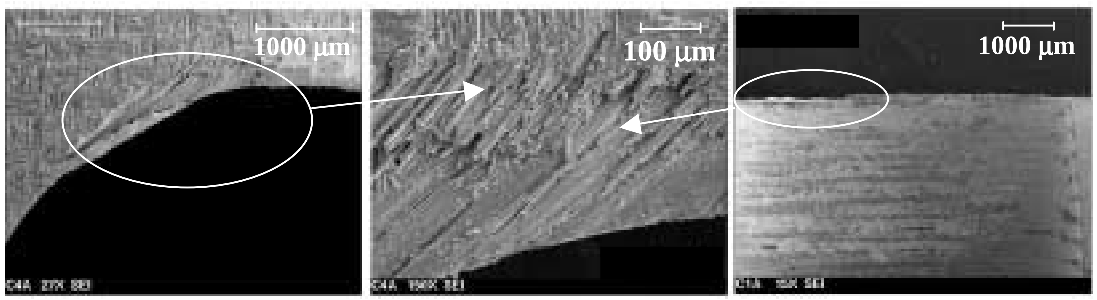


Figure 13 Bearing plane of laminate in joint with clearance C4



(a) Joint with C1 clearance



(b) Joint with C4 clearance

Figure 14 SEM images of sectioned holes after loading to 15kN

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