Effects of Variable Clearance in Multi-Bolt Composite Joints on Load Distribution and Quasi-Static Strength

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ABSTRACT

In this paper, the effects of variable clearance in multi-bolt, composite joints on load distribution and quasi-static strength have been studied experimentally. Both single-lap and double-lap configurations have been examined and two different methods of measuring load distribution have been used. Specialised jigs have been used for positioning the bolts in the holes and drilling the joints. The clearances examined ranged from neat-fit to clearances slightly larger than those allowed in the aircraft industry. Clearance has been found to have major effects on the load distribution in bolted joints, but negligible effect on ultimate strength. However, clearance had significant effects on initial failure such as bearing failure in one hole. The effects on initial failure may have relevance for limit load design of aircraft.

1. INTRODUCTION

Mechanical fastening remains the primary means of joining composite components in modern aircraft structures, due to the need for disassembly and inspection during the lifetime of the aircraft. The topic of bolted composite joints has been the topic of academic and industrial research for more than 30 years, but the majority of previous literature has involved neat-fit fastener holes. During manufacture however, the diameters of both the fastener and hole will follow a statistical distribution within allowable limits and fits. This is a function of process capability within the manufacturing environment and a range of bolt-hole fits are therefore unavoidable, because in any manufacturing process, a trade-off exists between maximising process quality (i.e. 100% repeatability) and minimising costs such as tooling and rework [1].

Quite a few studies have been performed on the effects of clearance in pin-loaded or single-bolt joints [1-7], but very few studies exist on the effects of clearance in multi-bolt joints. Fan and Qiu [8] performed a study of the effects of clearance on load distribution in multi-bolt joints using a purely analytical approach. Their configuration was a four-fastener, single-shear joint made of carbon–fibre laminates and the analysis was two-dimensional. Clearances examined included neat-fit, 30 μm and 60 μm, in 5 mm diameter holes. They found that with clearance fits in the inner two holes, a substantial amount of the load was transferred to the outer two bolts. They also found that the load distribution in this case became more even as the load increased. However, no experimental verification was performed. Kim and Kim [9] and McCarthy and McCarthy [10] also reported shifts in load away from clearance fit holes in finite element studies. The only experimental study on the topic was performed by Stanley et. al. [11], which confirmed that clearance fit holes result in an increased share of load at other holes. However this study was limited to single-lap joints and did not consider the effects of clearance on strength.

The present paper presents an experimental study of the effects of variable bolt-hole clearance in multi-bolt composite joints on load distribution and quasi-static strength. Both single-lap and double-lap joints are considered and two different methods of measuring load distribution are presented. The effects of clearance on both ultimate failure load and the load at which initial failure (e.g. bearing failure at one hole) occurs are considered. The work was performed as part of an EU sponsored project on bolted joints in composites [12].

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. Further details on these specimens are supplied in the companion paper on fatigue [13], the only difference being that regular steel nuts were used here instead of the locknuts that were used in the fatigue study.

