The effect of clearance on single lap countersunk composite joints

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Abstract

An experimental investigation was conducted into the effects of bolt-hole clearance on the static strength and damage progression behaviour of single lap countersunk composite bolted joints. Joints were manufactured from carbon/epoxy plain weave fabric and tested with three different bolt clearance levels. The experimental results showed that the bolt-hole clearance had a minimal effect on the ultimate failure load of the bolted joint. However, a significant reduction (approx. 22%) was observed in the bearing damage initiation load, consistent with difference in the through-thickness damage profile. Finite element analysis was conducted, and was able to accurately capture the load-displacement behaviour and through-thickness damage profile of the joints.

Keywords: composite, countersunk, clearance, bolted joint, fastened, through thickness damage.

Introduction

Despite the many advantages of adhesive bonding, bolted joints are still used to fasten composite aircraft structures because of the ease of assembly/disassembly, minimal surface preparations, use of common tools between metal and composite structures and airworthiness certification. The lack of robust non-destructive inspection techniques for detecting weak bonds means that certifying adhesively bonded repairs in the field remains unresolved. However, the introduction of bolts leads to complicated three-dimensional (3D) stress fields near the bolt hole [1]. For composite laminates, the use of countersunk (CSK) fasteners further elevates the stress concentration above what pertinent to straight holes. To take full advantage of fibre-reinforced composite materials in structural elements, appropriate methods for stress and failure analysis are required to enable efficient design and optimisation of joints.

As the use of composite material increases in the aerospace industry, it is important to establish the effects of manufacturing imperfections on the load-carrying characteristics of the structure. The bolt-hole clearance (CL) is one such imperfection that can alter the behaviour of composite joints, particularly in the case of multi-row joints. The principal effect of clearance is the reduction in the contact angle between bolt and hole, as illustrated in Fig. 1. The presence of clearance has been investigated in several publications [2-5]. In Ref. 2, a 40 μm clearance was shown to result in a 12% reduction in joint strength together with a shift in the location of the maximum tangential stress towards the bearing plane. Similar results showing a change in the location of maximum tangential stress and significant increase in radial stress were reported in Ref 3. A significant reduction in bearing strength at 4% hole deformation was found in Ref. 4. However, the ultimate bearing strength showed limited dependence on bolt-hole clearance. In Ref. 5 the effects of hole clearance was compared between a quasi-isotropic and highly orthotropic laminates. The effect of the bolt-hole clearance was found to be important with regard to the bearing strength at 4% hole deformation with a significant reduction in bearing strength relative to near-fit joints. However, the ultimate bearing strength of the laminates exhibited no dependency on the bolt-hole clearance [5]. It is clear from a review of the published literature that previous studies have focused on straight shank bolts, and very little data have been published on the effect of clearance on joints with CSK fasteners.

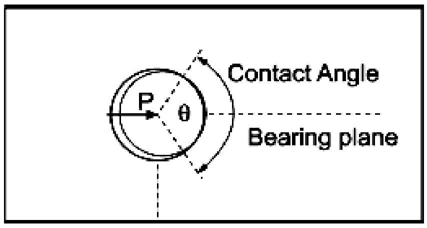


Fig. 1: Contact angle for bolt-hole loading [5]

In this work, experimental and numerical investigations were conducted to assess the effect of clearance on single lap CSK bolted composite joints. One objective of these investigations was to characterise the strength and damage behaviour of countersunk bolted joints with varying degree of clearance. The experimental testing involved quasi-static loading of CSK joints at three clearance levels, as well as detailed microscopy analysis of damaged sections following failure. In the numerical analysis the clearance was modelled, the key damage mechanisms seen in testing were incorporated, and the results compared with the experiments.

Experiments

Experimental testing was conducted on a 100 kN MTS®- 810 test machine in accordance with Ref 7. An extensometer was used to record the displacement across the bolt region. The tests were conducted in displacement control, with a loading rate of 0.5 mm/min. The experimental setup of the single lap joint is shown in Fig. 2. The figure also shows the location of the extensometer tabs and strain gauge (SG) numbering. The extensometer tabs were located as close as possible to the hole to reduce the contribution of bending and rotation in the measured displacement. No lateral support was used to prevent secondary bending. As bearing failure is a progressive non-catastrophic damage, tests were stopped after a drop in the load was noted in the load-displacement curve together with significant visible bending and increased crackling noise.

