EXPERIMENTAL AND COMPUTATIONAL STUDIES OF MECHANICALLY FASTENED JOINTS IN COMPOSITE AIRCRAFT STRUCTURES

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ABSTRACT

This paper presents an overview of the many issues involved in testing and modelling composite bolted joints. The study concentrates on bolt-hole clearance as it provides an interesting and practical test case. It is shown that clearance affects the stress state around the hole, and severely interrupts the bolt load distribution in multi-bolt joints. This leads to a significant influence on the initial (bearing) failure load in multi-bolt joints, although the influence on final failure load is minimal. Clearance affects joint fatigue life in a similar fashion.

1. INTRODUCTION

One of the key challenges facing the European aerospace industry today is to develop composite fuselage and wing structures, optimally designed with respect to a host of criteria including weight, safety, manufacturability, and maintainability. A critical aspect of this challenge is mechanical fastening of composite substructures. Because joints represent potential weak points in the structure, the design of the overall structure tends to follow from, and be significantly limited by, the design of the joint.

The EU Framework project BOJCAS [1]: Bolted Joints in Composite Aircraft Structures focused on this issue, and in particular on improved analysis and design methods, validated by extensive and detailed experimental testing. The University of Limerick coordinated this project and focused its own research on tools for automated generation of three-dimensional finite element models of bolted joints, static and fatigue testing of single and multi-bolt composite joints, non-destructive testing and fractography of joint specimens, progressive damage modelling, revised strength criteria for bearing failure, and the effects of bolt-hole clearance on load distribution, static strength and fatigue life of composite joints. This work by the University of Limerick resulted in 18 publications in international peer-reviewed journals [1-18] and an award for Best Paper in the journal *Composite Structures* in 2005. The present paper provides an overview of the key findings from this body of work on the above listed topics, and attempts to draw lessons for ways forward in this important research area.

2. PROBLEM DESCRIPTION

An extensive experimental and numerical programme was carried out to examine the performance of composite bolted joints under static and fatigue loading. The underlying thread running through the work was the effect of bolt-hole clearance. Bolt-hole clearance is academically very interesting since it delays the load take-up at a particular bolt and introduces three-dimensional stresses into the laminates due to the bolt tipping or rotating in the hole. Apart from its academic interest, clearance is an important parameter to consider in aircraft design since it is always present (to some extent) due to tolerances on both the bolts and the drilled holes in the joint plates. Indeed, within an f7/H10 ISO fitting used by at least one aerospace manufacturer, clearances can range from nominally 0 µm (i.e. neat-fit) up to 86 µm for a 6 -10 mm diameter bolt. To examine the case for out-of-tolerance holes clearances as large as large as 240 µm were examined herein. TAB 1 lists the clearances examined and their corresponding identification code used in this paper.

TAB 1 Clearances examined and corresponding codes

Code	C1	C2	C3	C4
Clearance (µm)	0	80	160	240

FIG 1 and FIG 2 show some typical joints that were examined experimentally and numerically. All the joints presented in this paper were manufactured from HTA/6376 carbon fibre/epoxy material, manufactured by Hexcel (UK). This high-strength material is currently used in the aircraft industry. The lay-up used was quasi-isotropic with stacking sequence $[45/0/-45/90]_{ns}$. The bolts used were aerospace grade Titanium alloy fasteners with nominal diameter 8 mm, with an f7 ISO tolerance. Steel nuts together with steel washers were also used.