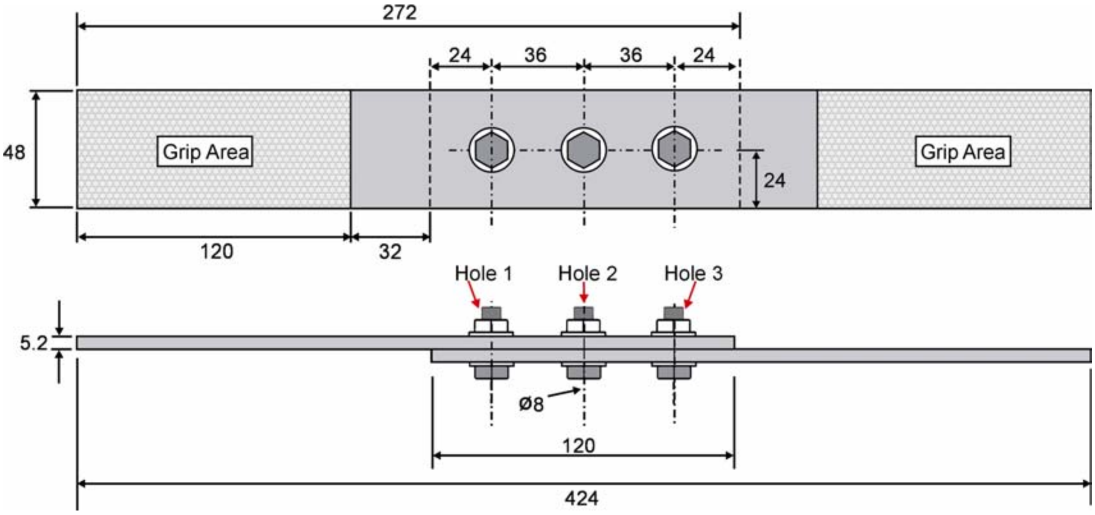


Figure 1 Single-lap specimen geometry with hole numbering (all dimensions in mm)

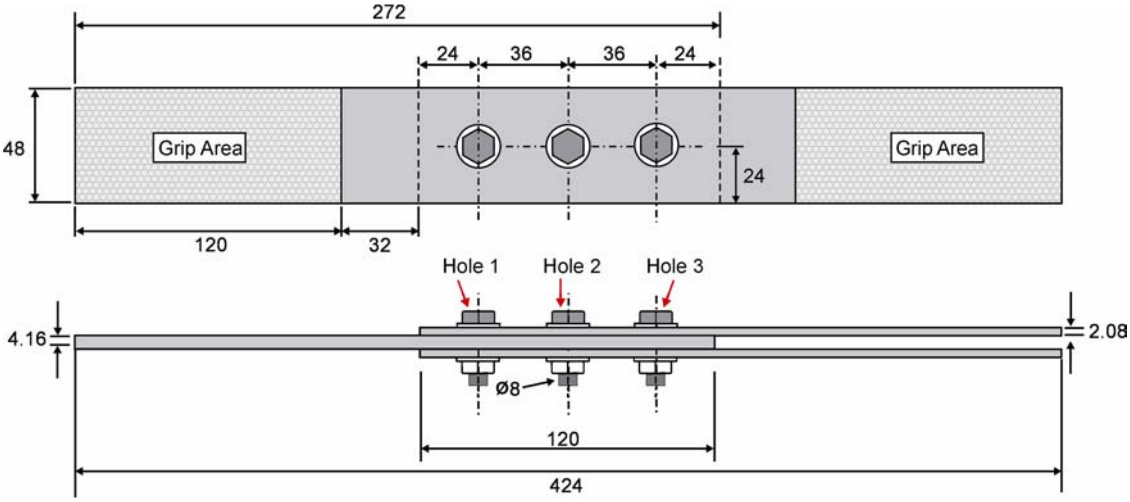


Figure 2 Double-lap specimen geometry with hole numbering (all dimensions in mm)

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. Four 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. Even with these tight tolerances on the bolts and the reamers, some variability was possible for each nominal clearance. The four intended nominal clearances together with the possible ranges for each clearance are given in Table 1. Clearance Cl was intended to represent a neat-fit. Clearance C2 represents the upper range of the ISO fitting f7/H10. Clearance C3 represents, according to Di Nicola and Fantle of United Technologies-Sikorsky Aircraft [1], 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.

Table 1 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	"	"	78	102
C3	160	8.145	8.154	"	"	158	182
C4	240	8.225	8.234	"	"	238	262

The present study involved six different clearance conditions for each joint type, as shown in Table 2 for the single-lap joints and Table 3 for the double-lap joints. In most cases only one loose-fit hole was drilled, except for one case (C1_C3_C3 for single-lap and C3_C3_C1 for double-lap) in which two loose-fit holes were used.