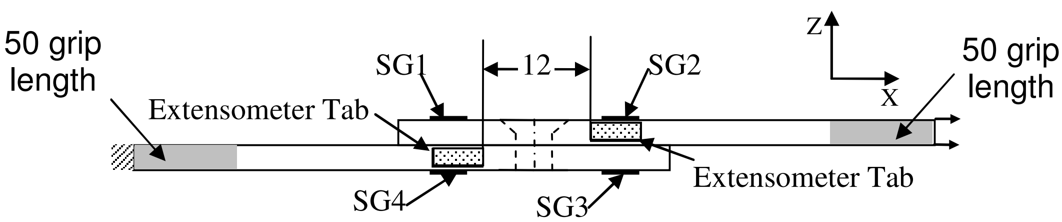


Fig. 2: Experimental setup for single lap joints (dimension in mm) [6]

Test coupons were made of plain weave pre-preg material in accordance with the manufacturer's recommended curing process. A quasi-isotropic lay-up sequence $[(0/90/45/-45)_4]_S$ was used for single lap tests designed according to Ref. 7. The geometry of the single lap joint is provided in Fig. 3, together with strain gauge locations for lower and upper laminates, *SLB* and *SLT* respectively. Table 1 provides the dimensions and clearances used for the single lap joint tests. All the joints were torqued up to 2.1 Nm using calibrated torque wrench. The effects of torque were also studied and have been reported previously [6]. The tested clearance levels were beyond the recommended aerospace tolerance of -0/+75 µm [3], though were chosen to investigate the severity of tolerance beyond aerospace standards.

Table 1: Single lap dimensions (mm) and clearance (µm)

L	*t*	*w = e*	*D*	*A*	*OL*	*SLT*	*SLB*
152.4	3.52	31.75	4.76	9.5631	63.5	5	7
		CL1		CL2 (% *D*)		CL3 (% *D*)	
Clearance		0		240 (5.04)		440 (9.24)	