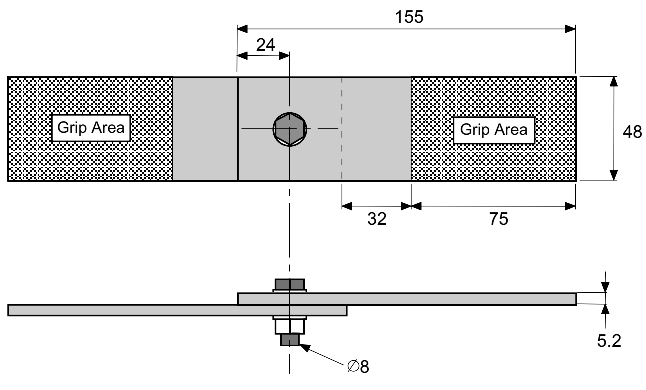


FIG 1 A single-lap, single-bolt composite joint

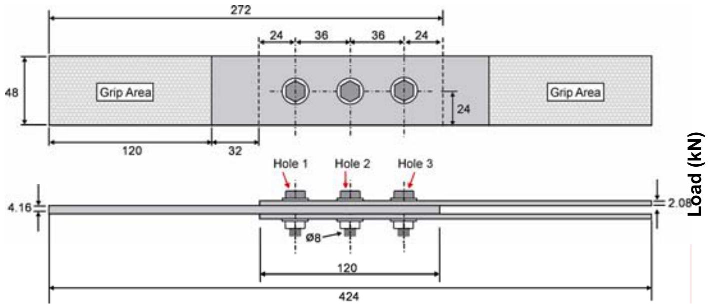
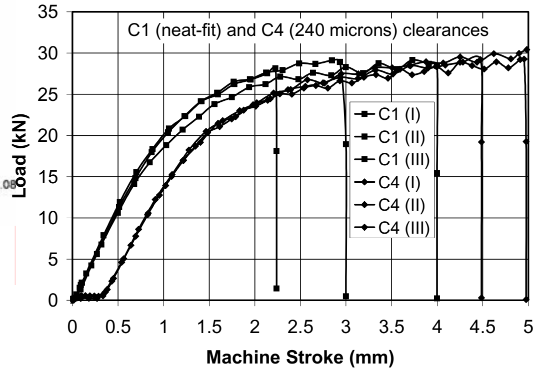
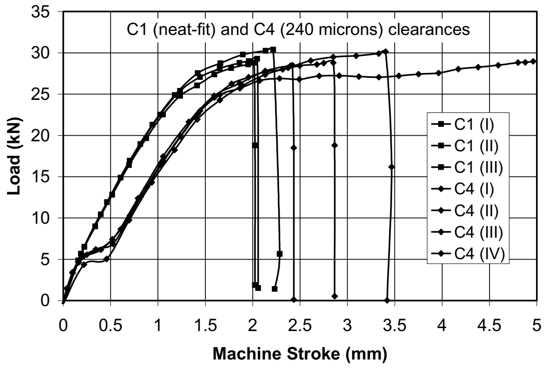


FIG 2 A double-lap, multi-bolt composite joint



(a)



(b)

FIG 3 Tensile tests on single-lap, single-bolt joints (a) low bolt torque, (b) high bolt torque

3. EXPERIMENTAL ANALYSIS

This section describes some of the key findings from the experimental programme.

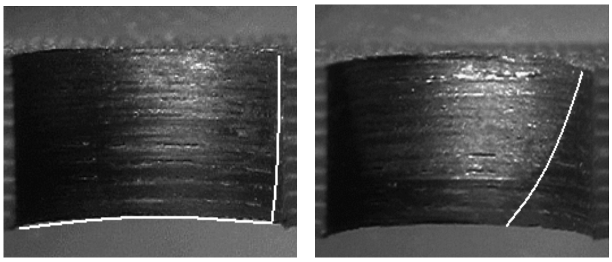
3.1 Clearance Effects in Single-Bolt Joints

FIG 3 shows load-deflection curves obtained from experiments (3-4 repeats of each were performed) on quasi-isotropic C1 and C4 clearance joints, with low (FIG 3(a)) and high (FIG 3(b)) levels of bolt torque. Measurement of bolt torque is described in Section 3.2. For the low torque joints in FIG 3(a) a close analysis of the data revealed the following:

1. A reduction in slope (i.e. stiffness) occurs with increasing clearance.
2. The C4 joint has a slight tendency to stiffen as load increases. This is not exhibited by the C1 joint. Above approximately 9 kN the slope drops due to the development of damage in the joints.
3. There is a delay in load take-up for the C4 clearance joint that is slightly larger than its nominal clearance.

For joints with high levels of bolt torque shown in FIG. 3(b), the initial delay in load take-up is not evident in the C4 joint. This is because with highly torqued joints, high friction forces exist between the two laminates and these forces are sufficient to completely react the applied load. However, once the applied load overcomes these static friction forces at approximately 5 kN, the plates start to slip, the bolt-hole clearance is taken up and the bolt then starts transmit load. This explains the plateau region seen in the C4 curves.

An interesting finding from the experiments on single-bolt joints is the maximum contact area that developed between the bolt and the hole during loading, as shown in FIG 4. During the experiment, the bolt was found to leave a silver-coloured imprint on the inside of the hole, as shown, thus indicating the maximum contact area that developed during the experiment. As can be seen, nearly full contact was obtained with the C1 clearance joint while there is a significantly smaller footprint left by the C4 clearance joint. These variations in contact area cause changes in joint stiffness and the finite element models in Section 4.1 describe this process in more detail. References [2-4] give a detailed description of the effects of clearance in single-bolt composite joints.