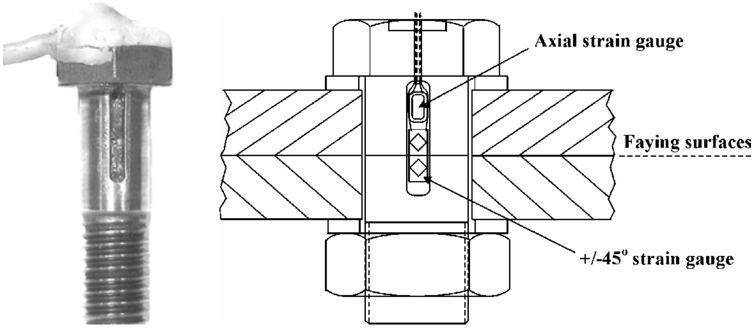
Table 2 Joint clearance cases for single-lap joints

	Nominal Clearance (μm)		
Case Code	Hole 1	Hole 2	Hole 3
C1_C1_C1	0	0	0
C1_C1_C2	0	0	80
C1_C1_C3	0	0	160
C1_C1_C4	0	0	240
C1_C3_C1	0	160	0
C1_C3_C3	0	160	160

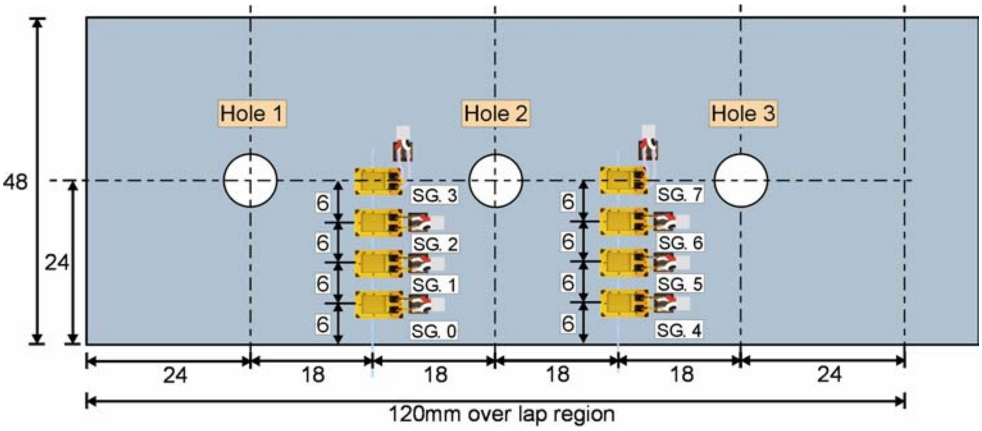
Table 3 Joint clearance cases for double-lap joints

	Nominal Clearance (μm)		
Case Code	Hole 1	Hole 2	Hole 3
C1_C1_C1	0	0	0
C1_C3_C1	0	160	0
C1_C1_C4	0	0	240
C2_C1_C1	80	0	0
C4_C1_C1	240	0	0
C3_C3_C1	160	160	0

For the single-shear specimens, load distribution was measured using specially manufactured instrumented bolts, while for the double-shear joints strain gauges across the width of the specimen were used, as shown in Figure 3. The shear load carried by the instrumented bolts was measured by ±45° strain gauges affixed in shallow slots on either side of the bolt, and located at the faying surface (i.e. shear plane) of the assembled joint. The bolts were calibrated using single-bolt, single-lap joints, with similar dimensions to the current multi-bolt joint. Further details on the operation of the instrumented bolts can be found in [11]. For the double-lap joints, each specimen was instrumented with strain gauges on the outer (splice) plate as shown in Figure 3b. The method used to estimate bolt load was similar to the method used in [14], and involved a numerical integration of the strain across the width, which when multiplied by the laminate stiffness gave the average stress at the section. From this the load at each of the strain-gauged sections was calculated, and the bolt loads deduced from free-body diagrams (assuming load carried by friction was negligible). The method assumes that the strain is constant through the thickness of the splice plate so is only applicable for double-lap joints. Note also that only half the width of the specimens was instrumented and the strain was assumed to be symmetric about the centreline.