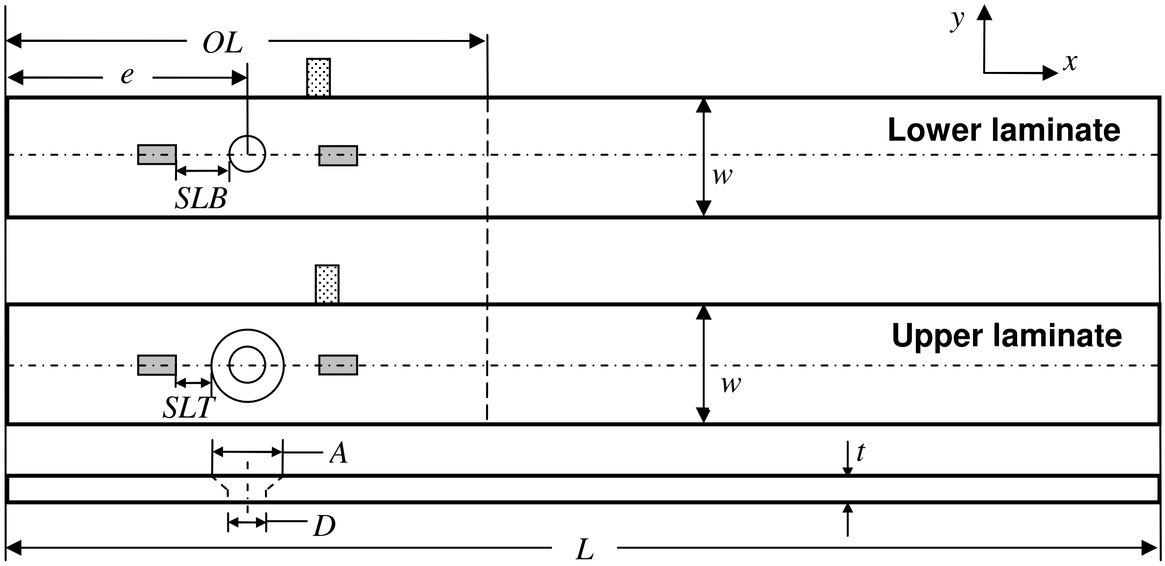


Fig. 3: Single lap joint dimensions

The effect of CL on the contact condition between the bolt and laminate can be seen in Fig. 4. Clearance led to delayed contact between bolt and hole in both the CSK and straight shank region. For the case of no clearance (CL1), the joint carried load from the start of the loading. However, in the case of clearance (CL2 and CL3) once the load was applied, the gap between bolt and hole was first traversed by the bolt/nut assembly, during which time some load was carried by the joint due to static friction. This led to two different stiffnesses of the joint. The initial stiffness (Stiffness1) was due to static frictional force whereas the second (Stiffness2) was due to initial contact between the bolt and laminate as shown in Fig. 5. The figure shows that Stiffness1 is higher than Stiffness2. Once the static friction was overcome, the laminate travelled the initial clearance. During this phase the load was resisted by dynamic friction and this phase appears as a region of almost no change in load with an increase in displacement as shown in Fig. 5.

Fig. 4: Change in contact due to clearance

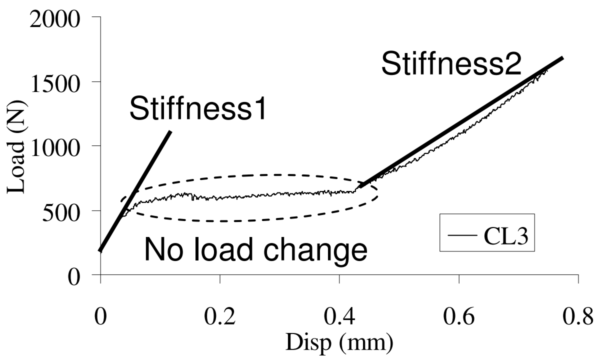


Fig. 5: Typical load-displacement behaviour of a joint with CL

Each clearance was tested three times and averaged results are presented. The effect of clearance on the load-displacement behaviour can be seen in Fig. 6. The markers show the location of the ultimate failure load (UFL) for each joint. It can be seen from the figure that as the clearance increased the region of no load also increased. An increased CL led to a reduction in the UFL. The stiffness of the joint did not seem to be significantly affected by the clearance. Except for the initial lag no significant difference was seen in the load-displacement profile for each joint.

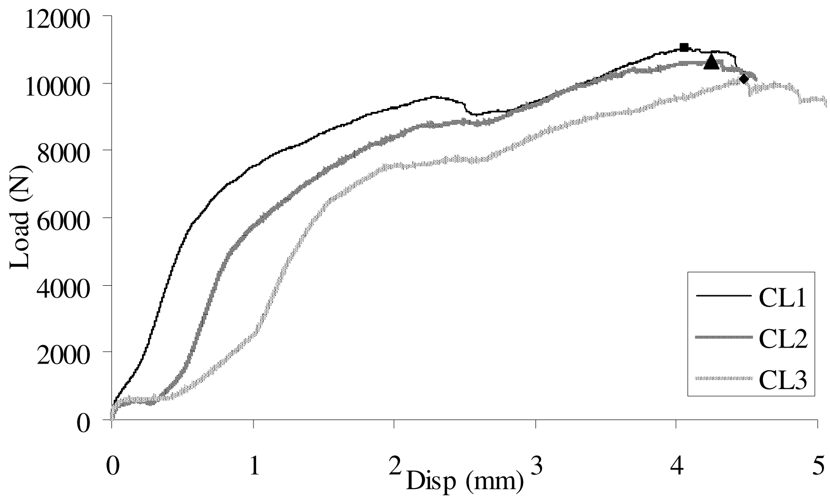


Fig. 6: Effect of CL on load-displacement behaviour

The bearing load (BL) was calculated using the approach described in the ASTM Standard [8], which is based on using a maximum displacement of 4% of the bolt diameter to determine a load suitable for design purposes. Table 2 provides a summary of the major results from the experimental analysis. Clearance only led to 4.73% reduction in the averaged UFL of the single lap joint. This result is similar to the results achieved by other authors [4,5]. However, the effect of clearance on BL was much more significant. For the CL2 joint, BL reduced by approximately 17%, which reduced to 22% for the CL3 joint compared with the CL1 joint. The adverse effect of CL on BL reduced as CL was increased. The amount of bending seen in each joint was also seen to increase with increasing clearance. These aspects demonstrate why for aerospace purposes the recommended maximum clearance is -0/+75 µm, whereas the values for CL2 and CL3 were around 3 and 6 times greater than this respectively.