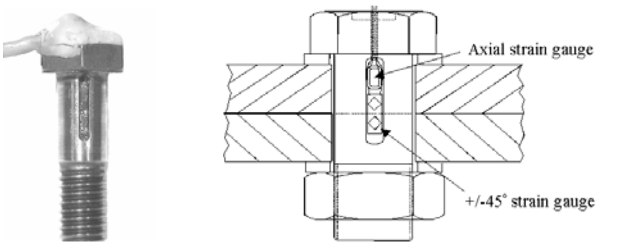


(a) (b)

FIG 4 Maximum contact area developed during loading (a) C1 clearance joint (b) C4 clearance joint

3.2 Measurement of Bolt Torque

As shown previously, the level of torque applied to the bolt significantly affects the friction forces in the joint and so an understanding of the relationship between applied torque and axial load in the bolt is an important consideration for joint testing and modelling. For this study, the pre-load was determined for different torque levels ranging from so-called “finger-tight” conditions (0.5 Nm) to the full torque recommended by the manufacturer when used with composites (16 Nm), using two tests. The first test involved applying an axial load to an instrumented bolt, shown in FIG 5, and determining the relationship between axial load and voltage in the axial gauges on the bolt. The second test involved torquing the bolt in an assembly of two composite plates. From this second test the relationship between torque and axial gauge voltage was determined. Combining the results from both tests, the relationship between torque and pre-load was determined and is shown in FIG. 6. As can be seen, there is a nearly linear relationship between applied torque and axial load in the bolt. A full outline of this procedure can be found in Reference [5].



(a) (b)

FIG 5 Instrumented bolt used to measure bolt pre-stress (a) Instrumented Bolt, (b) Schematic showing joint plates and washers

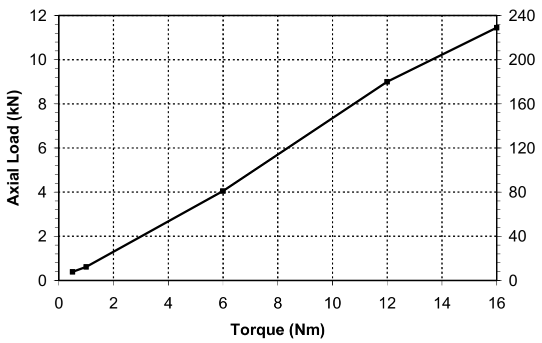


FIG 6 Relationship between axial load/stress and applied torque in an 8 mm diameter Titanium bolt

3.3 Stiffness Reduction Method to Determine Bearing Strength

Another output from the University of Limerick testing and analysis was a new method to determine the bearing strength of composite bolted joints [2]. The method is applicable for detecting damage at lower levels than that present with the often used 2% offset strength criterion. The method may be of particular interest 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 at 30% drop in stiffness").

FIG 7 shows the bearing stress/bearing stain curve for a single-bolt, single-lap joint. In addition, the slope of this curve (i.e. the bearing stiffness) is plotted as a function of the bearing strain. Use of even a 0.3% offset criterion as a measure of initial failure can be seen to involve a significant amount of damage as evidenced by loss of joint stiffness. In fact the loss in joint stiffness is believed to correlate better with joint damage levels than offset stress, so the approach suggested here is to use a percentage drop in joint stiffness as a failure measure rather than an offset criterion. This approach is more physically based and is less susceptible to user variations than offset strength criteria. A full description of the method is provided in Reference [2].

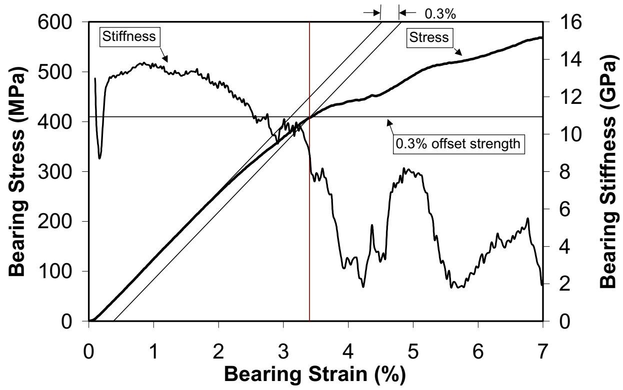


FIG 7 Alternative method to determine bearing strength

Apart from predicting failure, the stiffness plots can provide some useful information about the behaviour of joints. 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 8 shows this plot for the smallest and largest clearances (C1 and C4) examined. The following points are evident from FIG 8. Firstly, the reduction in stiffness with increased clearance is clearly seen, at all stress levels up until significant damage has occurred. Secondly, the stiffness of the larger clearance (C4) joint increases more gradually with increasing stress than that of the C1 joint, and reaches a maximum later. This is consistent with the findings of the finite element studies discussed in Section 4.1.

