Effects of Variable Clearance in Multi-Bolt Composite Joints on Fatigue Life

V.P. Lawlor, M.A. McCarthy, W.F. Stanley

Composites Research Centre, Dept. Mechanical and Aeronautical Engineering,
University of Limerick, Ireland

ABSTRACT

This paper presents an experimental study of the effects of variable bolt-hole clearance in multi-bolt composite joints on fatigue life. Both single-lap and double-lap configurations have been examined. Specialised tooling and jigs have been used for drilling the holes to a high level of precision in terms of position and size. The clearance cases examined were joints with all neat-fit holes and joints with one loose-fit hole. The loose-fit clearance was slightly larger than that allowed in the aircraft industry. Constant amplitude, fully reversed loading was performed, with precautions taken to avoid specimen buckling and excessive temperature rise. A variety of failure modes were found in the single-lap joints, while the double-lap joints failed through hole elongation only. A clearance-fit hole has been found to reduce fatigue life. The number of cycles to *initiation* of hole elongation was particularly sensitive to the presence of a loose-fit hole.

1. INTRODUCTION

An understanding of bolted joint behaviour is essential to the design of efficient aerospace structures from carbon-fibre reinforced polymer materials. 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 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 concerned with single-bolt joints. Of the few studies on the effects of clearance in multi-bolt joints, almost all have dealt with quasi-static loading [1-4].

Concerning bolt-hole clearance and its effects on joint fatigue life, Hart-Smith [5] commented on the likely negative effects of clearance fits on the fatigue life of composite joints due to bolts moving back and forth in the hole under tension-compression fatigue loading. The author stated that the fasteners in composite joints should not be loose. On the other hand, he stated that the laminates should not be damaged by the installation of fasteners with an excessive interference fit. Kim [6] presented similar findings and stated that the residual strength of a bolted joint depended on how well the bolt fits within the hole. When a loose bolt in a hole is shifted back and forth, the hole elongates at an increasing rate and failure occurs. A neat-fit bolt also promotes uniform sharing of load between multiple fasteners. Therefore Kim stated that it is important that all bolts in composites fit neatly. However neither of these publications gave a clear definition of just how much clearance is acceptable or how much the fatigue life is shortened by loose bolts. As noted above it is impossible in practice to ensure zero clearance in all holes, and a range of bolt-hole fits will be allowed in a production environment. Therefore some quantified information on this subject is desirable.

This paper presents an experimental study of the effects of variable bolt-hole clearance in multi-bolt composite joints on fatigue life. The study involved single-shear and double-shear, three-bolt specimens, with two different clearance conditions, tested under fully reversed, constant amplitude loading. Results are presented in terms of S-N diagrams, and an analysis of the failure mechanisms is given. The work was performed as part of an EU sponsored project on bolted joints in composites [7].

2. EXPERIMENTAL METHODS

The single-lap specimen geometry is shown in Figure 1 and the double-lap geometry is shown in Figure 2. Also shown in these figures for reference is the hole numbering used here. The width-to-diameter and edge-to-diameter ratios were the same for both joints (w/d = 6, e/d = 3). All tests were carried out with protruding-head titanium alloy bolts, torqued to finger-tight conditions, with steel washers on nut and head side and a locknut on the nut side. Locknuts were used in the fatigue tests since standard steel nuts would open quite easily under fatigue conditions, especially since the joints were only tightened to a finger tight torque. Finger tight conditions were used based on the finding of previous authors (e.g. [8]) that it is not acceptable to rely on the beneficial effects of torque because bolt loosening and viscoelastic effects in the composite under service conditions result in reduced bolt clamping effectiveness. The laminates were manufactured from graphite/epoxy HTA/6376, and had balanced, symmetric and quasi-isotropic lay-ups: $[45/0/-45/90]_{5s}$ for the laminates in the single-lap joints, $[45/0/-45/90]_{4s}$ for the centre (skin) plate in the double-lap joints, and $[45/0/-45/90]_{2s}$ for the outer (splice) plates in the double-lap joints. Nominal ply thickness was 0.13mm, giving the laminate thicknesses shown in the figures. All bolts, nuts and washers were aerospace grade, supplied by an aircraft manufacturer in the project consortium.

The bolts had nominal diameter 8 mm, with an f7 ISO tolerance. Variable bolt-hole clearances were obtained by using (nominally) constant diameter bolts and variable hole diameters. Two reamers of different diameters were used to finish the holes. The reamers were specially made for the project (by an aerospace supplier) with a tight (h6) tolerance. Further details on the actual clearances obtained with this tooling are given in the companion paper on quasi-static loading [9]. The different clearance cases studied are shown in Table 1. For the single-lap joints, case C1_C1_C1 (neat-fit clearances in all holes) and C1_C1_C4 (loose-fit clearance in Hole 3 of 240 microns on the diameter) were studied, while for the double-lap joints, C1_C1_C1 and C4_C1_C1 (loose-fit in Hole 1) were studied. Eight specimens of each clearance condition and joint configuration were considered, giving 32 specimens in all.