Table 2: Experimental results

	UFL (kN)	BL (kN)	% Δ UFL	% Δ BL
CL1	10.82	3.18	0	0
CL2	10.66	2.64	-1.43	-17.03
CL3	10.31	2.47	-4.73	-22.18

Microscopy

To further investigate the effects of the change in CL, microscopic analysis was performed on the single lap joint specimens after testing. For the single lap joint, bearing occurred on opposite sides of the hole for the upper and lower laminates. This was the leading (SG2) and trailing (SG4) hole edges for the upper and lower laminates respectively, as shown in Fig. 2. As such, sections were cut and inspected from these locations. One joint per CL level was analysed using microscopy. In the case of the single lap joint, the bottom surface of the upper laminate and the top surface of the lower laminate were in contact and formed the shear plane of the joint. The microscopic photos were taken at 5× magnification using a Leica optical microscope.

The damage profile for the upper laminate of CL1 joint can be seen in Fig. 7. Several different damage mechanisms have been identified in the figure. The most prominent failure mode was interlaminar and intralaminar shear cracks, which comprised of fibre kinking, fibre matrix cracking and matrix compression. An angular damage line almost parallel to the CSK slope was seen in the laminate, which comprised mostly of shear cracks. Delamination was reported in different locations through-the-thickness of the laminate. "Primary delamination" was defined as the delamination located ahead of the angular damage line close to the start of the CSK region. Any delamination behind the angular damage occurred as a consequence of severe damage in the angular line and therefore was termed "Secondary delamination". It can be seen that the straight shank of the upper laminate only experienced shear cracking and material loss close to the bottom layers (i.e. shear plane of the joint).