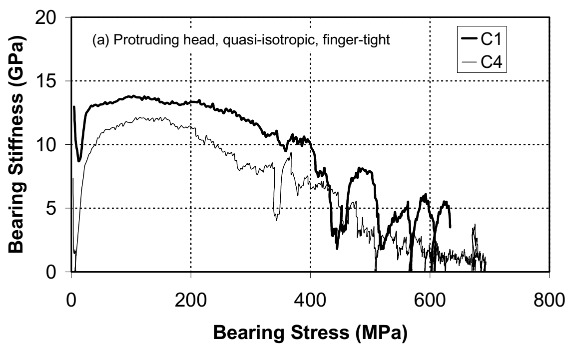


FIG 8 Bearing Stiffness plots for C1 and C4 clearance joints

3.4 Measurement of Load Distribution in Multi-Bolt Joints

Another powerful application of instrumented bolts is their ability to measure load distribution in multi-bolt joints. FIG 9 shows a three-bolt, single-lap joint with two instrumented bolts installed. For this particular joint all three bolts had a neat-fit C1 clearance. The resulting load distribution is shown in FIG 10 where it can be seen that the two outer bolts (i.e. Bolts 1 and 3) sustain a higher percentage of load than the middle bolt (Bolt 2). It is well know that the outer bolts in multi-bolt joints sustain higher loads than the inner bolts. However, interestingly, when a small C2 clearance (i.e. 80 µm) is introduced into Hole 1, the middle bolt (Bolt 2) becomes the most highly loaded, as shown in FIG 11. This highlights the importance of examining the effects of clearance.

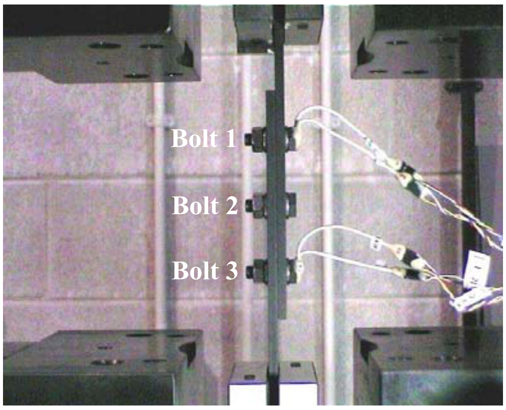


FIG 9 Measuring load distribution with instrumented bolts in a three-bolt, single-lap composite joint

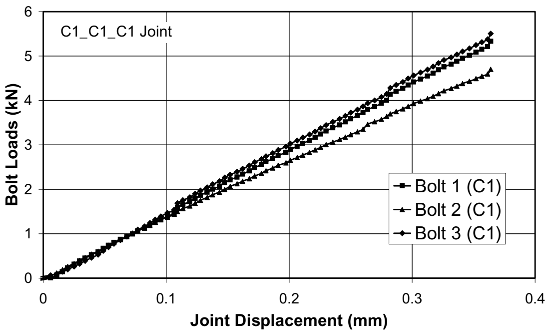


FIG 10 Load distribution in a three-bolt joint with each bolt having a neat-fit C1 clearance

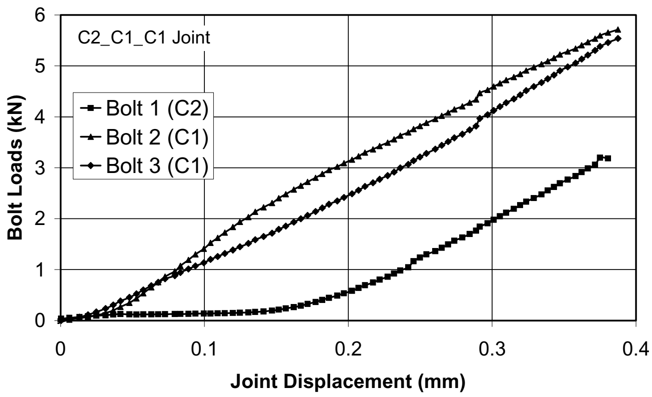


FIG 11 Load distribution in a three-bolt joint. Bolt 1 has an C2 (80 µm) clearance and Bolts 2 and 3 have a C1 (neat-fit) clearance

Instrumented bolts of the design used here are not suitable for double-lap joints. For double-lap joints strain gauges were affixed across the width of the joint, as shown in FIG 12. This method estimates the bolt loads by numerically integrating the strain across the joint width, which when multiplied by the laminate stiffness gives the average stress at the section. From this, the load at each of the strain-gauged sections can be calculated, and the bolt loads deduced from free-body diagrams. A detailed description of this method is outlined in Reference [9].