(a) Instrumented bolts used for single-shear joints



(b) Strain gauges used for double-shear joints

Figure 3 Load distribution measurement

Several precision jigs had to be designed and manufactured for accurate positioning and drilling of the holes, and assembly of the joints. Figure 4 illustrates a jig used to centre the bolts in the holes in the multi-bolt joints, prior to the test. Clearly, in practice, bolts would not be centred in holes in an aircraft. However, because of the quite large clearances being used here (by aeronautical standards), bolt position within the hole would have a strong impact on the results. Thus to focus on the effects of clearance and fix the conditions of the experiment as far as possible, bolt position had to be eliminated as a variable. This also would enable easier comparison with parallel finite element studies. Three cavities were machined into a block of a hard plastic (polyoxymethylene) to high precision in terms of size and position using a CNC machine. The cavities accepted the nuts and lower washer with a tight fit. The laminates were then added, and the correct positioning was achieved by inserting a tight-fitting bolt into a C1 hole (all specimens in the test series had at least one C1 hole), and tightening to 0.5 Nm torque. The other bolts were then automatically in the centre of their corresponding holes. A modification of this jig was necessary for the instrumented bolt tests, to accommodate the wiring and protective dental cement around the balancing resistors on the head of the instrumented bolts (see Figure 3a) – further details on this modified jig can be found in [11]. A purpose designed drilling jig is described in the companion paper on fatigue [13].

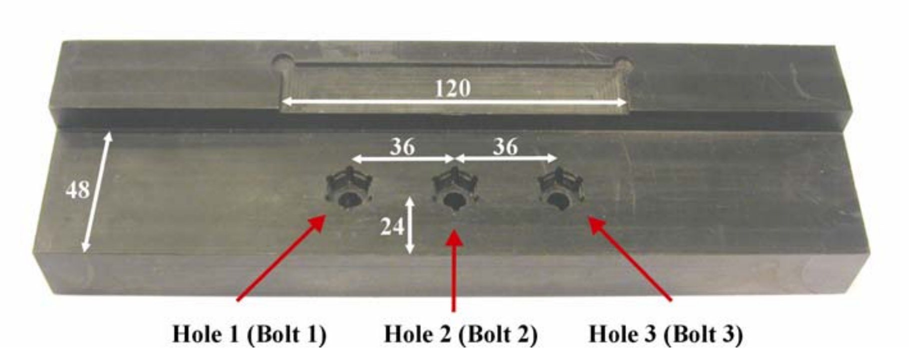
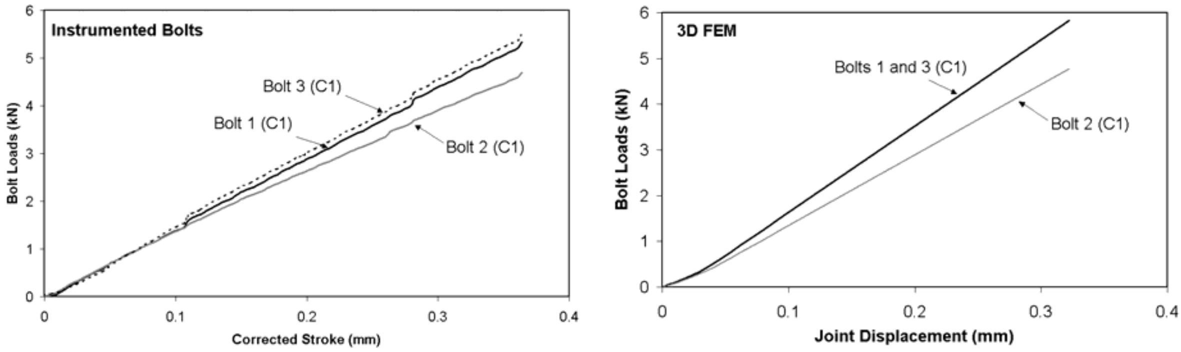


Figure 4 Multi-bolt joint assembly jig for ordinary bolts (all dimensions in mm)

