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Bolt-hole clearance effects and strength criteria in single-bolt, single-lap, composite bolted joints

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Abstract

Effects of bolt-hole clearance on the stiffness and strength of composite bolted joints were investigated. The configuration studied was single-lap, single-bolt. Four different clearances were obtained using variable size reamers, ranging from neat-fit to 240 μm. The specimens were manufactured in accordance with ASTM standard D5961/D5961 M-96, from graphite/epoxy HTA/6376, with quasi-isotropic and zero-dominated lay-ups. Both protruding head and countersunk bolts were used, with two different applied torque levels. Specimen dimensions were chosen to obtain bearing as the primary mode of failure, with ultimate failure being mostly through bolt failure. Joint stiffness, 2% offset bearing strength, ultimate bearing strength and ultimate bearing strain were obtained according to the Standard. In addition, an alternative definition of strength was derived, which has some advantages over the offset method, and the results were evaluated according to this definition. Increasing clearance was found to result in reduced joint stiffness and increased ultimate strain in all tested configurations. Finger-tight joints with protruding head bolts showed a link between clearance and strength, but countersunk and torqued joints did not. A delay in load take-up also occurred with the higher clearance joints, which has implications for load distributions in multi-bolt joints.
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1. Introduction

An understanding of bolted joint behaviour is essential to the design of efficient aerospace structures from carbon-fibre reinforced polymer materials. Maximum joint efficiencies in composite structures tend to be less than for metals, so poorly designed joints detract significantly from the weight advantage of composites over metals. In a typical manufacturing environment, the diameter of fasteners and holes will vary within certain allowed tolerances. The combination of bolt and hole tolerances will result in a range of allowable bolt-hole fits, which in composites are generally clearance rather than interference fits, due to concerns over damage caused to the composite during insertion of the fastener, and also possibly removal of the fastener during inspections.

Though a large body of literature exists on composite bolted joints, the majority of the studies have involved neat-fit fastener holes. The studies that have considered the effects of clearance have mostly been analytical [1–3] or numerical [4–13] in nature. From these, a number of conclusions have been drawn. Most studies have shown that the bolt-hole contact area reduces significantly with small amounts of hole oversize, resulting in increased peak bearing or radial stress [1,4,6,8,10,11]. The contact area has also been found to increase with load in clearance fit joints, but not in neat-fit joints [1,6,8,10,12]. The *location* of the peak circumferential stress has been found to vary with clearance, generally being found to be near the end of the contact region [1,6,10]. Hyer et al. [1] also pointed out that the *direction* of the peak circumferential stress changes with clearance, which could affect strength due to the laminate being loaded off-axis. The effect of clearance on the *magnitude* of the circumferential stress seems to depend on whether friction is included in the analysis [6,10], and is not as significant as the effect on radial stress magnitude. The effects of clearance in multi-bolt joints have been studied in

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[3,9,13] and it has been found that variable clearance can result in re-distribution of loads between the holes.

The increase in magnitude of the peak bearing stress, as well as the change in direction of the peak circumferential stress, has led many researchers to conclude that increasing clearance should result in reduced load capacity in the joint [1,6,8,11]. However, the meaning of "load capacity" has not been well defined in these papers, and experimental evidence has not been supplied to support this hypothesis. In contrast to analytical/numerical studies, experimental studies of the effects of clearance are few in number. DiNicola and Fantle [14] performed experiments on the bearing strength of clearance-fit fastener holes in toughened graphite/epoxy woven laminates, with quasi-isotropic and $\pm 45^\circ$ lay-ups. The test method followed "ASTM D953 Test Method for Bearing Strength of Plastics". They used a compressometer (similar to an extensometer) to measure hole deformation, and calculated 4% hole deformation strength (4% HDS) and maximum bearing strength. Four clearances were examined, neat-fit, 76, 152 and 279 μm, with pins of nominal diameters 3.18 and 6.35 mm. Three repeats of each configuration were performed, with the exception that neat-fit clearances were only tested for the 6.35 mm holes. For the 6.35 mm holes, they found that 4% HDS *increased* as clearance increased from neat-fit to 76 μm, for both lay-ups. However, for both hole sizes and both lay-ups, they found that 4% HDS *decreased* as clearance increased from 76 to 279 μm, in some cases by as much as 30%. In other words, 4% HDS first increased and then decreased with increasing clearance. The authors explained this by noting that the failure mode of the neat-fit specimens was different from the clearance specimens. *Maximum* bearing stress was found to be independent of clearance, which the authors concluded was due to the complicated progressive damage mechanism involved. The effect of clearance on joint stiffness was not reported. Pierron et al. [15] investigated clearances in $\pm 45^\circ$ woven glass fibre epoxy pin joints, both experimentally and with finite element analysis. Clearances of 0.1, 0.5, 1, 1.5 and 2 mm with pins of 16 mm diameter were examined. The load deflection curves for their configurations had a smooth non-linear shape until a clear load drop-off at failure. The failure load was found to decrease by 30% from 0.1 mm clearance to 2 mm clearance. They also concluded that the joint stiffness did not vary much but did not quantify this. However, approximate measurements from their load deflection curves would seem to indicate a drop in stiffness of 15–20%, which is quite substantial. Naik and Crews [6] made the similar conclusion from their finite element study that clearance should be considered in strength analyses, but may have little effect on joint stiffness.

A feature common to all of the above studies is the pin joint configuration (single plate loaded by a pin), with the primary failure mode being bearing. The pin joint configuration is often considered representative of the central lap in a double lap joint. Recently Ireman [16] performed experimental and three-dimensional finite element studies on single-bolt, single-lap joints (without considering variable clearance) and demonstrated the three-dimensional nature of the stresses and failure propagation in such cases. The single-lap, single-bolt joint is one of the standard configurations for characterisation of mechanically fastened composite joints in MIL-HDBK-17 [17,18], 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 [18]. The aim of this paper is to examine the effects of clearance in single-lap, single-bolt composite joints, by means of a comprehensive experimental test programme. Over 60 tests have been performed for this paper, involving four clearances, two lay-ups, two torque levels, and two bolt types. A three-dimensional finite element study of these tests is also being carried out, and will be reported on in a later paper. This work forms part of the EU research project, BOJCAS— Bolted Joints in Composite Aircraft Structures [20].

2. Experimental methods

The specimen geometry is shown in Fig. 1. The test procedure and joint geometry were based on the ASTM standard D 5961/D 5961 M – 96 [19]. 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 accentuate the three-dimensional effects introduced via variable clearance, and to be more representative of joints in primary structures. 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 followed from this ratio.

The carbon fibre/epoxy material used was HTA/6376, manufactured by Hexcel (UK), a high-strength material currently used in the aircraft industry. Two different lay-ups were used: one quasi-isotropic with stacking sequence $[45/0/-45/90]_{5s}$, the other zero-dominated with stacking sequence $[(45/0_2/-45/90)_3 45/0_2/-45/0]_s$. The latter lay-up is representative of lay-ups suitable for composite aircraft wing skins. The ply thickness was nominally 0.13 mm, yielding a nominal laminate thickness of 5.2 mm when cured. The bolts used were aerospace grade Titanium alloy fasteners with nominal diameter 8 mm, with an f7 ISO tolerance. Both protruding head and countersunk fasteners were used. Steel nuts together with steel washers were also used.

An important decision for this study was the range of clearances to examine. Examination of the above-mentioned references shows a wide variation, with larger clearances generally only examined by authors interested in non-aerospace applications [4,11,15]. For example, as mentioned above, Pierron et. al. [15] looked at clearances from 0.1 to 2 mm with 16 mm diameter pins (i.e. 0.6–11.1% of hole diameter), but their interest was in composite structural components for the railway industry. Lanza DiScalea et al. [11] looked at clearances up to 37%. For the aerospace industry, Hyer et al. [1] give an upper bound of 1% on clearance, but DiNicola and Fantle [14] state that 50–150 μm are typical for aerospace structures. In fact, DiNicola and Fantle examined clearances up to 279 μm, which for their smallest diameter holes (3.18 mm) represented 8.8% of hole diameter. Ireman [16] cited use of the f7/H10 ISO fitting, and this fitting is in use by at least one European aircraft manufacturer. Table 1 shows the tolerances on bolt and hole for this fitting, and the resulting fits, for some sample bolt diameters. From this, the absolute upper bound of 150 μm given by DiNicola and Fantle appears valid, though the largest *percentage* clearance in Table 1 (2.3%) is considerably less than that used in their study. It can be seen that the allowable percentage clearance decreases with increasing hole diameter.

The clearances chosen for this study were neat-fit, 80, 160, and 240 μm. For a nominal 8 mm hole diameter, this represents percentage clearances of 0, 1, 2 and 3%. From Table 1, the first two clearances are seen to be within aerospace tolerances, while the latter two are slightly outside. The latter two are thus of interest in examining the possible effects of out-of-tolerance aerospace holes (or fasteners), and also in non-aerospace applications.