The stiffness reduction method in Section 3.3 above was also found to be useful for detecting bearing failure in multi-bolt joints. See FIG 13 for the high degree of correlation between the load at first bearing failure measured from the strain gauges and the load at first bearing failure measured using the joint stiffness reduction method. The latter method is highly advantageous as no instrumentation is required.

A summary of the effects of clearance on the first bearing failure (bearing failure in one hole) in double-lap multi-bolt joints is given in TAB 2. As can be seen, clearance can have a major effect on first bearing failure. Its effect on ultimate failure however was found to be negligible. This is mainly due to the fact that bearing failure causes elongation of the failed hole which evens up the clearance distribution in the joint for subsequent increased loading. Several scenarios involving different combinations of clearances in multi-bolt joints are discussed in more detail in References [6-9].

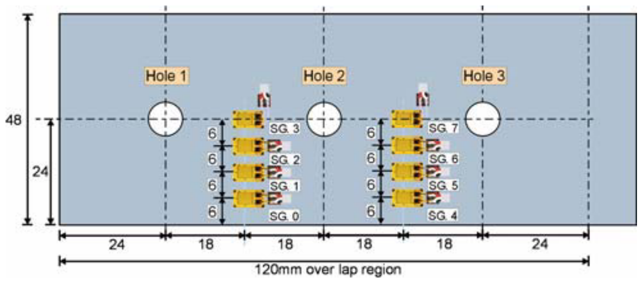


FIG 12 Alternative method to measure load-distribution in multi-bolt joints

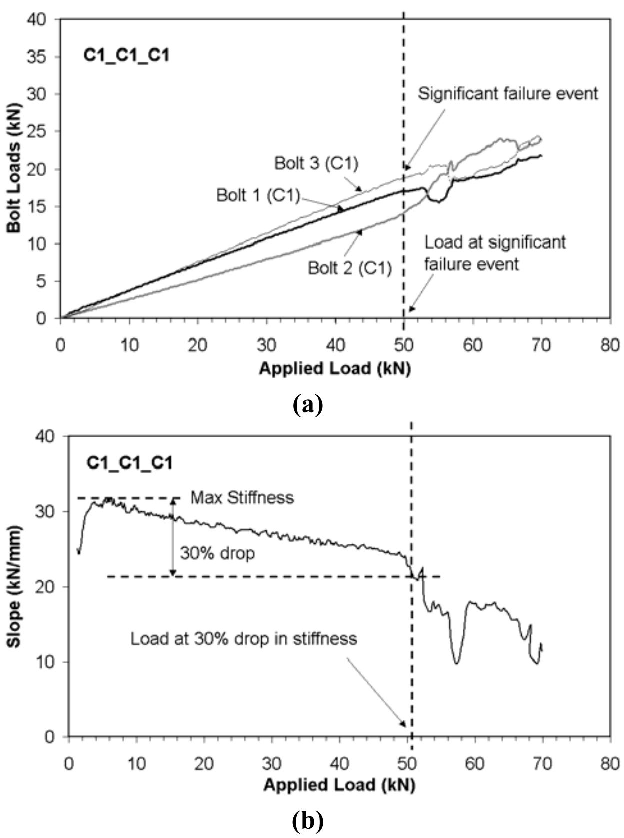


FIG 13 (a) Development of load distribution with increasing load in double-lap multi-bolt joints as measured by strain gauge method in FIG 12, (b) Joint stiffness reduction in same joint. Note correlation between bearing failure load detected by strain gauges and by stiffness reduction method

TAB 2 Effects of clearance on loads at first bearing failure

Code	Load at first bearing failure (kN)	Percentage Difference from C1_C1_C1
C1_C1_C1	50	0%
C1_C3_C1	44	12%
C1_C1_C4	44.3	11.4%
C2_C1_C1	43.2	13.6%
C4_C1_C1	40	20%
C3_C3_C1	37.2	25.6%

3.5 Fatigue Testing of Multi-Bolt Joints

The above strain gauge method was also used to measure load distribution in multi-bolt, double-lap joints loaded in fatigue. FIG 14(a) shows the load distribution in a joint loaded in fatigue in which one bolt (Bolt 1) has a C4 clearance, with the other two bolts (Bolts 2 and 3) having a neat-fit. After 200 load cycles, the loose-fit bolt (bolt 1) does not react much load, as shown in FIG 14(a). However, by 20,000 cycles this bolt transfers a significant amount of load and it appears that a process of load equalisation is taking place, as shown in FIG 14(b). The reason for this is elongation of the tight-fit holes due to damage, as can be seen in the X-ray image in FIG 15. This equalises the clearances in the holes, which equalises the load distribution. Thus similarly to the situation for static loading, clearance was found to influence the number of cycles to initial damage detected by hole elongation, but was found to have a smaller effect on ultimate fatigue life.