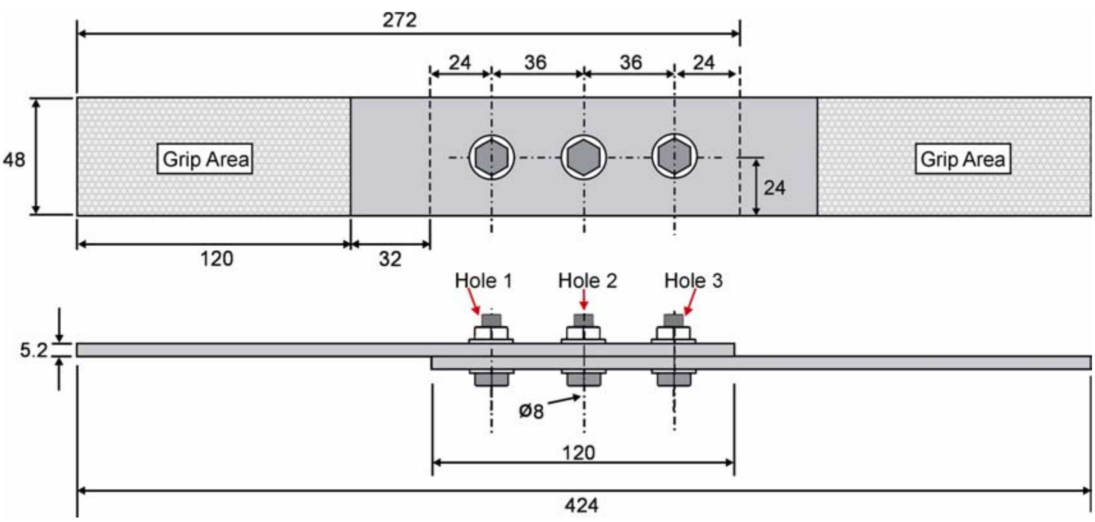


Figure 1 Single-lap specimen geometry with hole numbering (all dimensions in mm)

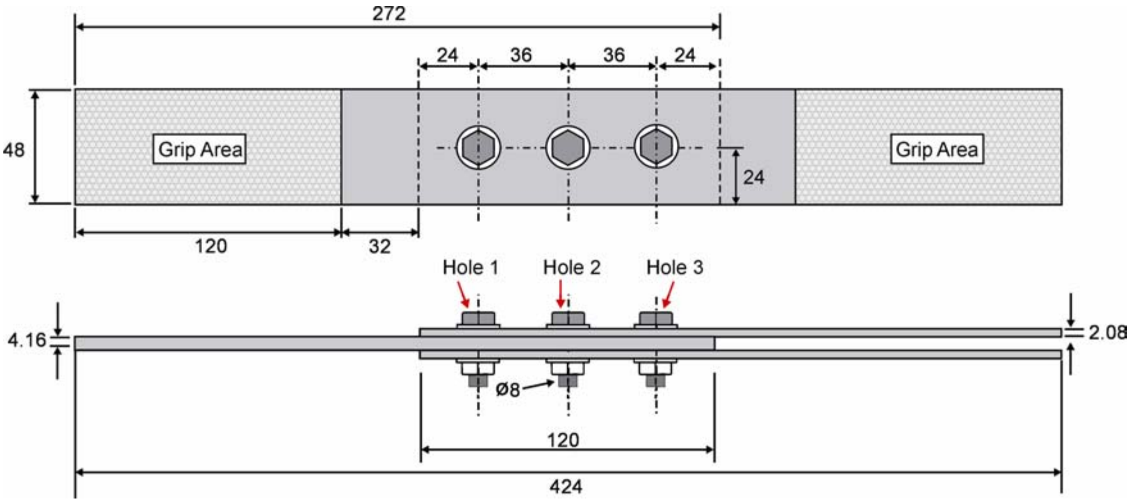


Figure 2 Double-lap specimen geometry with hole numbering (all dimensions in mm)

Table 1 Joint clearance cases

	Nominal Clearance (μm)		
Case Code	Hole 1	Hole 2	Hole 3
C1_C1_C1	0	0	0
C4_C1_C1	240	0	0
C1_C1_C4	0	0	240

For precision drilling of the holes, a multi-bolt drilling jig was designed as shown in Figure 3 (the configuration shown is for drilling of the single-lap joints). All material used was mild steel ground flat stock except for the precision dowel pins. Of critical importance was the location of two of these dowel pins, which fixed the position of the edges of the laps of the joint to give a precise overlap length of 120 mm. These pins were located in a stationary back-stop against which the laminates were placed. A moveable slide was then pushed up against the other edges of the laminates to prevent them from moving. The laminates were then clamped in position, with Perspex sheets placed above and below the area in which the holes were to be drilled to prevent entry and exit damage to the laminates; a slot was drilled in the jig to allow insertion of the Perspex sheets below the specimen. Drilling, reaming and countersinking was carried out on a Hurco 3-Axis digitally controlled milling machine. An edge finder in the machine head initially determined the principal locating datum lines. These datum lines consisted of the edge of the backstop and the sides of the dowel pins. These coordinates were entered into the machining program and all holes were subsequently drilled relative to these lines to a high degree of precision. Slight modifications to the drilling jig was necessary in order to accommodate the double-lap shear configuration. A second stationary back-stop was manufactured incorporating three locating pins. This enabled the three laps of the double-lap joint to fit securely in position when drilling giving a precise overlap length of 120 mm.