The chosen clearances could only ever be nominal, since there will always be tolerances on bolts and holes. To reduce the tolerance on the holes to a minimum, four reamers of different diameters were specially manufactured for this study to a tight (h6) tolerance, by an aerospace supplier. The bolts were supplied by an air

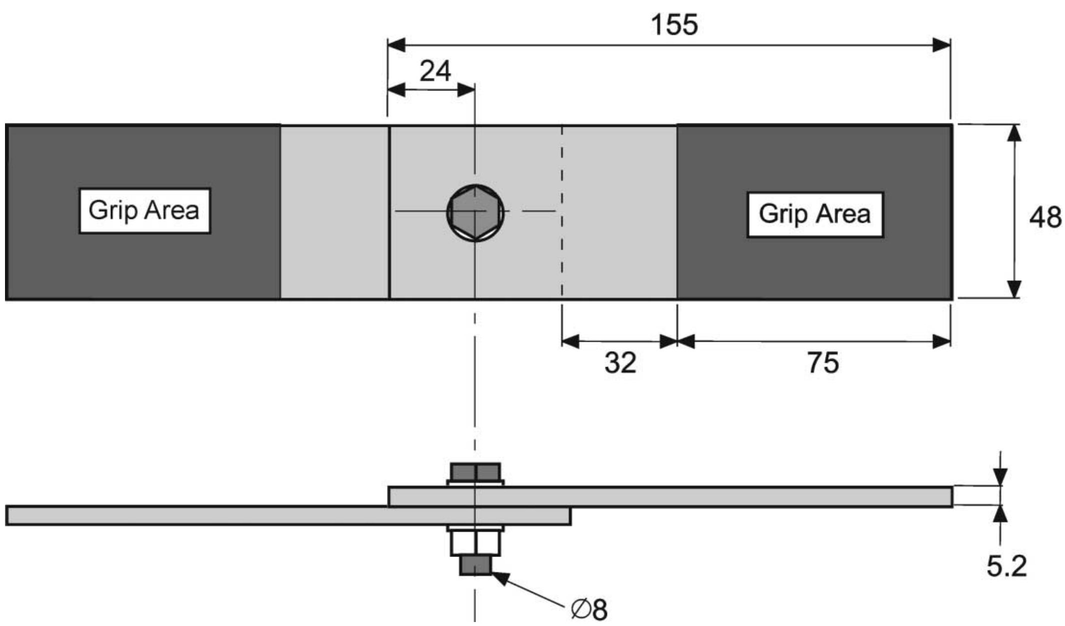


Fig. 1. Specimen geometry (all dimensions in mm).

Table 1
Bolt-hole clearances (ISO fitting f7/H10)[a]

d_{nom} (mm)	Bolt		Hole		Bolt-hole clearance	
	Δd_{max} (μm)	Δd_{min} (μm)	Δd_{min} (μm)	Δd_{max} (μm)	λ_{min} (μm)	λ_{max} (μm)
3–6	−22	−10	0	+48	10	70 (2.3% of 3 mm)
6–10	−28	−13	0	+58	13	86 (1.4% of 6 mm)
18–24	−41	−20	0	+84	20	125 (0.7% of 18 mm)

[a] d = Diameter, λ = clearance.

craft manufacturer in the BOJCAS project. The four intended nominal clearances together with the possible ranges for each clearance are given in Table 2. Each clearance was given a code, from C1 for neat-fit to C4 for 240 μm.

Two different torque levels were applied using a calibrated torque wrench. The first was 0.5 Nm, which was regarded as the lowest, repeatable torque that could be applied, hence representing "finger tight" conditions. Finger-tight represents the worst-case scenario of a bolt loosened during fatigue loading from an initial fully torqued condition. The second torque level was the full, recommended torque of 16 Nm.

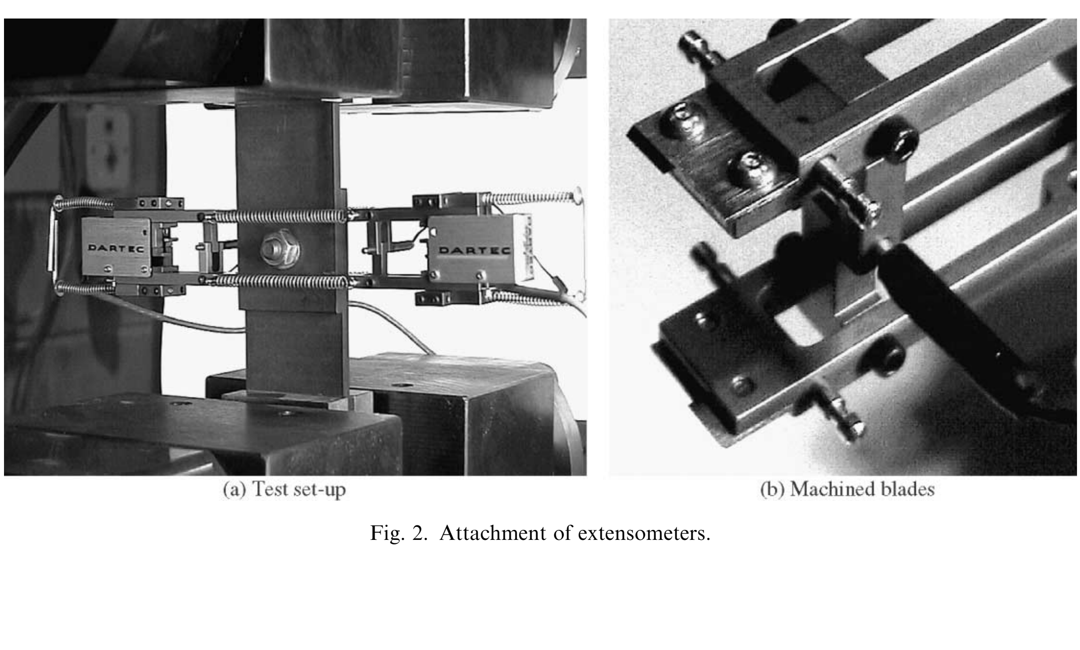
To produce consistent, accurate holes with no damage to the composite, a purpose-built drilling jig was used, utilising sacrificial material to avoid damage on both the entry and exit sides of the specimen. Drilling speeds and feeds were optimised in a pre-study, and holes were examined for damage using X-ray radiographs. To remove bolt position as a variable in the current study (especially for the larger clearance specimens), a mounting jig was designed to locate the bolt in the centre of the hole, prior to testing. This jig is described in more detail in [21].

For each test, load versus stroke of the test machine was recorded. In addition, a pair of extensometers was attached to the mid-section of the joint to enable calculation of bearing stress and strain in accordance with the ASTM standard [19]—see Fig. 2(a). In the standard, the gauge length is large enough to allow attachment of the extensometer arms outside the overlap region. However, in most of the tests in the present study, a gauge length of 25 mm was used, so both legs of each extensometer were within the overlap region of the joint. This necessitated machining down one half of each blade on each extensometer, as shown in Fig. 2(b). The decision to use a 25 mm gauge length was based on a desire to measure extension across only the hole, with as little extension of the laminate as possible included in the measurement. This was expected to maximise the difference seen due to clearance as well as enabling correlation later with finite element models. In one test series only (the countersunk joints) a 50 mm gauge length was used, which allowed attachment outside the overlap region. In general, response from the two extensometers (in a single test) was very similar, indicating little rotation of the joint (which could happen if alignment was poor, or the hole was not drilled exactly in the centre of the laminate). The readings from the two extensometers were averaged for each test.

In accordance with the ASTM standard [19], bearing stress vs. bearing strain curves were derived. The bearing stress was calculated from:

Table 2
Range of reamer/bolt sizes and resulting clearances in this study

Clearance code	Nominal clearance (μm)	Reamer diameter		Bolt diameter		Possible clearance	
		Min (mm)	Max (mm)	Min (mm)	Max (mm)	Min (μm)	Max (μm)
C1	0	7.985	7.994	7.972	7.987	−2	22
C2	80	8.065	8.074	7.972	7.987	78	102
C3	160	8.145	8.154	7.972	7.987	158	182
C4	240	8.225	8.234	7.972	7.987	238	262



(a) Test set-up (b) Machined blades

Fig. 2. Attachment of extensometers.

$$\sigma^{br} = \frac{P}{kDh} \tag{1}$$

where: P = load, D = diameter, h = coupon thickness, and k = load per hole factor (1.0 for single-fastener or pin tests and 2.0 for double-fastener tests—so $k = 1.0$ here).

Bearing strain was found from:

$$\varepsilon^{br} = \frac{(\delta_1 + \delta_2)/2}{KD} \tag{2}$$

where δ_1, δ_2 = displacements in extensometers 1,2, and K = 1.0 for double shear tests and 2.0 for single-shear tests (so K = 2.0 here).

In accordance with the standard, the actual thickness (in the vicinity of the hole) and hole diameters for each individual joint were used in the calculations, rather than nominal values. From these curves, the following parameters were obtained, as defined in Figs. 3 and 4 for typical C1 and C4 joints:

- 2% offset bearing strength
- ultimate bearing strength
- ultimate bearing strain.

Note from Fig. 4 that, in the C4 joint, there is a delay in initial load take-up due to the bolt being initially centred in the hole. Measuring the offset and ultimate strains from the "effective origin" makes for a fairer comparison between different clearances, since the initial delay in load take-up is factored out of the calculation.

3. Results and discussion

3.1. Load-deflection curves and modes of failure

All joints were loaded quasi-statically in tension, in stroke control at a rate of 0.1 mm/min. Figs. 5–7 show the load versus machine stroke for *finger-tight* specimens tested to failure. The figures cover three distinct configurations: protruding head bolts, quasi-isotropic lay-up (Fig. 5); protruding head bolts, zero-dominated lay-up (Fig. 6); and countersunk head bolts, quasi-isotropic lay-up (Fig. 7).