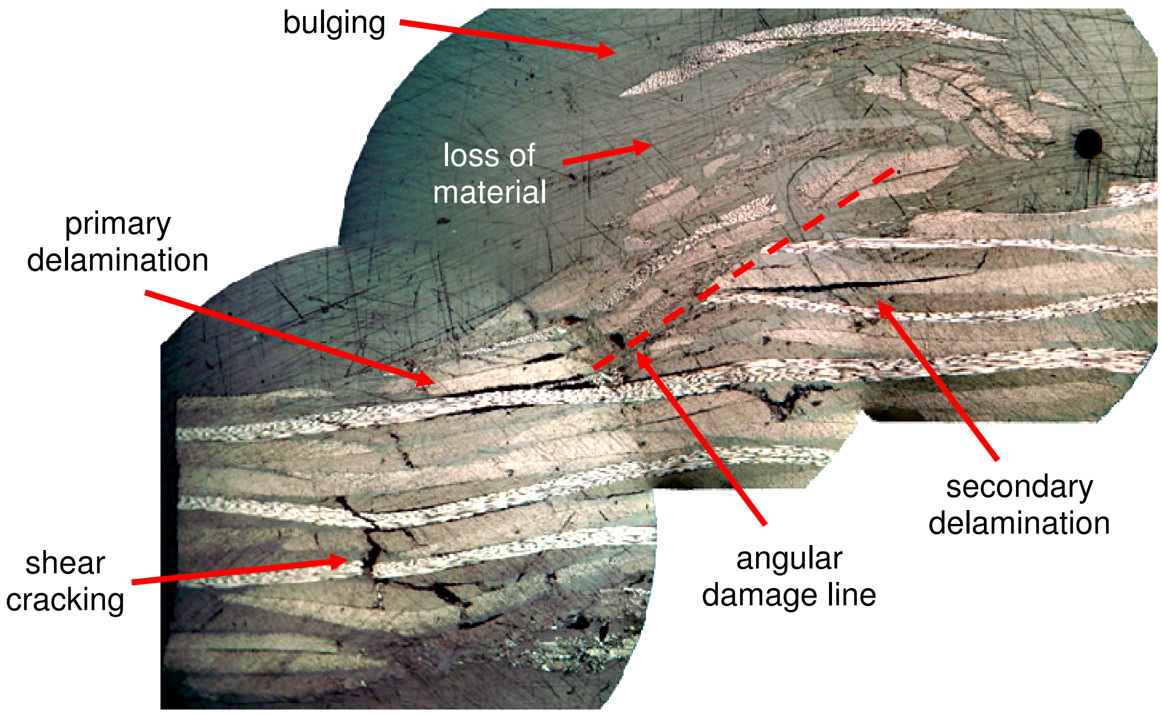


Fig. 7: Upper laminate damage profile for CL1

The damage profile of joints with clearance was significantly different to the damage profile of the CL1 joint (CL=0). The joints with clearance showed no bulging out of the top layers and no primary delamination at the start of the CSK region. A second angular damage band was seen, approximately parallel to the CSK edge and first damage line. For the CL2 joint, the damage bands were less parallel, as the upper laminate experienced significant bearing failure and the first damage band initiated separation at the top layers. Another important difference was that both the CL2 and CL3 laminates showed increased damage and material loss at the shear plane. Secondary delamination and shear cracks (inter- and intra-laminar) were still present for both cases.

The damage profile of the lower laminates can be seen in Fig. 8. The CL1 (no clearance) damage profile had a straight damage region close to the shear plane of the joint, however, the CL2 and CL3 joint showed two perpendicular angular damage bands. Similar to the damage profile of the upper laminate, the CL2 and CL3 joint experienced significant damage close to the shear plane of the joint. The other damage phenomena such as secondary delamination and shear cracking were present in all the joints. It is important to note that no primary delamination was reported for any lower laminates.