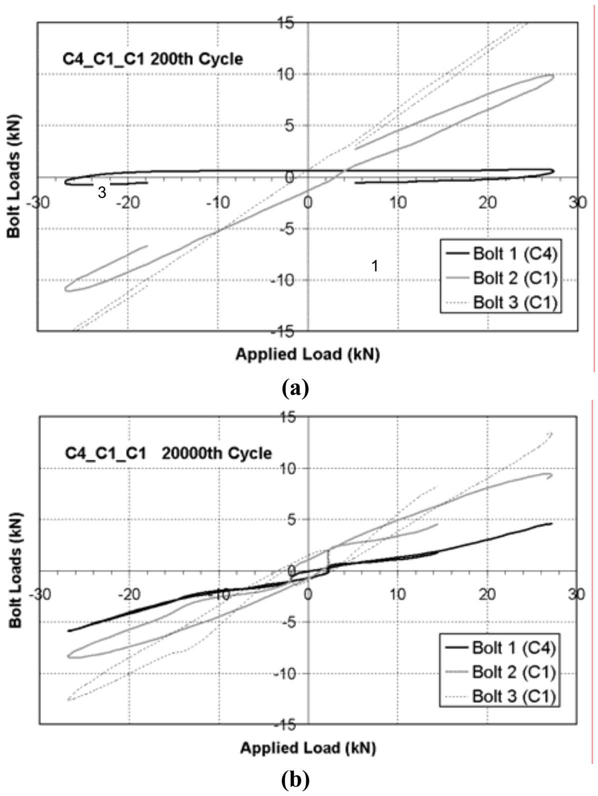


FIG 14 Load distribution in a 3-bolt, double-lap composite joint loaded in fatigue with Bolt 1 having a C4 clearance and the other two bolts having a neat-fit clearance (a) 200th cycle load distribution, (b) 20,000th cycle load distribution

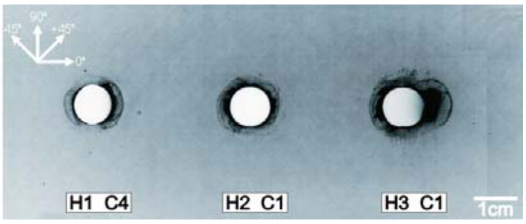


FIG 15 X-RAY image showing damage in the joint after 20,000 load cycles

4. NUMERICAL ANALYSIS

Full three-dimensional finite element modelling of composite bolted joints is necessary in order to capture through-thickness effects such as bolt clamp-up, delamination, out-of-plane stresses, and influences of bolt rotation and secondary bending in single-lap joints. Detailed three-dimensional finite modelling is, however, quite an involved task due to the time necessary to produce appropriate meshes and debug contact and friction at interfaces (of which there are many, especially in multi-bolt joints). References [10, 11] give detailed information on how to build finite element models of joints in MSC.Marc while [12] details joint development in ABAQUS.

The main difference between modelling in different codes is the definition of the contact interfaces. Apart from that, the procedures and results from the models are quite similar. For example, a comparison of different codes (including MSC.MARC, ABAQUS and ANSYS) was carried out in the BOJCAS project [1] in a round-robin exercise on modelling a single-lap, single-bolt composite joint. Excellent agreement between the different codes was obtained and this comparative study is reported on in [10].

In order to reduce model development time an automated tool for generating bolted joint finite element models was developed at the University of Limerick. This tool, entitled BOLJAT, was developed in MSC.Patran and can rapidly generate detailed joint models for both single-bolt and multi-bolt composite bolted joints by simply keying in joint dimensions, such as bolt diameter, plate thickness etc. FIG 16 shows the BOLJAT interface along with a single-lap, single-bolt finite element model generated by the programme. The BOLJAT tool was used to create the FE models presented in the following sections. A description of BOLJAT's capability can be found in [13]. Some further development has taken place since that that paper was published, and further development is planned.