The following general observations can be made. For all tests, the load-deflection curves possess a region that appears linear, and for tests at a given clearance, the slope of this region is very repeatable. Looking closely reveals that the slope reduces with increasing clearance within each configuration. There is a delay in initial load take up, dependent on the clearance. This delay is generally slightly larger than the nominal clearance in each case, and is very repeatable for a given clearance (the countersunk joints are not quite as good in terms of repeatability in load take-up, but the four sets of curves at each clearance are still distinctly separated, Fig. 7). The repeatability in delay in load take-up is due to the jig used to centre the bolt in the hole before each test. In preliminary testing without this jig, a great deal of scatter was present. All joints failed initially in bearing. The final failure mode was in most cases bolt failure, but

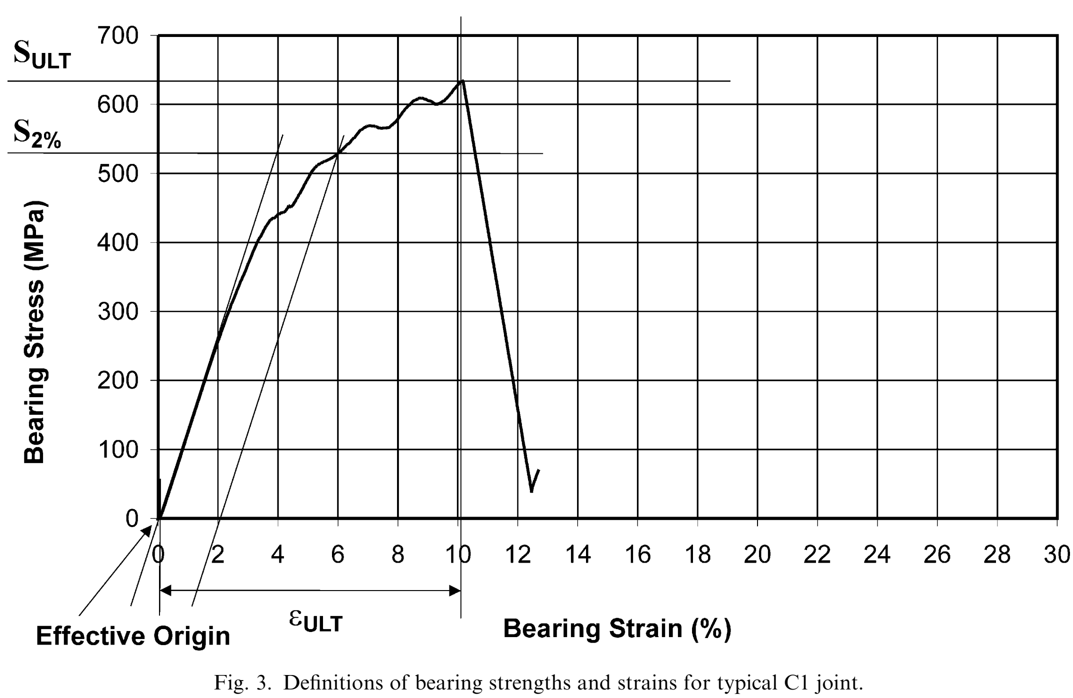


Fig. 3. Definitions of bearing strengths and strains for typical C1 joint.

some joints went to large displacements before the test was stopped to avoid damage to the extensometers. The joints with protruding head bolts (Figs. 5 and 6) were stopped at 5 mm stroke, but unfortunately, the countersunk tests were inadvertently stopped at 4 mm stroke. In general, within each test series, the maximum load does not show much dependency on clearance. However, for the joints with protruding head bolts

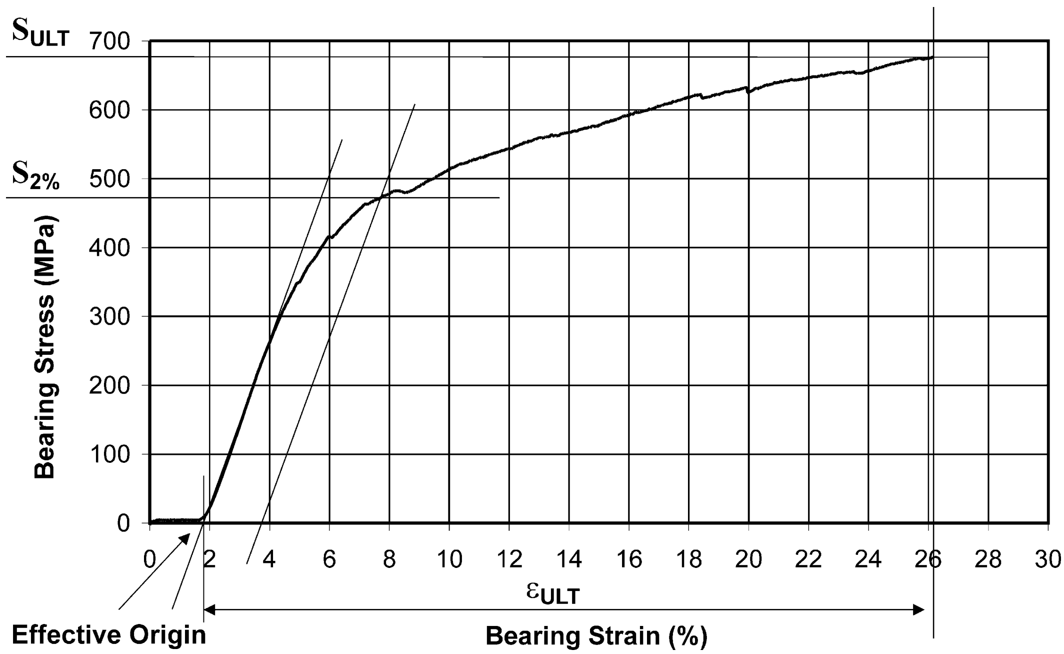


Fig. 4. Definitions of bearing strengths and strains for typical C4 joint.

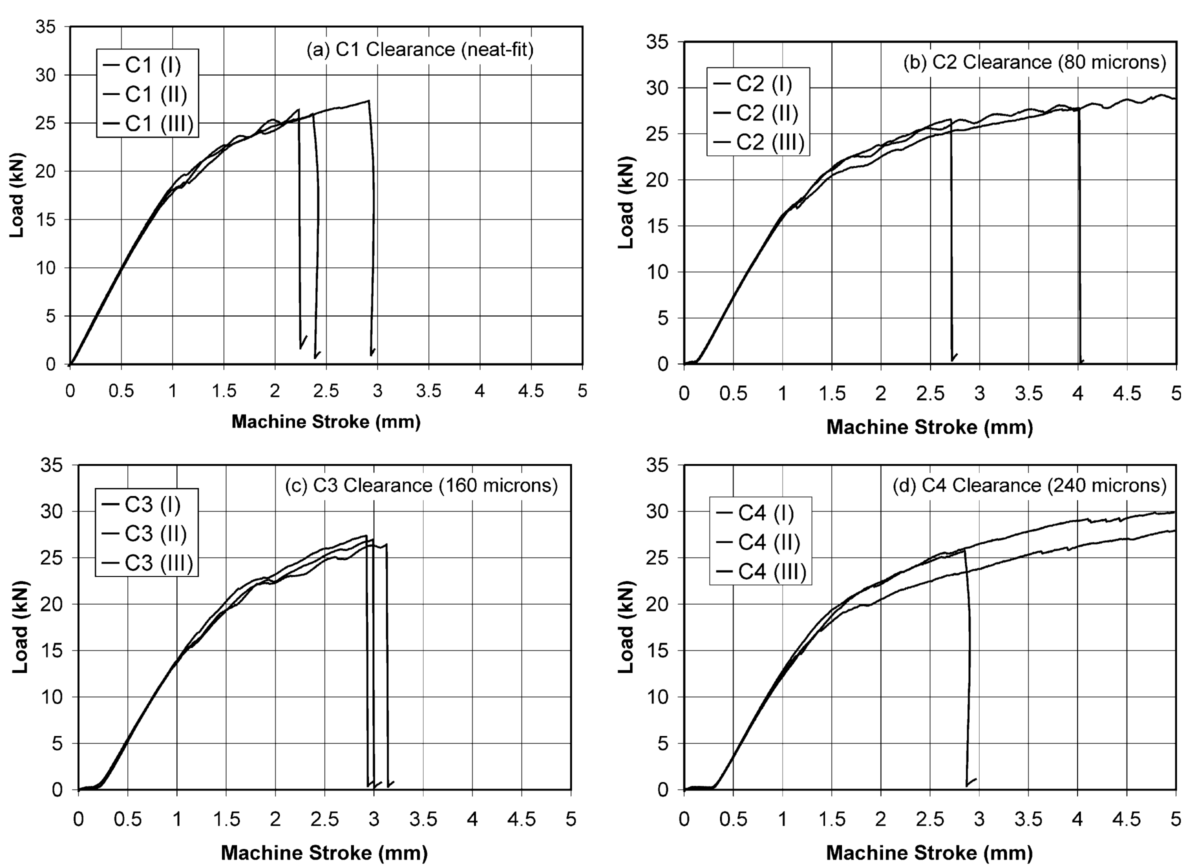


Fig. 5. Load-deflection curves for protruding head bolts, quasi-isotropic lay-up, finger-tight torque.

(Figs. 5 and 6), the joints with the lowest clearance (C1) fail (by bolt failure) at low displacements, while several of the larger clearance joints (C2, C3, C4) survive to significantly higher displacements. Finally, most of the joints with quasi-isotropic lay-up (Figs. 5 and 7) show a distinctly visible "knee" (i.e. sharp change in slope) in the load-deflection curve, above which curves at a given clearance, which had been identical to this point, begin to diverge. The knee is particularly noticeable with the countersunk joints (Fig. 7). The joints with zero-dominated lay-up do not show a clearly visible knee.