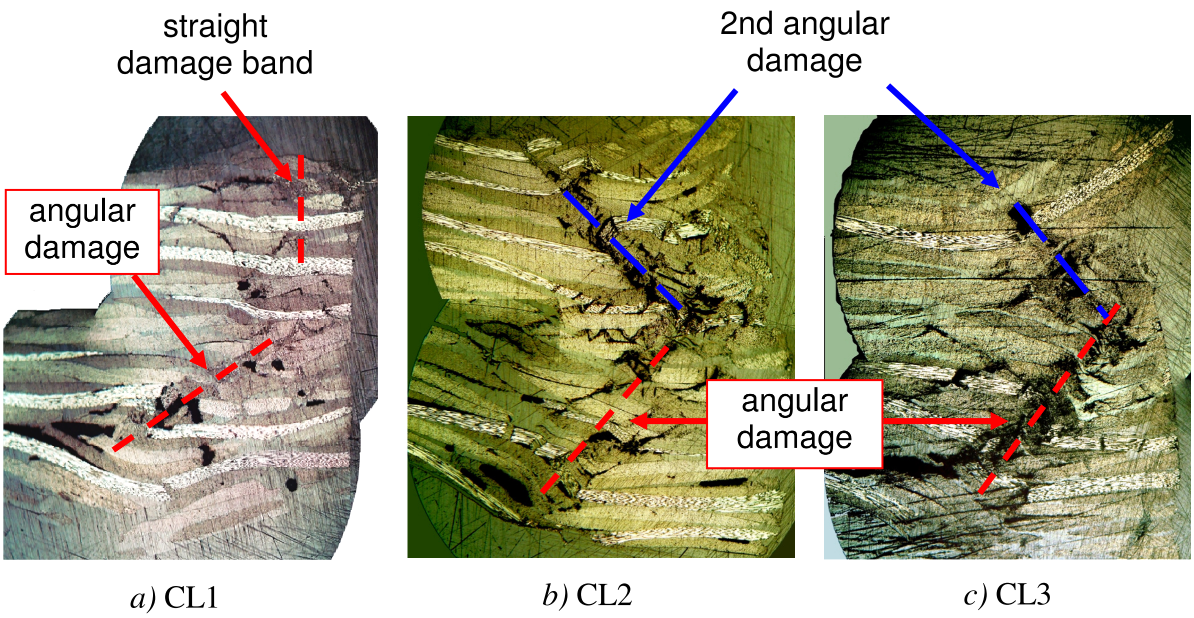


Fig. 8: Lower laminate damage profile

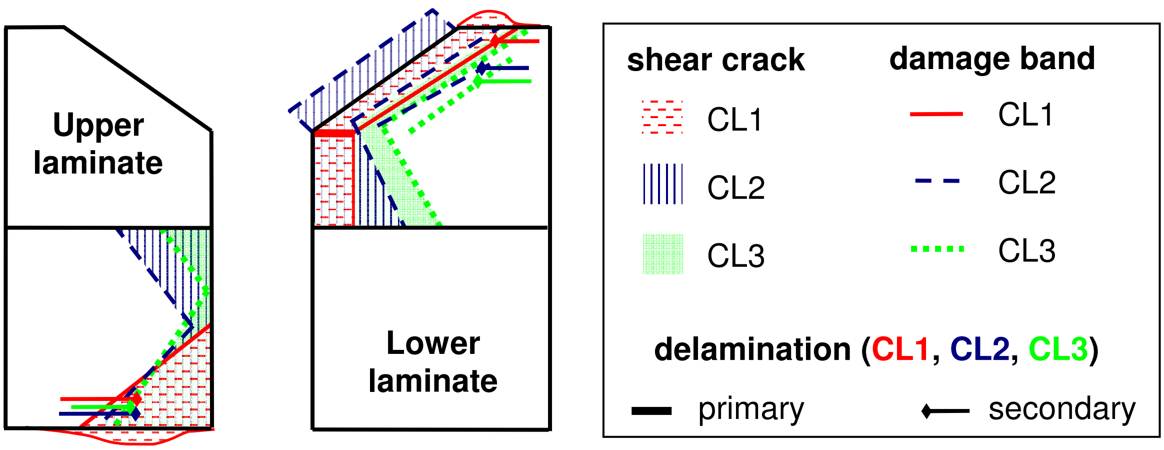


Fig. 9: Schematic of damage profile

A schematic showing the change in the through-thickness failure profile due to presence of clearance is provided in Fig. 9. The figure provides a summary of all the effects of increasing clearance on the though-thickness damage profile.

Finite Element Modelling

A finite element (FE) model was created in Abaqus®[9]. Each layer of plain weave carbon/epoxy composite was divided into two unidirectional plies to give the same stiffness and strength as the woven ply. The composite was modelled using 3D continuum shell elements, which enabled accurate definition of CSK geometry and application of the continuum damage model available in Abaqus 6.9. Hashin [10] failure criteria were used for composite failure initiation, while the crack-band based continuum damage mechanics approach was employed to capture ply fracture. Bolt torque was applied by displacing the bolt in the vertical direction. The nut and bolt were defined as a rigid entity as no damage was noticed in these during testing. A complicated contact region involving friction and multiple contact surfaces was defined for the single lap CSK joint as described in a previous publication [6]. One end of the lower laminate was fixed in all direction and the upper laminate was displaced in the longitudinal direction. The grip region of upper laminate was not allowed to displace in the vertical and lateral directions as the machine grip only displaced in longitudinal direction. The material properties used in the model are provided in Table 3, and were taken from Ref 6. A more detailed description of modelling approach (mesh sensitivity analysis, model calibration, etc.) can be found in Ref. 6.

Table 3: Material properties

Stiffness properties, GPa					
E_{11}	E_{22}	G_{12}	G_{13}	G_{23}	ν_{12}
85	5.2	2.4	2.4	1.9	0.3
Strength properties, MPa					
S_{11T}	S_{11C}	S_{22T}	S_{22C}	S	S_T
1009	865	81	188	69	62

A comparison between the load-displacement behaviour of experimental and FE results is shown in Fig. 10. All the models terminated due to numerical instability from excessive distortion. The CL1 joint reached UFL before termination, while for the CL2 and CL3 joints termination was before UFL was achieved. With regards to the load-displacement results, overall the numerical model was able to capture the behaviour reasonably well. For the CL2 joint, the model accurately predicted the entire load-displacement behaviour. For the CL1 and CL3 joints, the model captured the initial behaviour quite well, but over-predicted the non-linear region. In terms of the effect of clearance, the numerical results did not show any change of the initial joint stiffness, which agreed with the experimental findings.

A comparison between the FE predictions and experimental results is given in Table 4, which are provided at 2 mm applied displacement. This displacement was selected as it was in the non-linear region and all FE simulations were able to run to this point without termination. These results demonstrate that the numerical model gave reasonably accurate predictions of the load at 2 mm displacement.