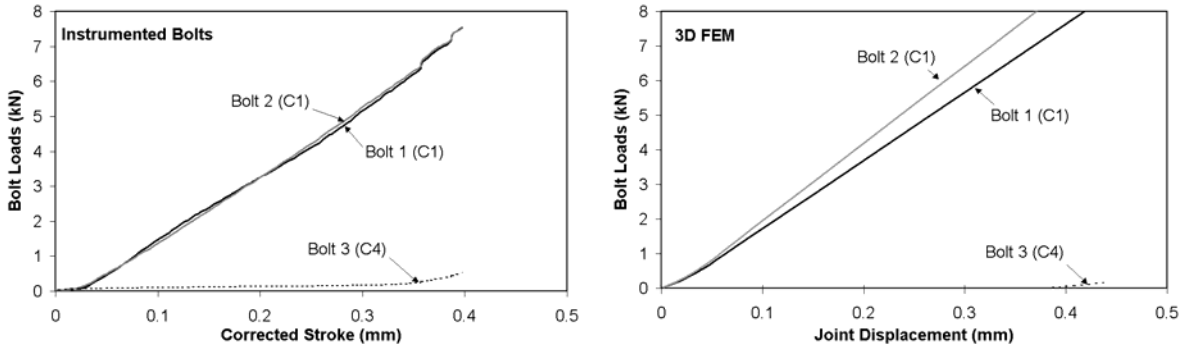
3. RESULTS

Figure 5 shows the load distribution in the single-lap joints for the C1_C1_C1 (all holes neat fit) case and the C1_C1_C4 case (240 μm clearance in Hole 3 – see Figure 1 for hole numbering). Shown also are results from a three-dimensional finite element study, details of which can be found in [10]. Note that the maximum applied load was set to 15 kN in the experiments to avoid damage to the instrumented bolts. In subsequent tests to failure with ordinary bolts the load deflection curve began to exhibit non-linearity at approximately 20 kN, so 15 kN represents approximately 75% of the "initial damage" load. From Figure 5, it can be seen that the finite element joint models were systematically stiffer than the actual joints (even with corrections made to the experimental results for machine compliance), but clearly the agreement between the experimental and numerical results in terms of load distribution is very good, giving confidence that the results are valid. The usual assumption in such a three-bolt joint is that the outer two bolts take equal load, while the inner bolt takes less load [15]. This was borne out in the C1_C1_C1 case, with the outer two bolts each taking ~35% of the load at 15 kN applied load. However, for the C1_C1_C4 case, the distribution has changed significantly. In this case, the bolt in the largest clearance hole (Bolt 3) initially does not take any load, since it has been centred in the hole by the positioning jig, and load is shared almost equally by Bolts 1 and 2. Bolt 3 is only just beginning to take up load at the maximum applied load of 15 kN, which as was noted earlier is quite close to the load at which non-linearity begins for this joint. Thus it could be expected that such a clearance situation may have a significant effect on the failure behaviour of this joint.

However in tests to failure of two single-lap configurations (C1_C1_C1 and C1_C1_C4), no significant difference was found for the ultimate tensile strength between the two sets of specimens. The situation was somewhat complicated by the occurrence of two different failure modes: net tension and bolt failure. However, of some interest was the occurrence in one C1_C1_C4 test of simultaneous failure of Bolts 1 and 2 (Figure 6). From Figure 5, the bolt load in these two positions would be expected to be nearly the same – therefore this simultaneous failure is not surprising. What is most interesting about this result is that under normal design rules the middle bolt in a joint of this type is not considered to be under threat of failure, but this shows that when variable clearances are accounted for, failure of the middle bolt can occur.



(a) C1_C1_C1 experimental (b) C1_C1_C1 finite element analysis



(c) C1_C1_C4 experimental (d) C1_C1_C4 finite element analysis

Figure 5 Load distribution in single-lap joints for two clearance cases: from instrumented bolts and from three-dimensional finite element analysis

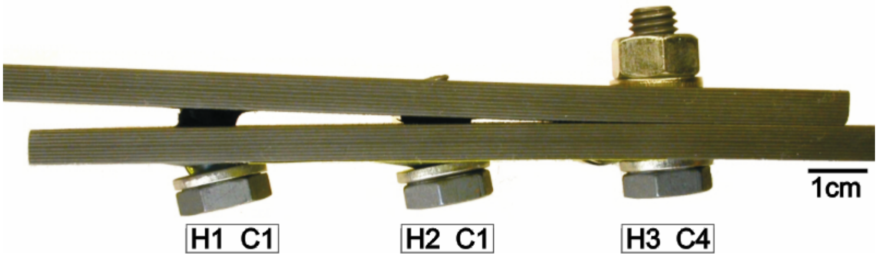


Figure 6 C1_C1_C4 single-lap joint that failed by simultaneous failure of Bolts 1 and 2