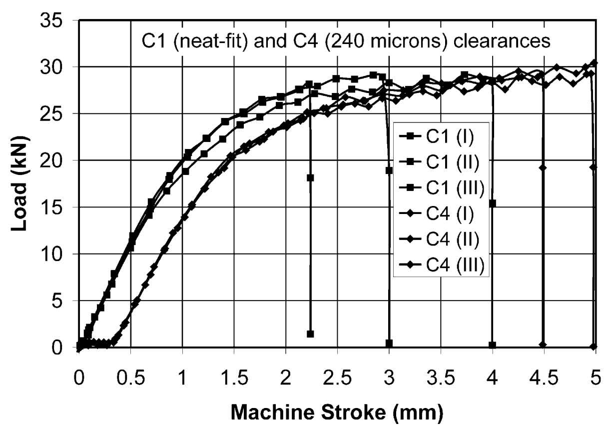


Fig. 6. Load-deflection curves for protruding head bolts, zero-dominated lay-up, finger-tight torque.

Figs. 8 and 9 show joints with protruding head bolts and countersunk head bolts respectively that failed by bolt failure. In all cases of bolt failure, the bolt failed at the threads. It can be seen that extensive bearing damage existed at the hole before the bolt failed. The bearing damage at the shear plane appears more extensive in the countersunk case, which is most likely due to the bearing load being taken almost entirely by the cylindrical portion of the hole in the countersunk laminate, as found by Ireman [16].

Fig. 10 shows the load versus machine stroke for joints torqued to the recommended in-service level (16 Nm). These joints had a quasi-isotropic lay-up and protruding head bolts. Fig. 11 shows close-ups of the initial behaviour of a C1 and C4 joint. The following characteristics can be noted. It is debatable whether any of the joints display linearity over any appreciable displacement range. However, it is clear that there is a distinct transition from an initial high slope (marked "*Slope 1*" in Fig. 11) to a lower slope ("*Slope 2*") at higher load levels. *Slope 1* scarcely seems constant even up to 2 kN applied load, while *Slope 2* seems reasonably constant between about 5 and 8 kN for the C1 clearance, and between 8 and 12 kN for the C4 clearance. *Slope 1* appears similar for both clearances, which is

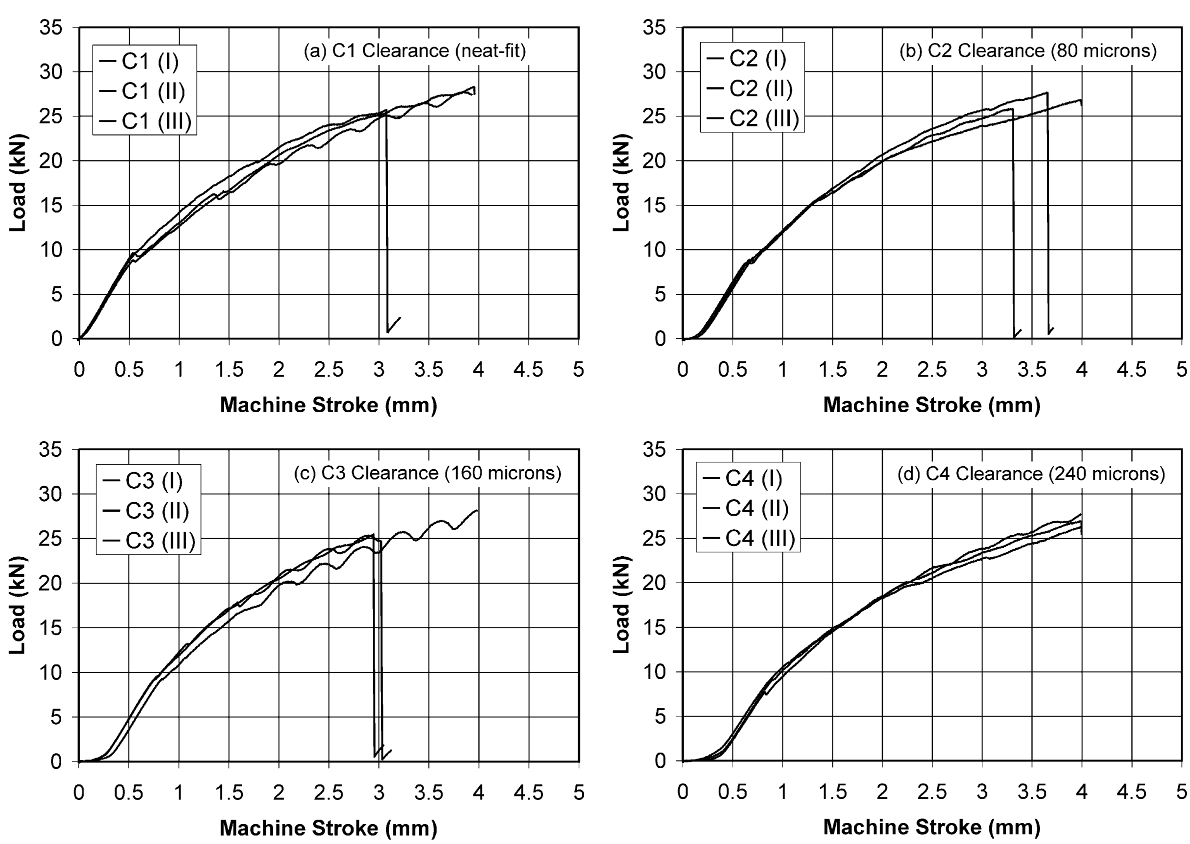


Fig. 7. Load-deflection curves for countersunk head bolts, quasi-isotropic lay-up, finger-tight torque.

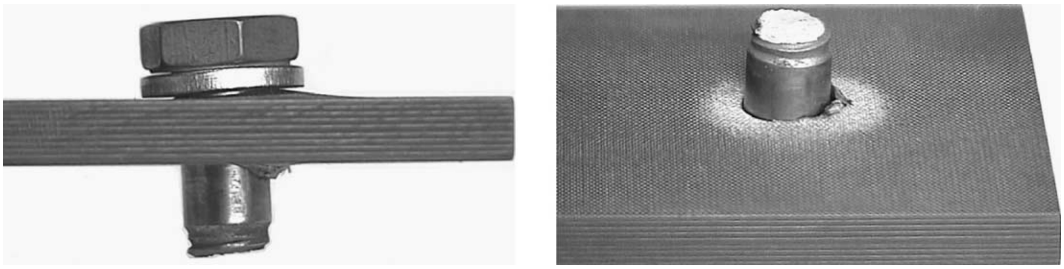


Fig. 8. Final failure of protruding head bolt.

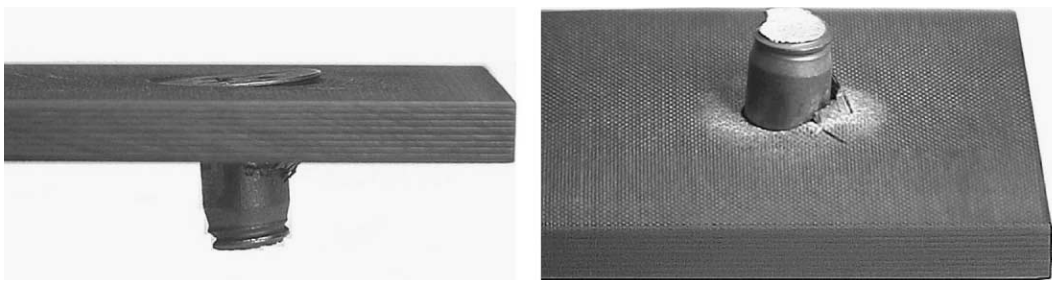


Fig. 9. Final failure of countersunk head bolt.

most likely because this region is dominated by static friction forces, which would be the same for all joints. The transition to a lower slope is presumably due to a change from static to kinetic friction, as the joint starts to slip. In the case of the C4 joint, the clearance is taken up in the transition region, during which the load is resisted entirely by kinetic friction forces. *Slope 2* is clearly less for the C4 joints than for the C1 joints, which would be expected since *Slope 2* should be due to the stiffness of the untorqued joint (which was shown to depend on clearance in the previous section) plus the stiffness due to kinetic friction. With regard to failure, all joints failed initially in bearing, and all joints except one failed finally through bolt failure. The joint that did not fail by bolt failure went to 5 mm stroke, at which point the test was stopped to avoid damage to attached extensometers. The clear knee in the load-deflection curve noted for the untorqued joints is not evident for these joints. Once again, there is no clear dependency of maximum load on clearance, but the ultimate displacement is distinctly larger for all the C4 clearance joints.

3.2. *Effect of clearance on joint stiffness*

To provide a consistent comparison of joint stiffness for the *finger-tight* joints, the slope was measured between 2 and 7 kN, over which all the curves were linear or close to linear. The ASTM Standard [19] recommends calculating stiffness between a bearing stress of 25 and 40 ksi (172 and 276 MPa), which corresponds (according to Eq. (1)) to a load range of 7–11.5 kN here. Clearly, the countersunk load-deflection curves (Fig. 7) do not display linearity over such a range and, as will be shown in Section 3.5, neither do several of the other configurations. The stiffness was calculated using machine stroke, as well as using extensometer displacement. In addition to the tests shown in Figs. 5–7, some extra repeats of tests to failure were done, and further tests were done to percentages of failure load for later microscopic analysis. These tests also allowed a calculation of slope. The average slopes calculated from machine stroke, for all finger-tight specimens (57 in total) are shown in Table 3, while the slopes calculated from extensometer displacement are shown in Table 4. The standard deviation is also shown, as an absolute value and as a percentage of the average value for that series. A two-sample students *t*-test assuming unequal variances was applied to the C1 values versus each of the other clearance values—a p value of $\leqslant 0.05$ indicates a statistically significant difference from the C1 group of results. Statistically insignificant results are *italicised*.