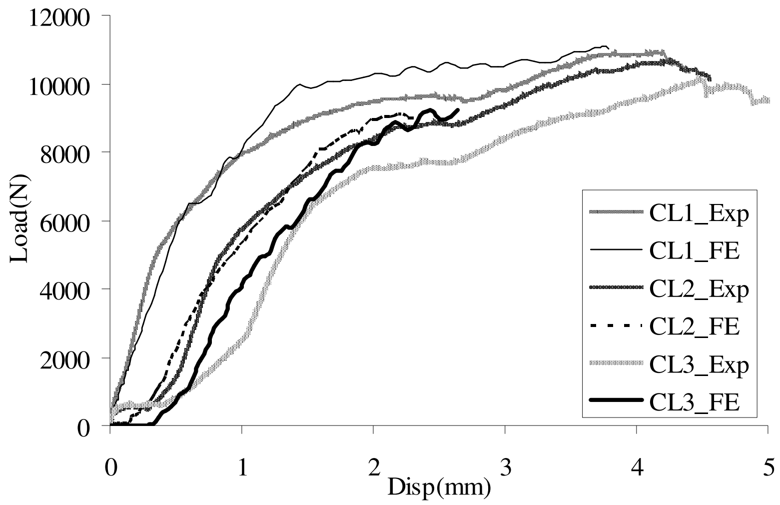
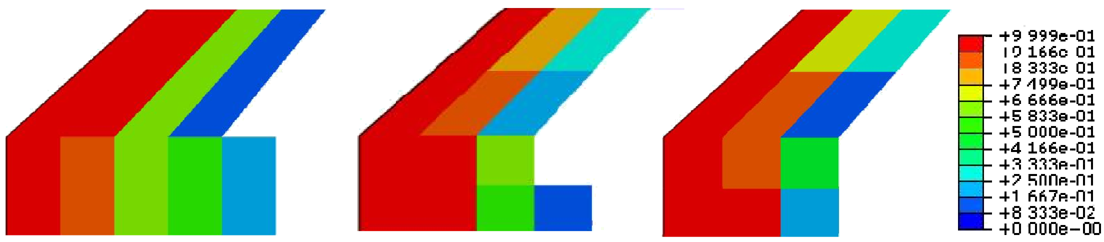


Fig. 10: Load-displacement behaviour (Exp and FE)

Table 4: Results summary

	Load at 2 mm displacement (kN)		
	CL1	CL2	CL3
Exp	9.47	8.38	7.55
FE	10.3	8.94	8.22
% Diff.	-8.76	-6.75	-8.97

The through-thickness failure profiles for the upper laminate obtained from simulation results are compared in Fig. 11, where the fibre compressive failure damage index is shown,. It can be seen from Fig. 11 that the straight shank region of the CL1 joint experienced uniform damage through-thickness. However, the CL2 and CL3 joint showed higher damage in the bottom layers of the straight shank region. It was difficult to determine the presence of the second angular damage band in the CSK region, however, it was possible to see a high damage intensity after the initial failure region in the CL2 and CL3 joints. This was not the case for the CL1 joint. This was also noticed during testing as the CL1 joint experienced greater bearing damage compared to the CL2 and CL3 joints. The FE damage profile resembles the damage profile seen in the microscopy analysis.



a) CL1 *b)* CL2 *c)* CL3

Fig. 11: Fibre compressive damage index for upper laminate at 2 mm applied displacement

The radial stress distribution around the hole at 1.5 kN applied load is compared in Fig. 12. It can be seen that the radial stress at the shear plane increased by approximately three times for CL2. However, only a slight increase in the radial stress was noted for CL3. A small reduction in contact area led to a minor variation in the radial stress for CL3 joint. A comparison between the radial stresses at the start of the CSK region is also shown in Fig. 12. The 0^o and 90^o layers were in the straight shank and $\pm 45^o$ layers were in the CSK region. It can be seen that the presence of clearance led to stress reversal in the region close to the 0° location. For CL2 some negative radial stress was present in the 0^o ply, however, for CL3 the stress distribution was completely positive. The radial stress distribution at the start of the CSK region showed significant sensitivity to clearance.