To determine if clearance caused any difference in failure *initiation*, the slope of the load deflection curve was calculated and plotted against load, in line with a method outlined in [7]. One sample curve from each clearance case is shown in Figure 7. The slope was calculated here with a moving window size of 7 points, since the point-by-point slope gave a very noisy plot. It can be seen that the C1_C1_C4 joint takes longer to reach its maximum stiffness (due to the late take-up of load and gradual build-up of contact area in the C4 hole). It can also be seen that both joints gradually lose stiffness from about 20 kN on, presumably due to relatively minor damage such as matrix cracking, up to about 35 kN. Then at 36 kN and even more so at 41 kN, the C1_C1_C4 joint shows a sharp drop in stiffness, which is presumably due to some more significant damage event such as fibre buckling or fracture, or perhaps a sharp growth in delamination. The C1_C1_C1 joint does not show any sharp drop in stiffness until about 47 kN. Thus, significant failure events occur at lower loads in the larger clearance joint. To provide an objective measure of this, the load at which the slope has dropped by 30% from its maximum value (as suggested in [7]) was calculated for all six joints, and the results are shown in Table 4. On average, the larger clearance joints exhibited a 30% drop in stiffness at a 5% lower load value than the neat-fit joints, indicating that significant damage occurred first in the larger clearance joints.

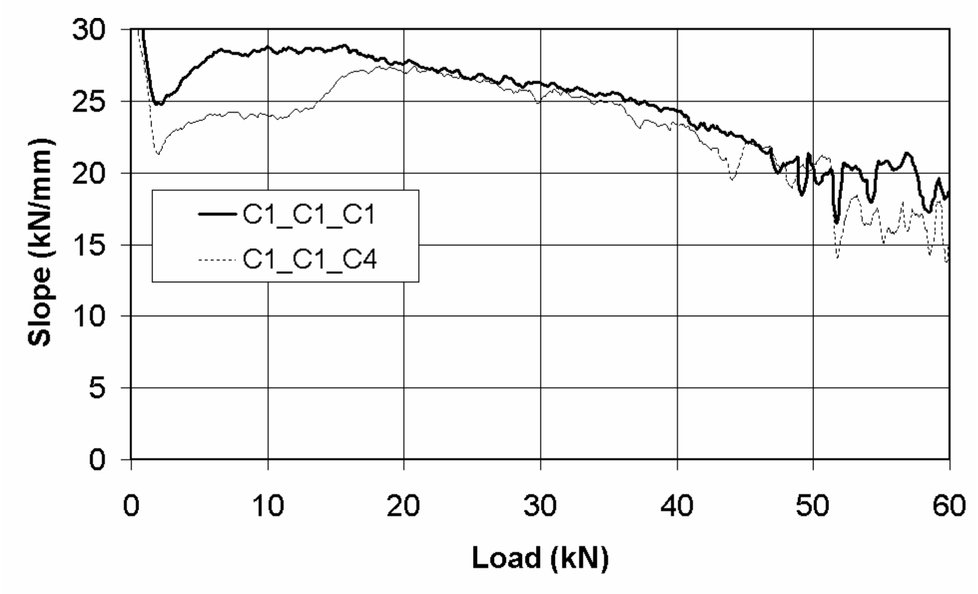
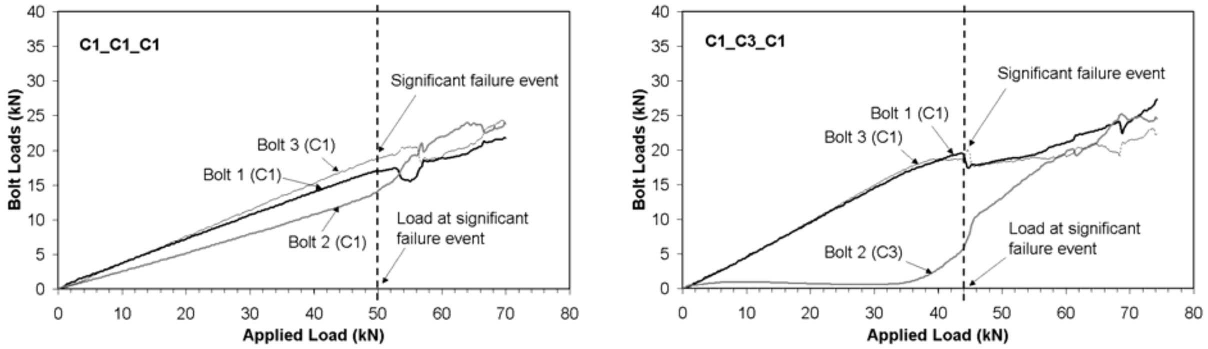