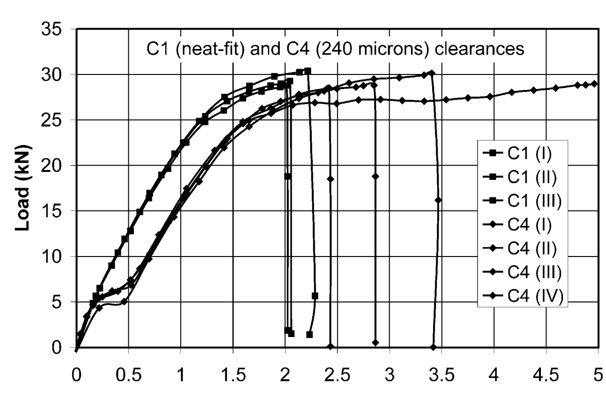
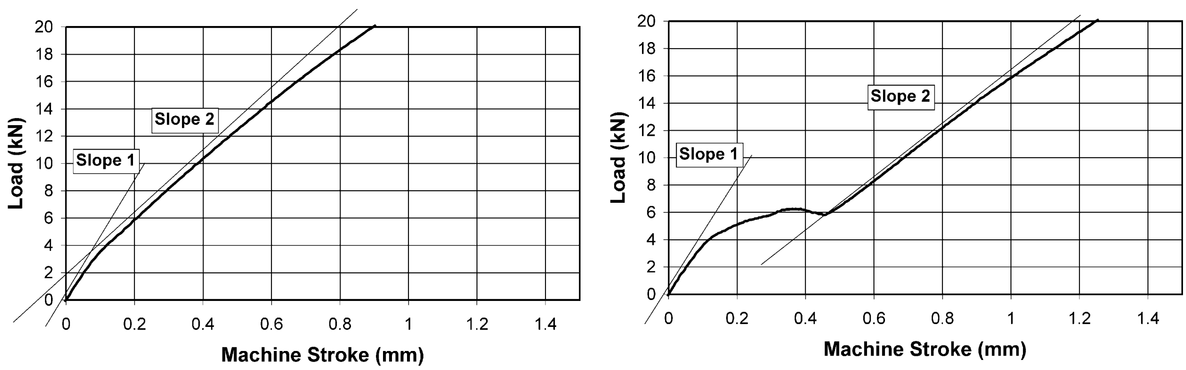


Fig. 10. Load-deflection curves for protruding head bolts, quasi-isotropic lay-up, full (16 Nm) torque.



(a) C1 clearance

(b) C4 clearance

Fig. 11. Initial stages of torqued tests.

Table 3
Effect of clearance on stiffness of finger-tight joints (stiffness based on stroke readings—units: kN/mm)

Configuration	Protruding head, quasi-isotropic				Countersunk head, quasi-isotropic				Protruding head, zero-dominated	
Clearance	C1	C2	C3	C4	C1	C2	C3	C4	C1	C4
No. of tests	9	5	6	9	3	3	3	3	7	9
Average value	20.43	20.04	18.93	18.31	19.39	18.39	18.60	17.29	23.11	20.80
S.D. (% of mean)	0.61	0.37	0.58	0.63	0.37	0.28	0.27	0.20	0.69	0.32
	(3.0%)	(1.8%)	(3.0%)	(3.5%)	(1.9%)	(1.5%)	(1.4%)	(1.1%)	(3.0%)	(1.6%)
Diff from C1 (p value)	–	*−1.9%*	−7.3%	−10.4%	–	−5.2%	−4.0%	−10.8%	–	−10.0%
		(0.081)	(0.00027)	(1.03e-6)		(0.010)	(0.021)	(0.0017)	–	(1.9e-05)

Table 4
Effect of clearance on stiffness of finger-tight joints (stiffness based on extensometer readings—units: kN/mm)

Configuration	Protruding head, quasi-isotropic				Countersunk head, quasi-isotropic				Protruding head, zero-dominated	
Clearance	C1	C2	C3	C4	C1	C2	C3	C4	C1	C4
No. of tests	9	5	6	9	3	3	3	3	7	9
Average value	35.44	35.32	31.94	30.57	28.08	26.52	27.19	24.92	35.74	31.88
S.D. (% of mean)	1.96	1.24	1.86	1.96	0.90	0.44	0.55	0.21	2.07	1.09
	(5.5%)	(3.5%)	(5.8%)	(6.4%)	(3.2%)	(1.7%)	(2.0%)	(0.9%)	(5.8%)	(3.4%)
Diff from C1 (p value)	–	*−0.3%*	−9.9%	−13.7%	–	−5.6%	*−3.2%*	−11.3%	–	−10.8%
		(0.446)	(0.0025)	(3.92e-5)		(0.037)	(0.120)	(0.0138)	–	(0.00077)

Referring firstly to the stiffnesses obtained from machine stroke (Table 3), the results all show good repeatability within each group (low standard deviations), and there is clearly a statistically significant dependency between stiffness and clearance. It can be seen that increasing clearance results in decreasing joint stiffness in each of the three configurations. The drop in stiffness is small for the C2 clearance, but is consistently at a level of about 10–11% for the C4 clearance.

Turning to Table 4, the stiffness values calculated from extensometer displacement have higher standard deviations than in Table 3 (particularly for the protruding head configurations, both of which used 25 mm gauge length extensometers), but the postulate that increasing clearance causes a stiffness reduction again easily passes the test of statistical significance. The drop in stiffness is generally slightly larger when calculated by this method. The stiffness reduction is believed to be due to reduced bolt-hole contact area with increasing clearance, which has been demonstrated in several finite element studies [1,4,6,8,10–12].

Comparing the stiffness of different configurations, the stroke readings in Table 3 indicate that the joints with protruding head bolts are slightly stiffer than those with countersunk bolts, while the joints with zero-dominated lay-up are about 12% stiffer than those with quasi-isotropic lay-up. The extensometer readings in Table 4 indicate that the difference in stiffness between the two lay-ups (quasi-isotropic versus zero-dominated) is considerably less than that shown in Table 3.

However, this result is not contradictory since the extensometers measure the local stiffness at the hole, which would not be expected to be as influenced by lay-up as a measurement over the full length of the joint. Finally, another unfortunate aspect of the countersunk joint tests is that 50 mm gauge length extensometers were used, whereas all other tests involved a 25 mm gauge length. This means that the countersunk joint extensometer stiffnesses cannot be directly compared with the other configurations (which was not realised until after the tests were performed). Attempted corrections for the material between the 25 and 50 mm gauge lengths, using simple spring theory, do not work due to the amount of secondary bending in these joints. This problem does not affect the conclusions above with respect to clearance effects, nor does it prevent comparisons between configurations with regard to strength in the following sections.

Concerning the effect of clearance on the stiffness of the torqued joints, close examination of the load-deflection curves shows that they are not linear at all initially, i.e. even from the very smallest loads, the slope is dropping away from *Slope 1* (see Fig. 11). However, after the joints have slipped, there is a short period where the curves are quite linear (parallel to *Slope 2* in Fig. 11), so the effect of clearance on this slope (calculated from extensometer measurements) is shown in Table 5. It can be seen that clearance causes quite a substantial drop in this stiffness.

Table 5
Effect of clearance on *Slope2* (see Fig. 11) of fully torqued joints (based on extensometer readings—units: kN/mm)

Clearance	C1	C4
No. of tests	3	4
Average value	50.37	37.06
S.D. (% of mean)	0.99 (2.0%)	1.74 (4.7%)
Diff from C1 (*p* value)	–	−26.4% (2.6e-05)

3.3. Effect of clearance on strength and ultimate strain

The bearing stress was calculated according to Eq. (1) and the bearing strain was determined from the extensometer readings according to Eq. (2). The 2% offset bearing strengths were then calculated according to the method illustrated in Figs. 3 and 4, and the results are shown in Table 6. Note that only tests which went to high enough loads to enable calculation of this value are included, i.e. some tests to percentages of failure loads are not included. Clearly, the trend for offset strength is not as clear-cut as for stiffness, with only the finger-tight joints with protruding head bolts (quasi-isotropic and zero-dominated lay-ups) showing a statistically significant effect. The drop in strength from the smallest to largest clearance is similar (7–8%) for both of these configurations. The other two configurations do not show a statistically significant trend. Interestingly, for the two configurations that included tests at C2 and C3 clearances, the trend with increasing clearance is firstly an increase in strength and then a decrease, which is the same trend found for pin-joints by DiNicola and Fantle [14]. Analysis with microscopy is planned for a future paper, which may give some insight into this result. Finally, for the countersunk joints, examination of the load-deflection curves in Fig. 7 shows that the 2% offset strength is largely determined by the severity of the "knee" in the curve, which seems to be a rather random event. For example, two of the three C1 curves [Fig. 7(a)] possess a substantial knee, but the other does not—the one that does not obviously has a significantly higher 2% offset strength.