The loading cycle applied to all samples was a constant amplitude sine wave with a stress ratio of R= -1 ($\sigma_{min}/\sigma_{max} = -1$). This fully reversed cycle is considered the most severe type of constant amplitude fatigue loading, and leads to the shortest fatigue lives.

The test set-up is illustrated in Figure 4. On the compressive stroke of the fatigue cycles, buckling of the joints was a strong possibility, so lateral supports were used to prevent this. Teflon sheets attached to brass backing plates were used to minimise friction between the contact surface of the specimen and the lateral support, which is similar to the approach taken in [10].

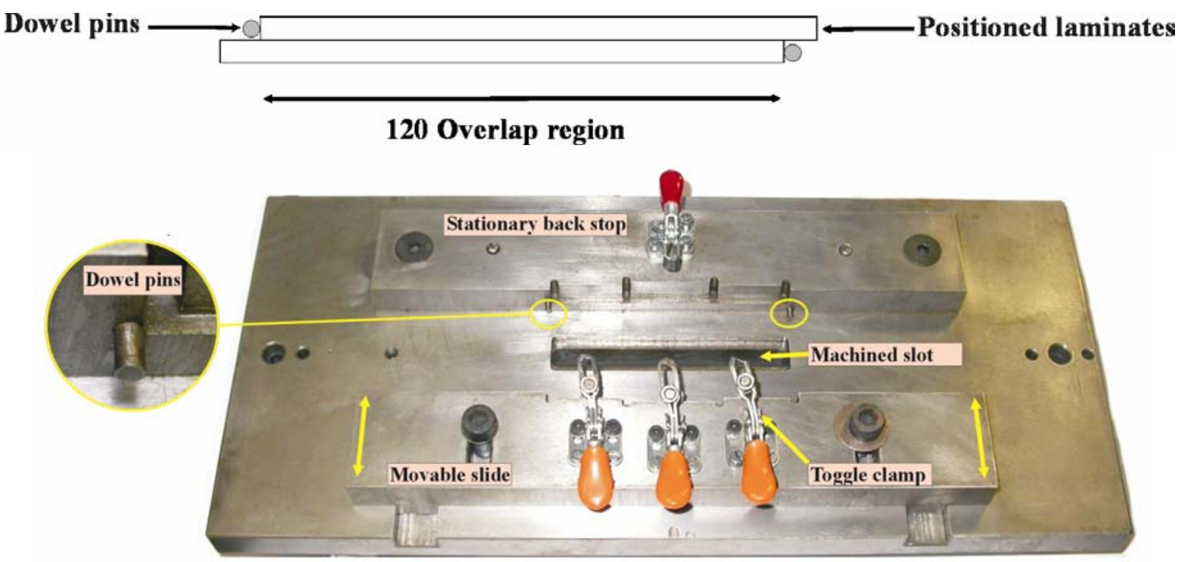


Figure 3 Multi-bolt joint drilling jig (single-lap version)