Figure 7 Slope of load deflection curves versus applied load for sample C1_C1_C1 and C1_C1_C4 single-lap specimens

Table 4 Loads at 30% stiffness drop in single-lap specimens

Specimen	Load at 30% stiffness drop (kN)
C1_C1_C1 (A)	51.06
C1_C1_C1 (B)	47.26
C1_C1_C1 (C)	51.00
Average	**49.77**
C1_C1_C4 (A)	48.25
C1_C1_C4 (B)	47.64
C1_C1_C4 (C)	46.20
Average	**47.36**

One advantage of the strain gauge method of load distribution analysis is that it is considerably less expensive than the instrumented bolt method. Thus in the case of the double-lap specimens, the instrumented specimens could be loaded to failure. Each of the six clearance configurations given in Table 3 was tested to ultimate failure. Figure 8 shows the load distribution results for two double-lap configurations (C1_C1_C1 and C1_C3_C1) obtained by the strain gauge method. Again the agreement with finite element analysis (not shown) was very good, and the results indicated that clearance could have a significant effect on load distribution. Concerning the effect of clearance on ultimate failure load, no discernible trend with variable clearance was evident with all specimens failing at loads between 67 and 74 kN (see horizontal axis of figure 8).



(a) C1_C1_C1 case

(b) C1_C3_C1 case

Figure 8 Load distribution in double-lap joints (measured from strain gauges)

An interesting feature of the strain gauge results in Figure 8 was the sensitivity shown by the strain gauges to what is presumably the first substantial failure event. At this point an abrupt change occurred in the strain gauge pattern. By converting bolt loads to bearing stresses at each hole, it was determined that this initial failure occurred when the bearing stress in the most highly loaded hole reached a level varying from 520 – 600 MPa. From communication with one of the aircraft manufacturers in the project, the bearing allowable for this particular laminate is 520 MPa. Therefore we can conclude that the event being picked up by the strain gauges is bearing failure in the most highly loaded hole(s). From Figure 8 we see that this initial bearing failure occurred in the C1_C1_C1 joint at 50 kN, whereas it occurred in the C1_C3_C1 joint at 44 kN. The lowest initial failure load was recorded for the C3_C3_C1 case and was 37.2 kN, which is more than 25% less than in the C1_C1_C1 case. Thus clearance had a significant effect on the initial failure load for the joint.

4. CONCLUSIONS

In this paper, the effects of variable clearance in multi-bolt, composite joints on load distribution and quasi-static strength have been studied experimentally. Both single-lap and double-lap configurations have been examined and two different methods of measuring load distribution have been used. Specialised jigs have been used for positioning the bolts in the holes and drilling the joints. The clearances examined ranged from neat-fit to clearances slightly larger than those allowed in the aircraft industry.

It has been found that clearance can have major effects on the load distribution in both single-lap and double-lap bolted joints, especially when joints are loaded in their linear region. The effects on ultimate strength however, were surprisingly not significant. Closer examination revealed though that clearance had significant effects on *initial* failure such as bearing failure in one hole, particularly for double-lap joints. Presumably, following such an initial failure, the failed hole elongates which tends to even out the clearances, resulting in negligible effects on ultimate failure. The effects on initial failure may have relevance for limit load design of aircraft.

ACKNOWLEDGEMENTS

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