Comparing configurations, Table 6 shows that increasing the applied torque level significantly increases the offset strength for both the C1 clearance (by 22.4%) and C4 clearance (by 27.1%) joints, which is consistent with findings of previous researchers [22,23,24]. The joints with countersunk bolts have 25–35% lower offset strength than those with protruding head bolts (depending on the clearance), while the joints with zero-dominated lay-up have only 2–3% higher offset strength

Table 6
Effect of clearance on 2% offset bearing strength (units: MPa)

Configuration	Protruding head, quasi-isotropic, finger-tight				Countersunk head, quasi-isotropic, finger-tight				Protruding head, zero-dominated, finger-tight		Protruding head, quasi-isotropic, torqued to 16 Nm	
Clearance	C1	C2	C3	C4	C1	C2	C3	C4	C1	C4	C1	C4
No. of tests	4	5	6	4	3	3	3	3	4	6	3	4
Average value	529.8	541.2	517.0	490.0	347.7	373.3	391.3	365.0	544.0	501.0	649.0	622.8
S.D. (% of mean)	13.9 (2.6%)	19.6 (3.6%)	26.2 (5.1%)	12.8 (2.6%)	26.4 (7.6%)	8.3 (2.2%)	17.0 (4.4%)	11.4 (3.1%)	28.8 (5.3%)	8.27 (1.7%)	29.5 (4.6%)	15.9 (2.6%)
Diff from C1 (*p* value)	–	*+2.2%* (0.17)	*−2.4%* (0.17)	−7.5% (0.0029)	–	*+7.4%* (0.12)	+12.6% (0.048)	*+5.0%* (0.19)	–	−7.9% (0.031)	–	*−4.0%* (0.13)

Table 7
Effect of clearance on ultimate bearing strength (units: MPa)

Configuration	Protruding head, quasi-isotropic, finger-tight				Protruding head, zero-dominated, finger-tight		Protruding head, quasi-isotropic, torqued to 16 Nm	
Clearance	C1	C2	C3	C4	C1	C4	C1	C4
No. of tests	4	5	6	4	3	6	3	4
Average value	638.8	674.2	657.2	650.8	691.7	683.3	696.3	691.8
S.D. (% of mean)	16.5 (2.6%)	52.8 (7.8%)	40.0 (6.1%)	40.4 (6.2%)	18.9 (2.7%)	26.7 (3.9%)	25.0 (3.6%)	35.0 (5.1%)
Diff from C1 (p value)	–	*+5.5%* (0.11)	*+2.9%* (0.17)	*+1.9%* (0.31)	–	*−1.2%* (0.31)	–	*−0.7%* (0.42)

Table 8
Effect of clearance on ultimate bearing strain (units: percentage strain)

Configuration	Protruding head, quasi-isotropic, finger-tight				Protruding head, zero-dominated, finger-tight		Protruding head, quasi-isotropic, torqued to 16 Nm	
Clearance	C1	C2	C3	C4	C1	C4	C1	C4
No. of tests	4	5	6	4	3	6	3	4
Average value	12.13	16.48	14.95	19.08	15.17	22.50	8.57	15.01
S.D. (% of mean)	1.96 (16.2%)	5.48 (33.2%)	2.67 (17.8%)	5.82 (30.5%)	5.48 (36.1%)	3.90 (17.1%)	0.31 (3.6%)	6.21 (41.4%)
Diff from C1 (p value)	–	*+35.9%* (0.082)	+23.3% (0.047)	+57.3% (0.044)	–	*+48.4%* (0.065)	–	*+75.1%* (0.065)

than the quasi-isotropic joints, which is not statistically significant.

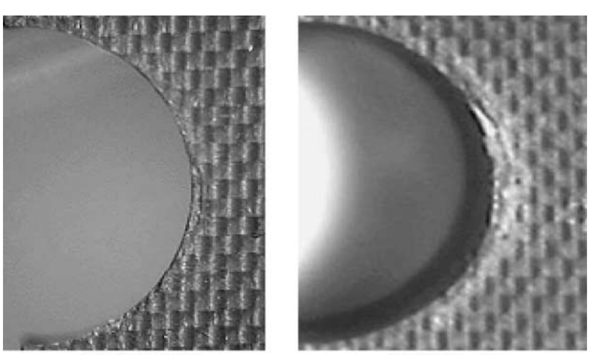
The ultimate bearing strength is the maximum bearing stress reached in the test, and results are shown in Table 7. There is a slight problem with this quantity since some tests were stopped at excessive deformations to avoid damage to extensometers. However, for the three configurations with protruding head bolts, only six out of 35 tests to failure were stopped in this way—the remainder failed through bolt failure—so a meaningful value of ultimate strength can be obtained. On the other hand, because the joints with countersunk bolts were stopped at 4 mm instead of 5 mm displacement, seven of the twelve tests were stopped, with only 5 tests failing by bolt failure. As can be seen from Fig. 7, measurement of ultimate stress for the countersunk configuration is not meaningful, so these results are not included in Table 7.

It can be seen that there is no statistically significant trend between clearance and ultimate bearing strength for any of the configurations in Table 7. This result is in agreement with the tests on pin joints by DiNicola and Fantle [14]. Comparing configurations, the difference between the three configurations is not statistically significant either, so the strong effect of torque on 2% offset strength is not repeated for ultimate strength. The closeness of all the ultimate strength values is most likely because ultimate failure was due to bolt failure and thus depended mostly on the strength of the bolt, rather than the laminate.

In contrast, Table 8 indicates that ultimate bearing strain increases significantly with increasing clearance. The countersunk joint results are not shown for the same reasons as above. Because of the high degree of scatter in the data, and small number of tests, the zero-dominated and torqued configurations do not quite pass the test of statistical significance, but the trend is upward with clearance for all configurations. Additionally, six of the higher clearance tests were stopped at 5 mm displacement (no C1 clearance tests were stopped), so if these tests had been allowed to continue, the ultimate strain would have been even higher for these tests. The reasons for the increase in ultimate strain with increasing clearance are believed to be illustrated by Fig. 12, which shows the damage in C1 and C4 clearance joints (protruding-head bolts, quasi-isotropic lay-up, finger-tight torque) both loaded to 15 kN (or 361 MPa bearing stress, which is well below the 2% strength—see Table 6). As can be seen, the damage is more extensive in the larger clearance joint. It is believed that because larger clearances result in smaller contact areas, and hence more concentrated loads on the laminate, more extensive damage occurs in the laminate. This means that more energy is absorbed through damage of the laminate, so that less has to be absorbed by plastic deformation of the bolt. This delays bolt failure until higher joint strain levels, and in fact (in such bolt-failure driven situations) results in greater overall energy absorption in the joint.

3.4. Alternative analysis of strength

In this section, an assessment of the measures of stiffness and strength in the ASTM Standard [19] is made, and some alternatives are examined. It has already been noted that some of the joints in this study did not display a linear load-deflection relationship at the load levels suggested in the Standard for calculation of stiffness. Three points are also worth making about the 2% offset strength. Firstly, at such stress levels, there is already extensive damage in the laminate, and the joint has lost its stiffness well before this. For example, the joints illustrated in Fig. 12 were only loaded to 70% of their 2% offset strength, yet show significant damage. Note that because $K=2$ for single-lap joints in Eq. (1), 2% offset strain corresponds to 4% hole deformation (deformation of 0.04D) which is used as a criterion in MIL-HDBK-17 [17], so this criterion is not unique to the ASTM Standard (for double-lap joints, the ASTM criterion corresponds to 2% hole deformation). Thus, designers should be aware of the possibly significant level of damage associated with the criterion. Additionally, in examining the effects of joint variables (such as clearance in this study), a criterion closer to the proportional limit might be preferable since joint behaviour becomes more random as failure progresses, thereby obscuring the effects that variables may be having.



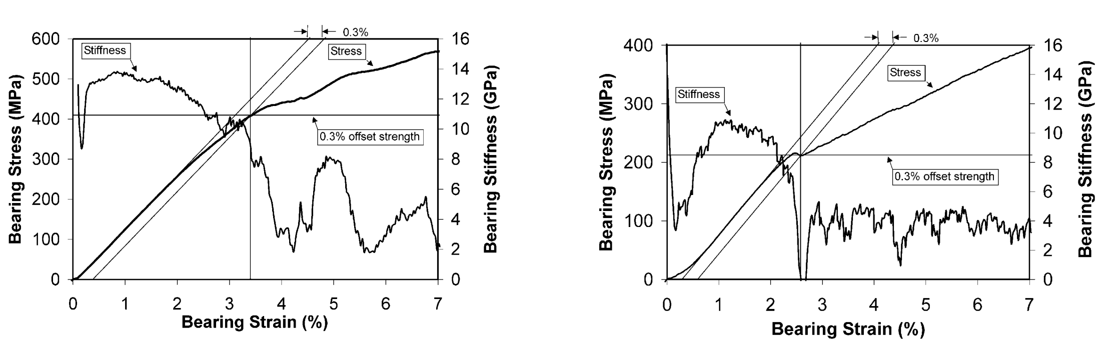
(a) C1 clearance (b) C4 Clearance

Fig. 12. Damage at 15 kN applied load.

A second point is that an offset strength is not directly based on any physical principle. This point is illustrated in Fig. 13, which shows bearing stress–strain curves for joints with protruding head and countersunk head bolts. Shown also is the slope of each of these curves (i.e. the bearing stiffness) as a function of bearing strain - note that the stiffness is on a different scale (shown on the right of the figure) from the stress. A calculation of 0.3% offset strength is shown for each curve. Note that 0.3% is not suggested as a suitable value, but is only selected to make the point. It can be seen that the two joints are in quite different states of damage at the 0.3% offset stress. The countersunk joint has undergone a total loss of stiffness, whereas the stiffness of the protruding head joint has only dropped by about 40%. Other examples could undoubtedly be found which would even better illustrate this point.

The third point is that some judgement is involved in calculating the slope of the linear region, and hence the 2% offset strength, which could lead to variability from operator to operator. In fact, Fig. 13 illustrates that a truly linear (constant stiffness) region rarely exists, so judgment will obviously be needed in deciding the region over which to calculate the slope. If the offset line happens to intercept the stress-strain curve at a region of fast-changing slope (at a "knee" in the curve), small differences in selection of the stiffness could lead to large differences in offset strength.