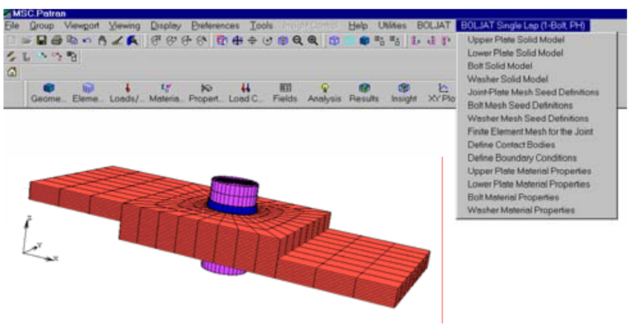


FIG 16 BOLJAT interface and a single-lap, single-bolt joint finite element model

4.1 Modelling the Effects of Bolt-Hole Clearance

Finite element analysis can accurately predict the effects of bolt-hole clearance in composite bolted joints. FIG 17 shows the load-deflection curve for C1 and C4 clearance single-bolt joints obtained numerically. These curves agree well with those obtained experimentally, shown in FIG 3(a). The model shows a delay in load take-up approximately equal to the clearance, as in the experiments. Attempts at best-fit straight lines are also shown in FIG. 17 and it can be seen that both curves show some initial non-linearity, but after this, the C1 curve is essentially linear. In contrast, the C4 curve shows a slight tendency to stiffen with increasing load, as was observed experimentally (see FIG 8). Comparing the two best-fit lines, it can be seen that the models predict a reduction in stiffness due to increasing clearance (as in the experiments).

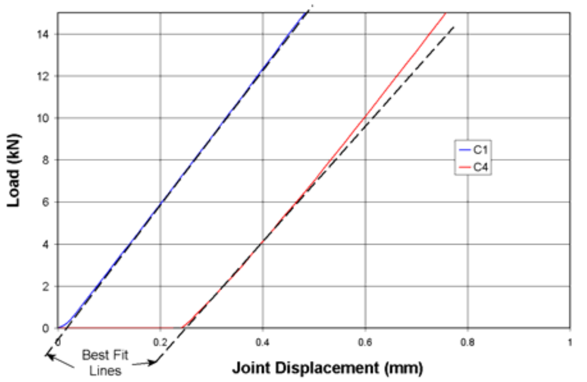


FIG 17 Numerical load-displacement curves for a C1 and C4 clearance joint

The explanation for these variations in stiffness lies in the development of the contact area between the bolt and the laminate. FIG 18 shows the growth of the contact area between the bolt and one of the laminates in the C1 and C4 clearance joints. For the C1 joint in FIG 18(a) it can be seen that the contact area gets up to its final value quite early in the loading history, with a contact angle of 160° - 170° which is fairly constant through the thickness. As can be seen, the predicted contact area is in good agreement with the experiment. In contrast, in the C4 joint, shown in FIG 18(b), significant contact is not made until clearance is taken up, and initial contact is over a very small contact arc. As the load increases, the bolt tilts, and the contact area grows quite gradually. Even at high loads, the contact area is still much less than in the C1 joint with a value of 100°- 105° at the shear plane, reducing to 55°-60° at the free face of the laminate. Note that the contact area in the model again agrees well with the imprint left by the bolt in the experiment. The gradual nature of the increase in contact area explains the continuing stiffening of the C4 joint with increasing load, while the lower final contact area explains the lower stiffness of the C4 joint compared to the C1 joint.

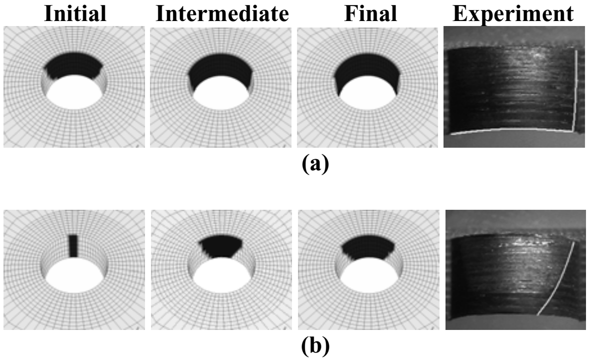


FIG 18 Development of the contact area with increasing load in (a) C1 clearance joint and (b) C4 clearance joint

Bolt-hole clearance has a strong effect on the stress state in composite bolted joints. For example, the radial stress in each ply of a C1 clearance, quasi-isotropic joint is shown in FIG 19(a). As can be seen the 0° plies carry the highest stresses since the fibres are aligned in the loading direction. All the 0° plies are most highly stressed at the 0° location, all the +45° plies are most highly stressed at the +45° location and all the -45° plies are most highly stressed at the -45° location. The 90° plies experience their highest stresses at an angle less than ±90° which varies through the thickness; the angle is less than ±90° since the contact angle is less than 180°.