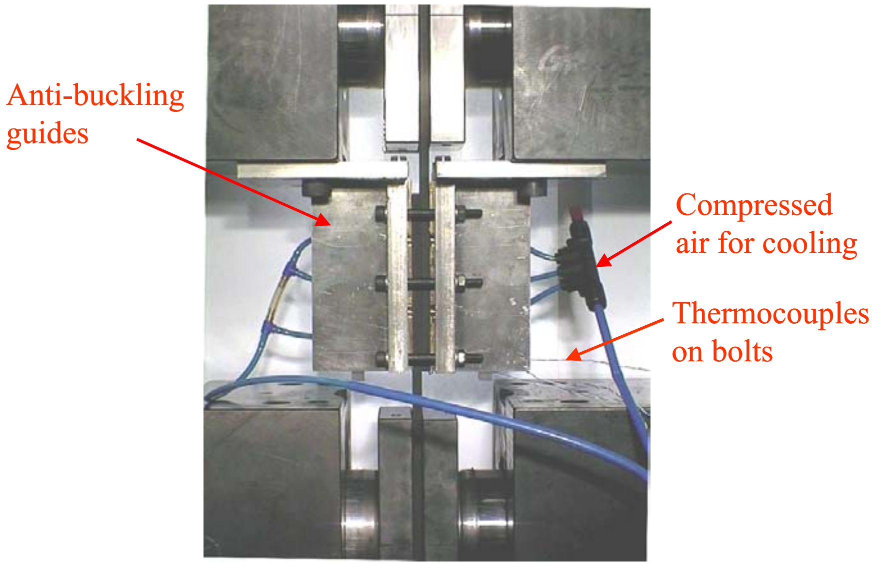


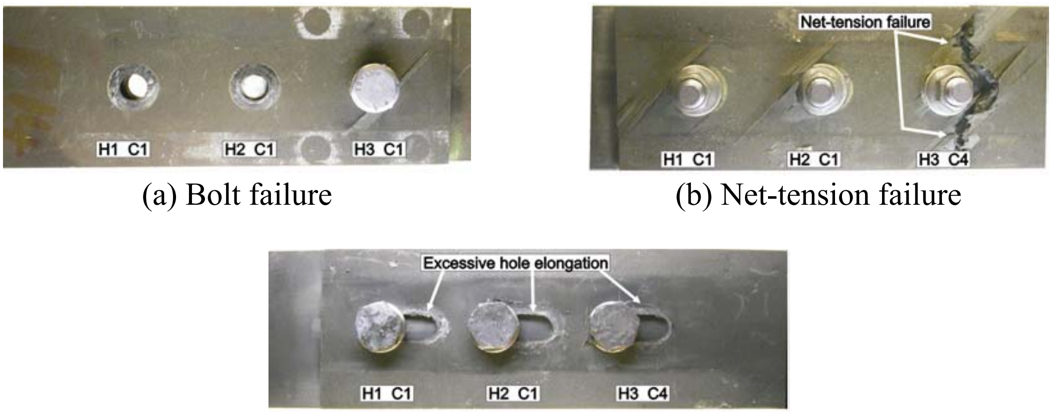
Figure 4 Test set-up for fatigue tests (showing single-shear specimen)

Another factor to be considered was the potential for significant temperature increase, due to relative motion between the joint parts. If it became excessive, it would cause premature failure of the joint. To help avoid this, frequencies of between 0.66 Hz and 5 Hz were used (higher frequencies were used for joints tested at lower loads). In addition, a cooling system using compressed air directed onto all three bolts was implemented, and the temperature of each bolt was monitored using thermocouples (see Figure 4). Bearing in mind that the temperature on the surface of the bolt is likely to be less than in the interior of the joint, the target maximum temperature for the bolt surface was set to 25^{o}C, and test frequency was adjusted to try to maintain temperatures below this. This criterion was somewhat more stringent that used by Starikov and Schön [10] who maintained the bolt temperature below 33^{o}C, but they did not use any cooling. Generally, the temperature criterion was met until close to final failure, when the temperatures rose sharply.

As suggested in [10], a hole elongation failure criterion, defined as an increase in peak-to-peak displacement of 0.8 mm, was used. The initial deflection of the joint was sampled at the start of the test and then the deflection was regularly sampled thereafter at set intervals. The difference between the displacement measured after a certain number of cycles (δ) and the displacement measured initially (δ_0) is referred to as $\Delta\delta$ and when $\Delta\delta$ reached 0.8 mm, the criterion was said to have been reached.

However, for the single-lap joints, on continuation of tests beyond this point, catastrophic failure eventually resulted in most tests, so a second failure criterion based on ultimate failure was also used. All tests were eventually stopped at a displacement of + or - 10 mm (which occurred suddenly in catastrophic failure cases and gradually in extensive hole elongation failure cases) to avoid damage to the machine. Thus when this displacement was reached, ultimate failure was said to have occurred, and the cause of the ultimate failure (i.e. bolt failure, net-section tension failure or excessive hole elongation) was recorded. Examples of the three different types of ultimate failure in the single-lap joints are shown in Figure 5.

Load levels were selected as percentages of the quasi-static strength, based on static test results, and were chosen in an iterative fashion as results became available, in order to try to give as wide a spread in fatigue life as possible.



(a) Bolt failure

(b) Net-tension failure

(c) Excessive hole elongation

Figure 5 Examples of the ultimate failure modes in the single-lap joints; double-lap joints exhibited hole elongation only

3. RESULTS

The fatigue life of the single-lap joints in terms of number of cycles to an increase in peak-to-peak displacement of 0.8 mm is shown in Figure 6. The fatigue life in terms of cycles to ultimate failure is shown in Figure 7. Information on the applied loads, frequency and ultimate failure mode is given in Table 2 for the C1_C1_C1 (all neat-fit) case and in Table 3 for the C1_C1_C4 (one loose bolt) case. Results from the quasi-static tests to ultimate failure are included in the tables and in Figure 7 for reference. From the tables, it can be seen that for the highest load (± 55 kN) the ultimate failure mode was net tension for both clearance configurations, while at lower loads it was bolt failure (with the exception of two specimens that exhibited large hole elongations without any catastrophic failures). The one specimen tested at ± 22.5 kN went to 10^6 cycles without reaching final failure. No particular pattern of bolt failure was evident, with some joints exhibiting two bolt failures, some three, some bolt failures being on the head side and some on the nut side.