An alternative analysis of strength is now presented which is only applicable at much lower levels of damage than the 2% offset strength. The method may be of interest, for example, to researchers using finite element analysis with progressive damage methods to track the progression of damage in the joint, or to designers seeking a criterion involving lower damage levels. The method is based on calculating the stress level at which the stiffness of the joint has decreased from its maximum value by a certain percentage (e.g. the "strength



(a) Protruding head bolted joint (b) Countersunk head bolted joint

Fig. 13. Example of how offset strength can correspond to different levels of stiffness loss.

at 20% drop in stiffness''). Before proceeding, it should be pointed out that the stiffness presented in Fig. 13 has been calculated as a moving average of the values from seven adjacent pairs of data points in the load deflection curve. Before this smoothing operation, the stiffness plot was extremely noisy which obscured the interesting trends. The window size of seven was chosen after experimentation, and is not suggested as being optimum—in fact, the appropriate window size depends on the frequency at which the original data was collected. Large window sizes though tend to miss ''significant events''.

It is instructive to plot bearing stiffness against bearing stress instead of strain, since the near rigid body motion that occurs in the finger-tight, large clearance joints, and shows up as bearing ''strain'', is factored out. Fig. 14 shows these plots for the largest and smallest clearances (C1 and C4) for each of the four configurations. Though some variability in these plots obviously occurs within a given configuration, nevertheless there are distinct shapes to the curves for each configuration that are well represented by these curves. The most variability in curve shape was found in the torqued C4 clearance joints, so two C4 configurations are shown for this configuration, which illustrate the range of this variability [Fig. 14 (d)]. The following points are evident from Fig. 14. Firstly, the reduction in stiffness with increased clearance is clearly seen for all configurations, at all stress levels up until significant damage has occurred. Secondly, the stiffness of the larger clearance (C4) joints increases more gradually with increasing stress than that of the C1 joints, and reaches a maximum later. This is consistent with the findings of previous researchers who have found from finite element studies that the bolt-hole contact area in neat-fit joints reaches its maximum almost immediately on loading, but increases gradually with load in clearance fit joints [1, 6, 8, 10, 12]. Thirdly, the stress levels advised in the ASTM standard [19] for calculation of the joint stiffness (172–276 MPa) are clearly not appropriate for most of the configurations tested here since a constant stiffness does not exist between these two levels.

Two quantities of potential interest are the stress at first significant stiffness loss, and the rate of stiffness loss after this occurs. Deciding where first ''significant'' stiffness loss occurs is contentious, as illustrated by the C1 curve in Fig. 14(a). A drop obviously occurs at about 100 MPa applied stress—on the other hand, one could take the view that the stiffness is essentially constant between 40 and 220 MPa applied stress, and that the first really significant drop occurs at 220 MPa. Taking this latter viewpoint, the stress at first significant stiffness loss was estimated for all tests—obviously there is some judgement involved in these values. In addition, the stress at percentages of stiffness loss from the *maximum* value (*not* the value at first ''significant'' loss) was also calculated—these latter values require no judgement since the maximum value and the percentage drop are not open for debate (the operator merely has to be careful to avoid some very high values which can occur at the start and end of the test). The only judgement that can influence the result is the choice of window size

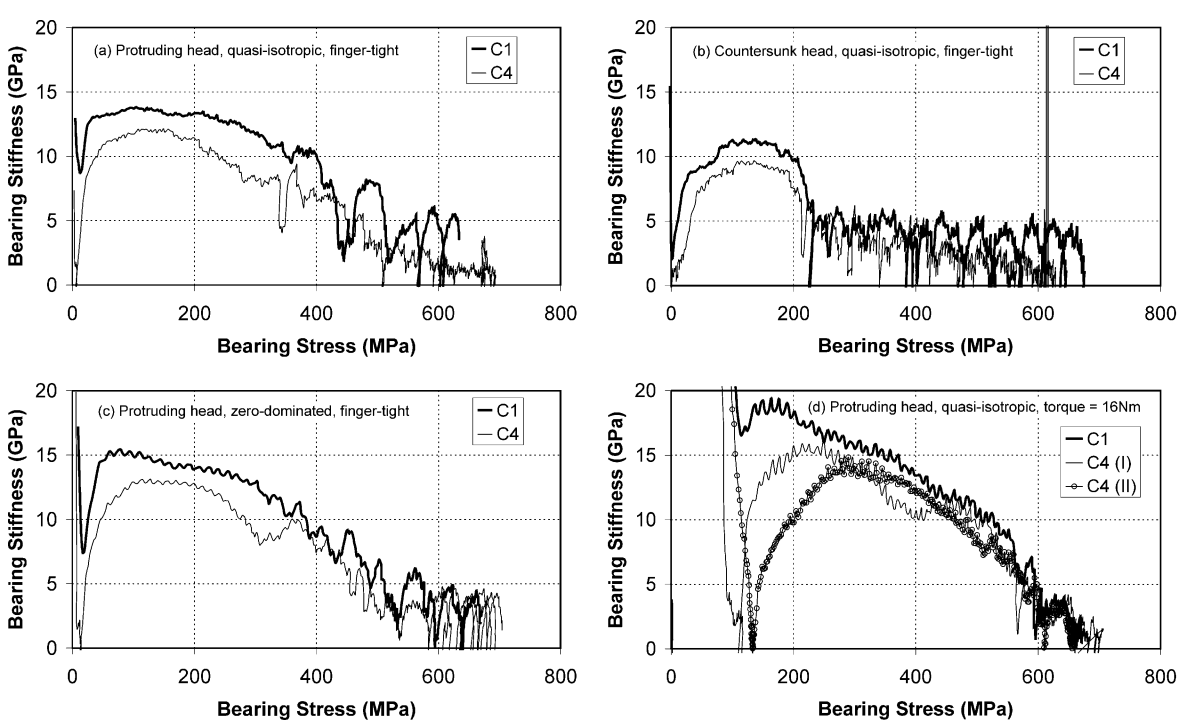


Fig. 14. Joint bearing stiffness variations with increasing applied bearing stress.

to use for smoothing the stiffness data at the start. The results from this analysis are shown in Fig. 15. Note that each data point is an average of several tests. Error bars are not shown as they would obscure the graph, but statistical variance is discussed below.

The results provide a map of the average progression of stiffness loss in each test series. Moving vertically in a graph, as the lines get closer together, the rate of stiffness loss is increasing [e.g. the catastrophic nature of the stiffness loss in the countersunk joints is seen by this method in Fig. 15(b)].

Fig. 15(a) shows that for the finger-tight joints with protruding head bolts and quasi-isotropic lay-up, the first significant stiffness loss occurs at lower stress levels with higher clearances, while the rate of stiffness loss up until 60% loss in stiffness, is faster in the larger clearance joints. The former point could be open to debate, but the latter point is not. The higher rate of stiffness drop-off in the larger clearance joints can also be clearly seen in the sample joints illustrated in Fig. 14(a) (between 200 and 300 MPa bearing stress). However from Fig. 15(a), at 70% loss in stiffness, the failure becomes more catastrophic and the effect of clearance is (temporarily at least) lost.

Fig. 15(b) shows that the catastrophic nature of the stiffness loss in the countersunk joints means that clearance has little effect on the rate of stiffness loss.

Fig. 15(c) rather interestingly shows that the low clearance (C1), zero-dominated joints start to lose stiffness at quite low applied stress levels, but the rate of stiffness loss is then quite slow. This is clearly illustrated by the sample joint shown in Fig. 14(c). The larger clearance joints reach each level of stiffness loss in Fig. 15(c) at lower stress levels than the low clearance joints, i.e. rate of stiffness loss is faster in the larger clearance joints.

The torqued joints are quite different from the others. The initial stiffness, before the joint begins to slip, is not shown in Fig. 14(d), because it is off-scale, but it is not even approximately constant, and starts to drop off as soon as load is applied. After slip, the C1 curve reaches a short region of constant stiffness (from 140 to 200 MPa), before dropping off. The stress at stiffness drop-off (about 200 MPa) is similar to that in the finger-tight