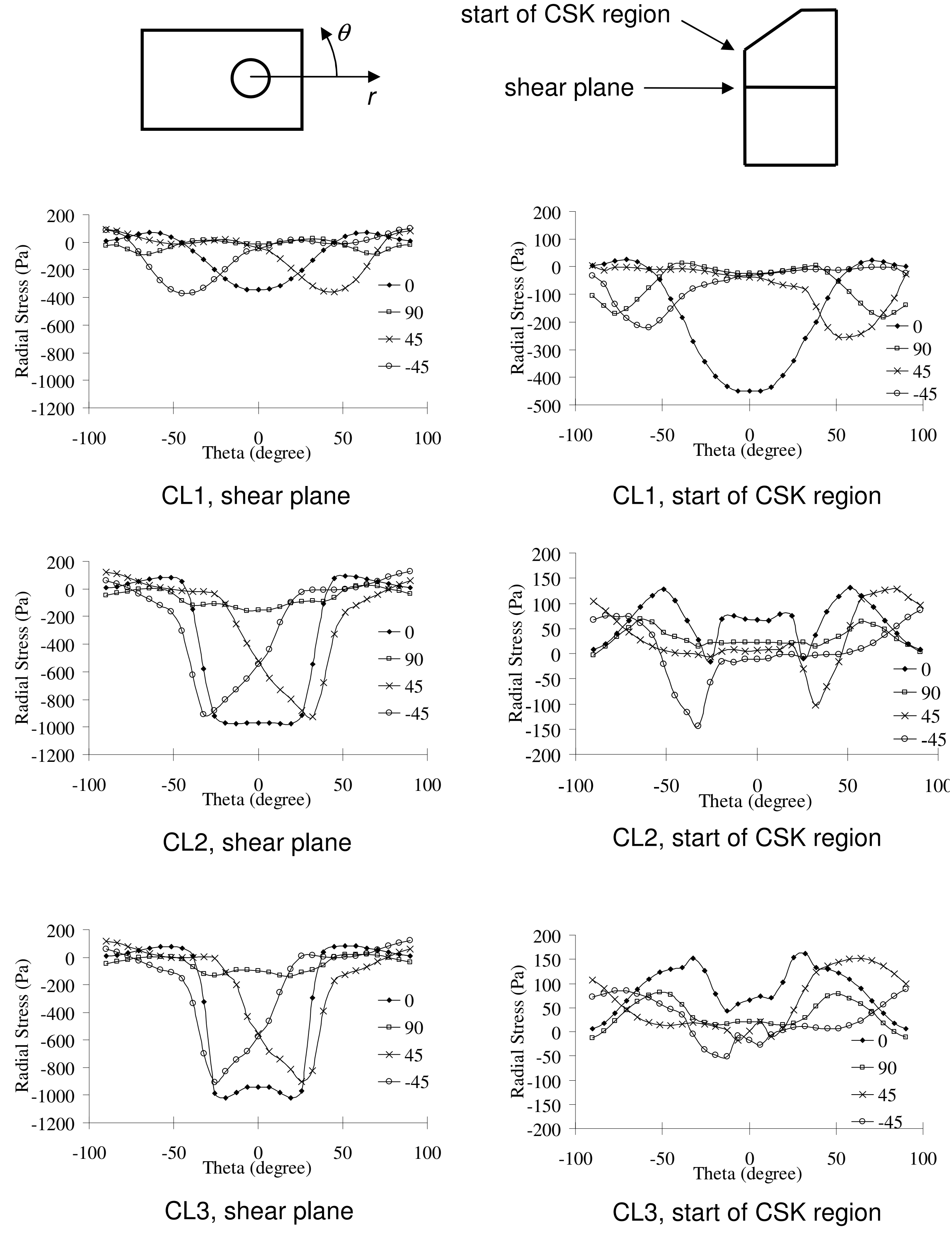


Fig. 12: Radial stresses at 1.5 kN applied load

Conclusion

An experimental and numerical investigation was conducted into the effect of clearance on CSK single lap joints made from plain weave carbon/epoxy prepreg. The results showed that for the configurations tested, increasing CL only slightly reduced the ULF. However, significant effect was noticed on the BL and the through-thickness damage profile. Increasing the CL to 440 mm reduced the BL by around 22% from the neat fit result. For the damage profile, the primary delamination that occurred at the start of the CSK region for the neat fit joint was not seen where the CL was increased. Furthermore, additional angular damage bands were seen in the through-thickness damage where CL was present. From the numerical analysis, the FE model gave reasonably accurate predictions of the load-displacement behaviour and through-thickness damage profile of the laminate, and confirmed the experimental results with regards to the effect of clearance. The FE model also showed that the increased clearance led to a variation in the radial stress distribution at the shear plane and start of the CSK region, and that the stresses at the CSK region were more sensitive to CL.

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