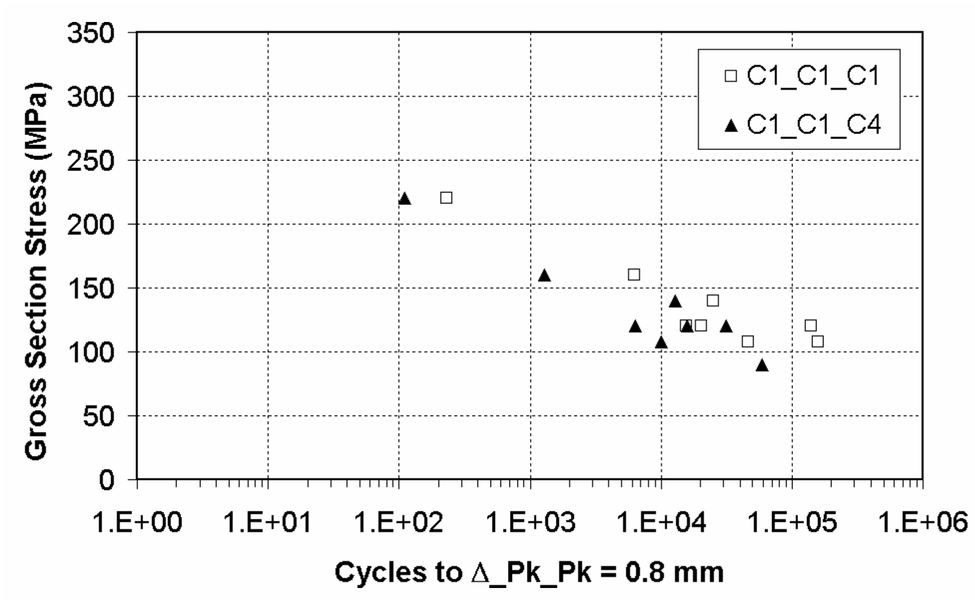


Figure 6 Single-lap joints - cycles to "Hole elongation failure", i.e. increase in peak-to-peak displacement of 0.8 mm

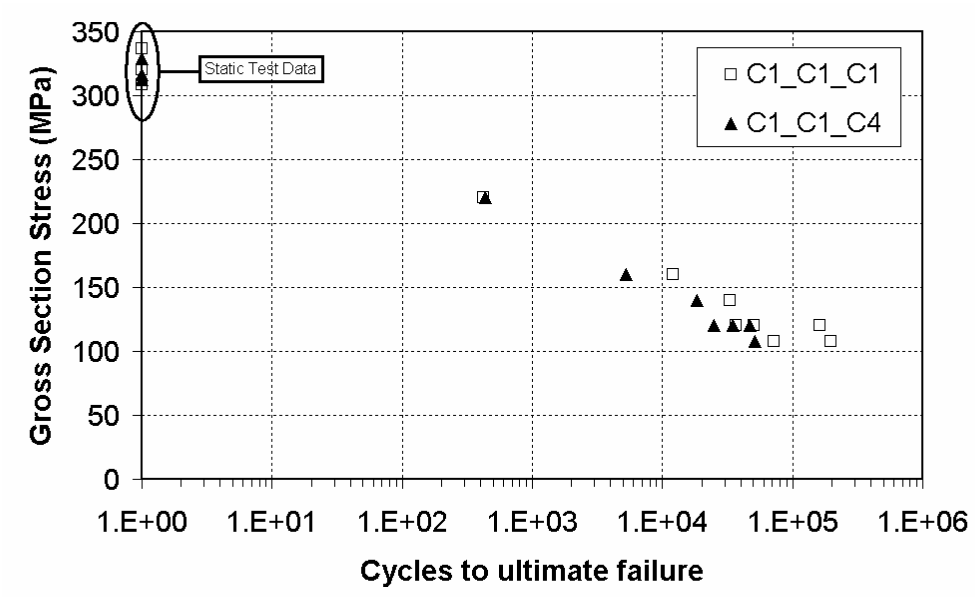


Figure 7 Single-lap joints - cycles to ultimate failure

Table 2 Fatigue data for single-lap joints with all-neat-fit bolt-holes (C1_C1_C1)

Specimen Number	Load (kN)	Frequency (Hz)	Number of cycles to hole elongation failure*	Number of cycles to ultimate failure**	Ultimate Failure mode
C1_C1_C1_Static_1	77	0 (quasi-static)	1	1	Bolt failure
C1_C1_C1_Static_2	84	0 (quasi-static)	1	1	Net tension
C1_C1_C1_Static_3	80	0 (quasi-static)	1	1	Net tension
C1_C1_C1_55_1	± 55	0.66	233	421	Net tension
C1_C1_C1_40_1	± 40	0.66	6225	12111	Bolt failure
C1_C1_C1_35_1	± 35	1	24844	32841	Bolt failure
C1_C1_C1_30_1	± 30	1	15695	36820	Bolt failure
C1_C1_C1_30_2	± 30	1	139088	162724	Bolt failure
C1_C1_C1_30_3	± 30	1	20438	50451	Hole elongation
C1_C1_C1_27_1	± 27	2	46451	72519	Bolt failure
C1_C1_C1_27_2	± 27	1	159102	196511	Bolt failure