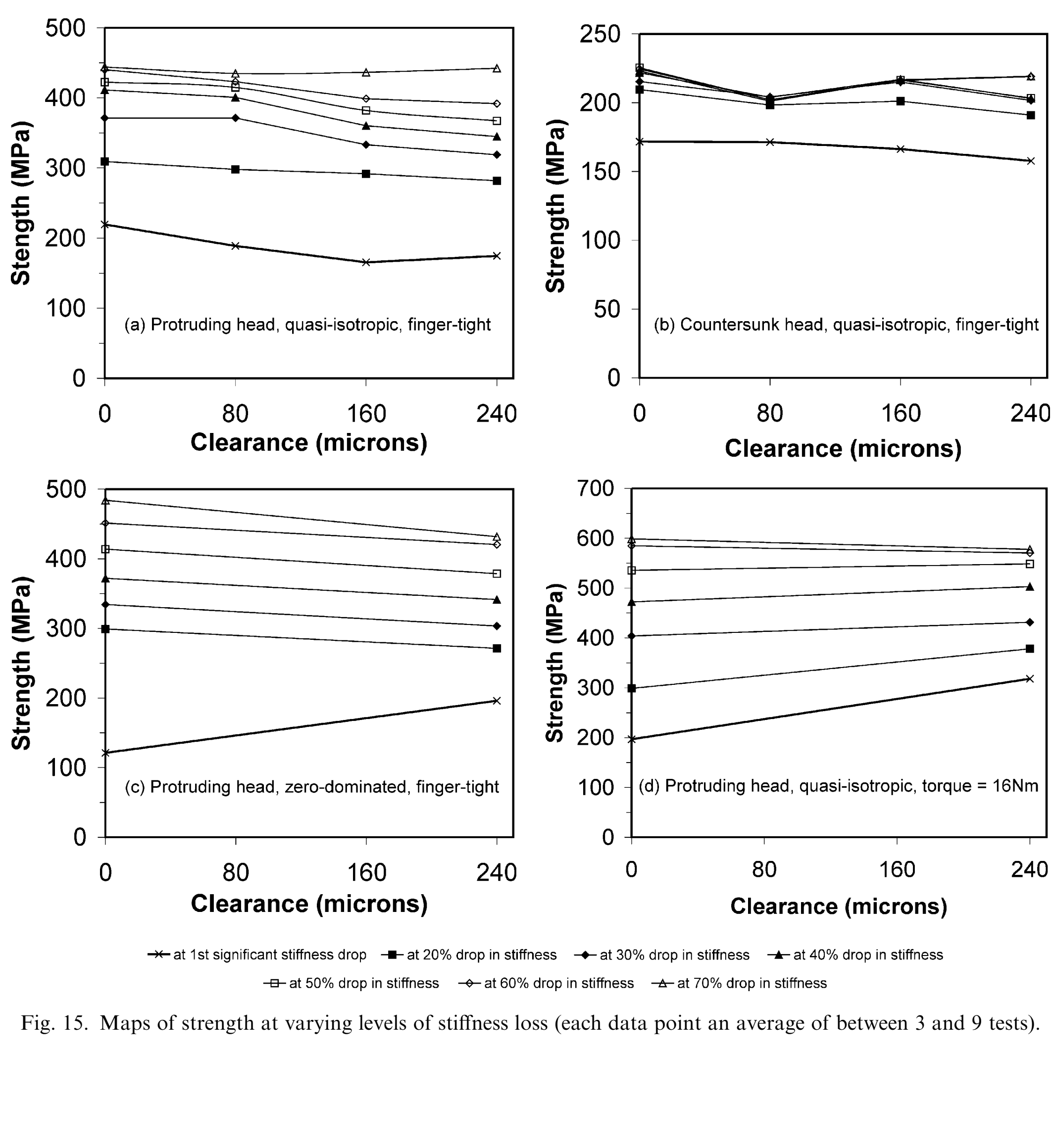


Fig. 15. Maps of strength at varying levels of stiffness loss (each data point an average of between 3 and 9 tests).

Table 9
Effect of clearance on strength at 30% drop in stiffness (units: MPa)

Configuration	Protruding head, quasi-isotropic, finger-tight				Countersunk head, quasi-isotropic, finger-tight				Protruding head, zero-dominated, finger-tight		Protruding head, quasi-isotropic, torqued to 16 Nm	
Clearance	C1	C2	C3	C4	C1	C2	C3	C4	C1	C4	C1	C4
No. of tests	4	5	6	7	3	3	3	3	4	6	3	4
Average value	371.4	371.3	333.1	318.9	215.4	204.2	215.0	201.7	334.3	303.5	403.9	431.5
S.D. (% of mean)	17.5 (4.7%)	26.4 (7.1%)	48.2 (14.5%)	24.8 (7.8%)	13.7 (6.4%)	1.5 (0.8%)	6.2 (2.9%)	20.8 (10.3%)	11.6 (3.5%)	21.7 (7.1%)	12.7 (3.1%)	53.2 (12.3%)
Diff from C1 (p value)	–	*−0.02%* (0.50)	*−10.3%* (0.060)	−14.1% (0.0017)	–	*−5.19%* (0.15)	*−0.19%* (0.48)	*−6.4%* (0.48)	–	−9.2% (0.0097)	–	*+6.8%* (0.20)

specimens [Fig. 14(a)], which is surprising since a significant percentage of the load should be taken by friction in the torqued joint. Thus, the actual bearing stress on the hole is likely to be considerably less than 200 MPa (for this reason the term ‘‘bearing stress’’ as calculated by Eq. (1) is probably not appropriate for torqued joints). An analysis with microscopy is planned for a future paper, which may give further insight into this result. Even though stiffness loss begins quite early, catastrophic stiffness loss is avoided until about 550 MPa, compared to about 400 MPa in the untorqued joint [Fig. 14(a)], which helps to explain the higher 2% offset strength in the torqued joints. The torqued C4 joints are quite scattered, but in general, these joints reach their maximum stiffness (after the joint has slipped) at higher stress levels than any other configuration. In fact, the C1 joint has lost substantial stiffness before the C4 joints even start to lose stiffness. However, Fig. 15(d) illustrates that, on average, the C1 joints eventually catch up with the stiffness loss in the C4 joints, so that by 70% stiffness loss, there is little to choose between the two clearances.

To illustrate the statistical significance of the results in Fig. 15, the strength criterion of ‘‘strength at 30% stiffness loss’’ is chosen for more detailed presentation in Table 9. Any other level of stiffness loss could of course be chosen as a criterion. It is noticeable that some of the results have high standard deviations that render the corresponding results statistically insignificant. High scatter can occur for example, when one curve has a high, narrow peak, that gives an unusually high maximum. Scatter could possibly be reduced by smoothing with a larger window size or by using judgement to pick the ‘‘maximum’’, avoiding ‘‘anomalous’’ peaks. This latter approach though would detract from the advantage this method has of not requiring operator judgement. It can be seen that the two configurations that show a clear, statistically significant link between strength (as defined by this criterion) and clearance are the finger-tight joints with protruding head bolts (both zero-dominated and quasi-isotropic lay-ups). These are the same configurations that showed a link between clearance and 2% offset strength, thus the ‘‘short-term’’ behaviour coincides with the ‘‘long-term’’ behaviour. However, comparing with Table 6, the link is stronger in the Table 9, since the differences between C1 and C4 clearances are larger, and the p values are smaller.

The strength criterion presented in this section has some advantages in that it does not require any judgement on the part of the user, and it is based more closely on the physics of the situation, than an offset criterion. However, it is not applicable after the first catastrophic stiffness loss, and it does suffer from a relatively high level of scatter. This latter problem could possibly be ameliorated with fine-tuning of the method. Though a criterion based on stiffness loss is more closely related to the physics of the problem than one based on an offset, it is still debatable to what extent ‘‘stiffness loss’’ is related to material damage. It is suggested that in low clearance joints, stiffness loss is a good measure of severe damage events such as fibre damage and delamination. However, in large clearance joints the stiffness is determined by two factors, one of which (bolt-hole contact area) has a positive effect on stiffness as the applied stress increases, the other of which (damage) has a negative effect on stiffness as the stress increases. The maximum stiffness is reached when the effect of damage outstrips that of contact area. Hence, significant damage may occur before the maximum stiffness is achieved.

4. Concluding remarks

Many previous studies, citing the higher radial stresses in clearance-fit joints, have postulated a lower load capacity as a result. However, little experimental evidence has been published to test this hypothesis. In the present study, clearances up to and slightly beyond those normally found in aircraft composite joints have been tested for a single-lap, single-bolt configuration for a representative range of lay-ups, torque values, and bolt types, and strength values have been obtained according to definitions in a Standard available in the public domain [19]. The results show that 2% offset strength shows a relatively small dependency on clearance, for finger-tight joints with protruding-head bolts (a drop of 7.5% at a clearance of 240 μm or 3% of hole diameter). Countersunk joints and fully torqued joints showed no such dependency. Ultimate bearing strength showed no statistically significant trend with clearance. The results are quite similar to those of DiNicola and Fantle [14] for pin joints, and it can be expected that if clearances as large as those used in their study were examined (up to 8.8%), losses in 2% strength as large as theirs might have been found. Losses in ultimate strength as high as 30% were found by Pierron et al. [15] but their clearances were as high as 11% and the smooth load-deflection curves from their $\pm 45^{\circ}$ woven glass fibre epoxy joints were not at all representative of the carbon/epoxy materials used in this study. Thus, for single-lap, single-bolt carbon/epoxy joints, the effects of clearances in the range used by the aircraft industry on joint strength, as defined by this ASTM Standard, have been shown here to be small.

On the other hand, some authors have indicated that the effects of clearance on joint stiffness would be much less significant than the effects on strength [6,15]. For the range of parameters tested here this has not been the case, with typically a 10% loss of joint stiffness occurring with a clearance of 240 μm. This may not be greatly significant in itself, but it does have implications for multi-bolt joints, where a large clearance in one hole would lead to low stiffness at that hole, and transfer of load to other holes.

Another result that has significance for multi-bolt joints is the delay in load take-up that occurred with the larger clearance joints. Obviously, in a production situation, bolts would not necessarily be centred in their holes, as they were here due to use of a special jig, but the results do indicate that larger clearance holes may not transfer any load for some portions of loading cycles in multi-bolt joints. This may have significant implications for failure at other holes, and for the joint as a whole.

Even though strengths, as defined in the ASTM Standard [19], did not show much dependency on clearance, Fig. 12 shows a significant difference in levels of damage in the laminate at similar load levels, due to clearance. Possibly because of this increased laminate damage, the bolts in the larger clearance joints survived longer, resulting in larger strain and energy absorption in the larger clearance joints. This may not have any practical consequences for design of joints for in-service loads, but could be of interest in the design of joints to absorb energy (e.g. in crashworthy structures). If one was to generalise this result, it may be that in joints with an ultimate failure mode of bolt failure, it is advantageous from an energy-absorption point of view to have a more damageable laminate.

Finally, the significant effect of clearance on damage seen in Fig. 12, compared to the relatively small effect on 2% offset strength, prompted a critical look at this criterion as a measure of strength. An alternative measure of strength, based on stress at a given percentage loss in stiffness has been presented, and the results show that, with this measure of strength, the link between clearance and strength is stronger. Again though, only the finger-tight joints with protruding-head bolts show a dependency—countersunk and torqued configurations do not. This alternative measure of strength has the advantages that it is not dependent on judgement of the user, and is more closely related to the physics of the problem than a measure based on an offset criterion.

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