* Hole elongation failure: Increase in Peak to Peak displacement of 0.8 mm
** Ultimate failure: Displacement to + or – 10 mm (due to bolt failure, net tension failure or extreme hole elongation)

Table 3 Fatigue data for single-lap joints with one loose-fit bolt-hole (C1_C1_C4)

Specimen Number	Load (kN)	Frequency (Hz)	Number of cycles to hole elongation failure*	Number of cycles to ultimate failure**	Ultimate Failure mode
C1_C1_C4_Static_1	78	0 (quasi-static)	1	1	Net tension
C1_C1_C4_Static_2	79	0 (quasi-static)	1	1	Bolt failure
C1_C1_C4_Static_3	82	0 (quasi-static)	1	1	Net tension
C1_C1_C4_55_1	± 55	0.66	110	439	Net tension
C1_C1_C4_40_1	± 40	0.66	1300	5290	Bolt failure
C1_C1_C4_35_1	± 35	1	12935	18607	Bolt failure
C1_C1_C4_30_1	± 30	1	16011	35128	Hole elongation
C1_C1_C4_30_2	± 30	1	6403	25116	Bolt failure
C1_C1_C4_30_3	± 30	1	31593	47080	Bolt failure
C1_C1_C4_27_1	± 27	1	10090	51284	Bolt failure
C1_C1_C4_22.5_1	± 22.5	1	58811	10^6 without failure	N/A

* Hole elongation failure: Increase in Peak to Peak displacement of 0.8 mm
** Ultimate failure: Displacement to + or – 10 mm (due to bolt failure, net tension failure or extreme hole elongation)

Figures 6 and 7 generally indicate a shorter fatigue life for the joints with a loose-fit hole (C1_C1_C4 joints) although there is some overlap between the two clearance cases. The separation between the data for the two clearance cases is somewhat greater for the hole elongation criterion than for the ultimate failure criterion.

Examination of the evolution of the peak-to-peak displacement appeared to indicate that the joints with a loose-fit hole began damaging earlier. To examine this further a plot was made of the number of cycles to an increase in peak-to-peak displacement of 0.2 mm, as shown in Figure 8. In this case there is a clearer distinction between the results for the two clearance cases, with no overlap of data. Therefore it appears that for the single-lap joints, clearance had its most significant effect on failure initiation and had less effect on ultimate failure.

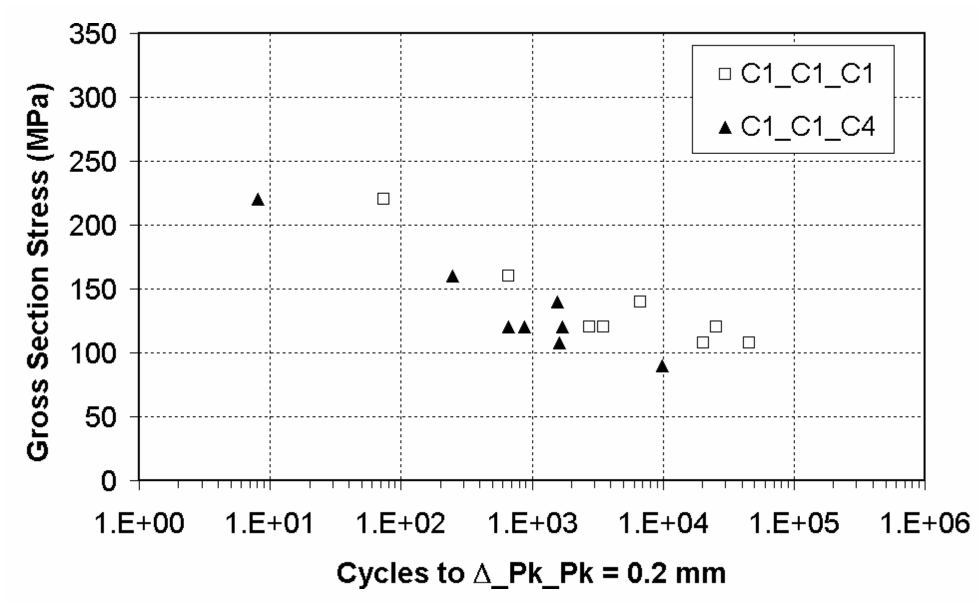


Figure 8 Single-lap joints - cycles to an increase in peak-to-peak displacement of 0.2 mm

For the double-lap joints, the same hole elongation failure criterion (peak-to-peak displacement increase of 0.8 mm) was used, but testing beyond this point only resulted in further (extreme) hole elongations and did not result in catastrophic failures such as bolt failure or net tension failures, so no ultimate failure criterion was used. Figure 9 shows the fatigue life of the double-lap joints using the hole elongation criterion. Information on the applied loads, frequency and ultimate failure mode is given in Table 4 for the C1_C1_C1 (all neat-fit) case and in Table 5 for the C4_C1_C1 (one loose bolt) case. The testing rig malfunctioned in one test, leaving usable results from 15 tests. Of these, two did not reach the prescribed hole elongation failure criterion (0.8 mm increase in peak-to-peak displacement), even after a very large number of cycles (approximately 12 and 24 million cycles respectively). Note that the test that went to 24 million cycles was performed mostly at 4.5 Hz, and so lasted two months. These two tests are indicated with an arrow in the S-N curve (Figure 9) to indicate "run-out". Again, Figure 9 indicates that a loose-fit hole shortens the fatigue life, although there is some overlap in the data. As was done for the single-lap joints, the cycles to a small increase in peak-to-peak displacement (0.2 mm) were also calculated, to see the effect of clearance on initiation of failure (not shown). Again, the distinction between the results for the two clearance cases was clearer when this criterion was used, indicating that clearance has its most significant effect on the initiation of damage.

4. CONCLUSIONS

In this paper, the effects of variable clearance in multi-bolt, composite joints on fatigue life have been studied experimentally. Both single-lap and double-lap configurations have been examined and fatigue life has been expressed in terms of cycles to a certain hole elongation and cycles to ultimate failure. Specialised tooling and jigs have been used for drilling the holes to a high level of precision in terms of position and size. The clearance cases examined were joints with all neat-fit holes and joints with one loose-fit hole. The loose-fit clearance was slightly larger than that allowed in the aircraft industry.

The single-lap joints displayed a variety of ultimate failure modes, with specimens fatigued at high load failing in net tension, while specimens fatigued at lower loads failed through bolt failure or hole elongation. In contrast no net tension or bolt failures were found for the double-lap joints. For both joint types, the joints with a loose-fit hole displayed a shorter fatigue life than the joints with all neat-fit holes. The effect was most pronounced on the number of cycles to failure initiation, and was less pronounced on the number of cycles to final failure. The reason for this is most likely as follows. In the joints with one loose-fit hole (e.g. C1_C1_C4 joint), failure initiates at one or both of the neat-fit holes (which are the most highly loaded holes initially). This failure will initiate earlier than in the joint with all neat-fit holes (C1_C1_C1), since the neat-fit holes in the C1_C1_C4 joint are more highly loaded than the corresponding holes in the C1_C1_C1 joint. Damage at the hole(s) where failure initiates then leads to hole elongation, which then tends to wipe out the initial differences in clearance that existed at the start of the test. This results in less of an effect on ultimate failure.

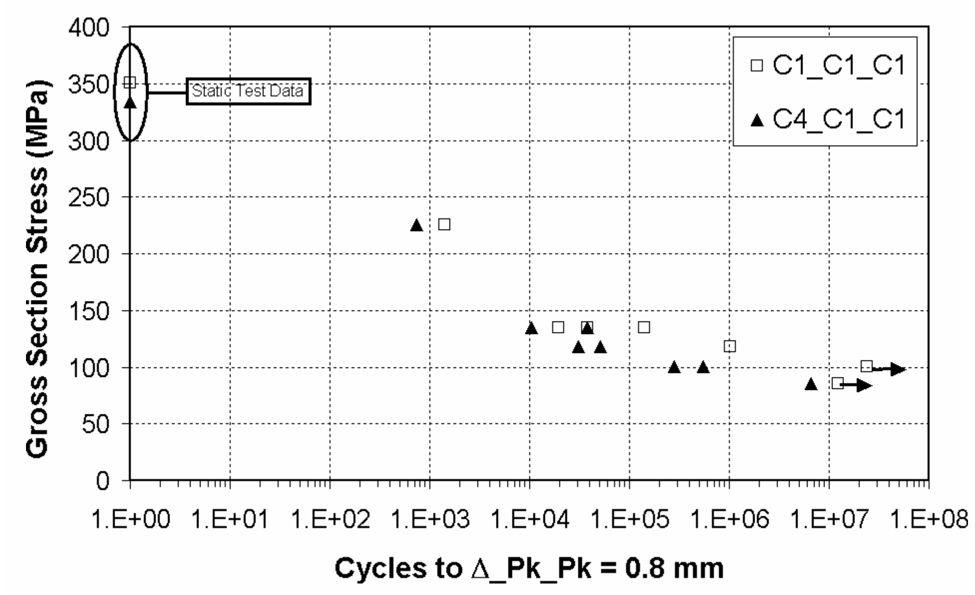


Figure 9 Double-lap joints - cycles to "Hole elongation failure", i.e. increase in peak-to-peak displacement of 0.8 mm. NOTE: Arrows indicate RUN-OUT, i.e. 0.8mm peak-to-peak increase was not reached

Table 4 Fatigue data for double-lap joints with all-neat-fit bolt-holes (C1_C1_C1)

Specimen Number	Load (kN)	Frequency (Hz)	Number of cycles to 0.2 mm Pk-Pk Increase	Number of cycles to 0.8 mm Pk-Pk Increase	Ultimate Failure mode	Total Number of cycles in test	Total Increase in Pk_Pk Displacement (mm)
C1_C1_C1_Stat	69.95	0 (quasi-static)	1	1	Net tension	1	-
C1_C1_C1_45_1	± 45	0.66	230	1,423	Hole elongation	2,143	14.556
C1_C1_C1_27_1	± 27	2	96,868	140,324	Hole elongation	147,405	1.987
C1_C1_C1_27_2	± 27	1	20,001	38,266	Hole elongation	46,625	17.91
C1_C1_C1_27_3	± 27	1	9,947	19,276	Hole elongation	25,466	4.83
C1_C1_C1_23_1	± 23.5	1.5	166,196	1,034,087	Hole elongation	1,098,514	4.811
C1_C1_C1_20_1	± 20	2	-	-	-	-	-
C1_C1_C1_20_2	± 20	3 - 4.5	7,863,248	Did not reach	Hole elongation	23,940,602	0.432
C1_C1_C1_17_1	±17	2.5 - 5	6,919,357	Did not reach	Hole elongation	12,226,420	0.462

Table 5 Fatigue data for double-lap joints with one loose-fit bolt-hole (C4_C1_C1)

Specimen Number	Load (kN)	Frequency (Hz)	Number of cycles to 0.2 mm Pk-Pk Increase	Number of cycles to 0.8 mm Pk-Pk Increase	Ultimate Failure mode	Total Number of cycles in test	Total Increase in Pk_Pk Displacement (mm)
C4_C1_C1_Stat	66.74	0 (quasi-static)	1	1	Net tension	1	-
C4_C1_C1_45_1	± 45	0.66	107	749	Hole elongation	1,348	17.767
C4_C1_C1_27_1	± 27	1	1,096	10,381	Hole elongation	18,363	9.515
C4_C1_C1_27_2	± 27	1	10,698	38,362	Hole elongation	47,218	4.74
C4_C1_C1_23_1	± 23.5	2.5	12,266	51,276	Hole elongation	62,283	7.875
C4_C1_C1_23_2	± 23.5	1.5	6,971	30,823	Hole elongation	39,720	2.878
C4_C1_C1_20_1	± 20	3	111,549	279,107	Hole elongation	476,982	5.23
C4_C1_C1_20_2	± 20	2.5	158,490	549,860	Hole elongation	615,743	1.03
C4_C1_C1_17_1	± 17	2 - 5	745,875	6,574,028	Hole elongation	9,844,391	0.894

ACKNOWLEDGEMENTS

This work was partially funded by "BOJCAS - Bolted Joints in Composite Aircraft Structures" which is a RTD project partially funded by the European Union under the European Commission GROWTH programme, Key Action: New Perspectives in Aeronautics, Contract No. G4RD-CT99-00036.

References

1. **Fan, W.** and **Qiu, C.,** "Load distribution of multi-fastener laminated composite joints", *International Journal of Solids and Structures*, **30**/21 (1993), 3013-3023.
2. **Kim, S.** and **Kim, J.,** "Finite element analysis of laminated composite plates with multi-pin joints considering friction", *Computers and Structures*, **55**/3 (1995), 507-514.
3. **McCarthy, M.** and **McCarthy, C.,** "Finite element analysis of the effects of clearance on single-shear, composite bolted joints", *Journal of Plastics, Rubber and Composites*, **32**/2 (2003), 65-70.
4. **Stanley, W., McCarthy, M., Lawlor**, **V.,** "Measurement of load distribution in multi-bolt, composite joints, in the presence of varying clearance", *Journal of Plastics, Rubber and Composites*, **31**/9 (2002), 412-418.
5. **Hart-Smith, L.,** "Design and empirical analysis of bolted or riveted joints" In Joining Fibre Reinforced Plastics, edited by Matthews, F.L., Elsevier Science, Chp. 6, (1987), pp.227-269.
6. **Kim**, **R.,** "Fatigue strength", ASM Engineered Materials Handbook, prepared by ASM International Handbook committee, Vol. 1 (1987), pp.436-444.
7. **McCarthy, M.,** "BOJCAS: Bolted joints in composite aircraft structures", *Air and Space Europe*, **3**/**4**/3 (2001), 139-142.
8. **Cooper, C.** and **Turvey, G.,** "Effects of Joint Geometry and Bolt Torque on the Structural Performance of Single Bolt Tension Joints in Pultruded GRP Sheet Material", *Composite Structures*, **32** (1995), 217-226.
9. **McCarthy, M., Lawlor, V., Stanley, W.,** "Effects of variable clearance in multi-bolt composite joints on load distribution and quasi-static strength, Proc. of ECCM-11, the 11th European Conference on Composite Materials, Rhodes, Greece, May 31st – June 3rd, 2004.
10. **Starikov, R.** and **Schon, J.,** "Fatigue resistance of composite joints with countersunk composite and metal fasteners", *International Journal of Fatigue*, **24** (2002), 39–47.