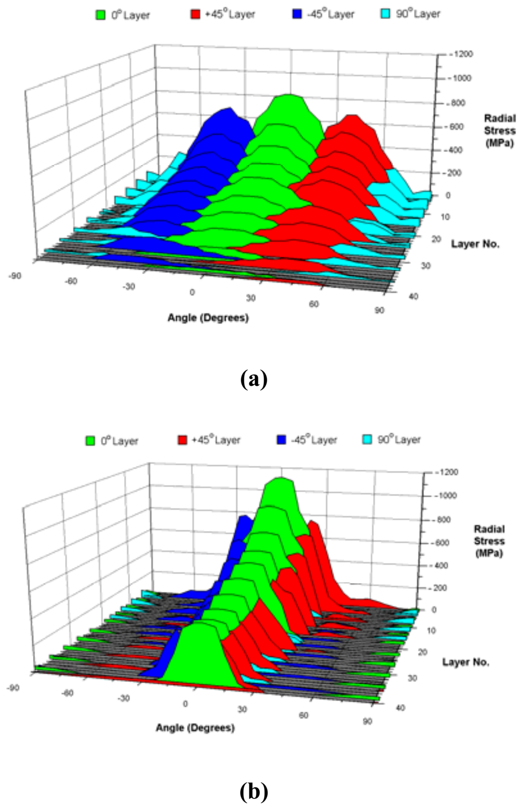


FIG 19 Stress distribution in each ply of (a) a C1 clearance joint and (b) a C4 clearance joint (NOTE: ply number 1 is at the joint shear plane)

For comparison, the radial stress distribution for a C4 clearance, quasi-isotropic joint is shown in FIG 19(b). It should be noted that both plots are shown at an applied joint load of 5 kN. Similarly to the C1 joint, the highest radial stresses in the C4 joint occur in 0° plies, but the magnitude of the stresses in these plies is considerably higher, which is due to the reduced contact area, as shown in FIG 18. FIG 19(b) shows that the radial stresses in the 0° plies are highest at the 0° location, as for the C1 case. However, differently from the C1 case, the +45° and -45° plies do not peak at their stiffest locations, but at an angle of approximately +15° and –15° respectively. This is due to the contact pressure being applied over a reduced contact angle. The peak radial stress value for these plies is also greatly increased compared to the C1 case. Although difficult to visualise, the 90° plies experience very low levels of radial stress at any location around the hole boundary with low peaks occurring at the 0° location. The tangential stresses are also significantly affected by clearance and a detailed study is presented in Reference [14].

4.2 Modelling Friction in Composite Bolted Joints

The important issue of friction in composite bolted joints is often ignored or given superficial treatment, since it introduces added difficulties to an already complex contact problem in terms of numerical convergence. However, friction can significantly alter the stress distribution in the laminate at the bolt-hole interface, and carries a major proportion of the load in torqued joints, so is important to model correctly. Reference [15] presents a detailed study on the performance of commonly used friction algorithms available in the MSC.Marc finite element code.

FIG 20 presents the main contributing factors in the load transfer in a single-lap, single-bolt composite joint with a C4 clearance. As can be seen most of the applied load is initially reacted by friction between the two composite plates. At approximately 0.1 mm joint displacement (Point A), the laminates begin to slide relative to each other and friction forces between the washers and the laminates begin to increase steadily until all the bolt-hole clearance is taken up. At approximately 0.38 mm joint displacement, the clearance is fully taken up and the bolt starts to transfer load and the friction forces between the two laminates and between the washers and the laminates start to reduce considerably. This analysis of the load transfer would be extremely difficult, if even possible, to predict experimentally, thus highlighting the important contributions that finite element analysis can make towards the understanding of joint behaviour.

Friction also significantly affects the stress distribution in composite bolted joints. For example FIG 21(a) shows the tangential and radial stresses in a pin-loaded laminate without friction present while FIG. 21(b) shows the same model with friction. As can be seen, friction significantly alters the distribution of the radial and tangential stresses around the hole boundary, while also introducing an additional shear stress.

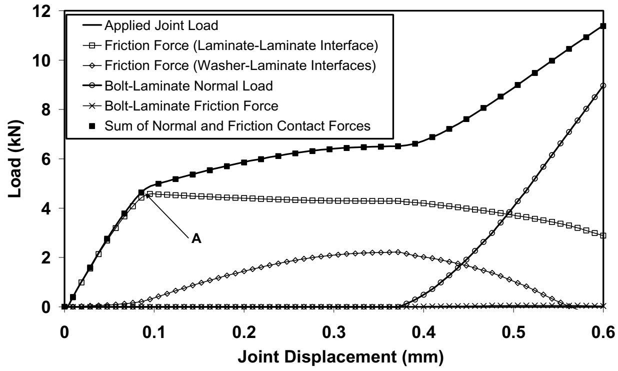
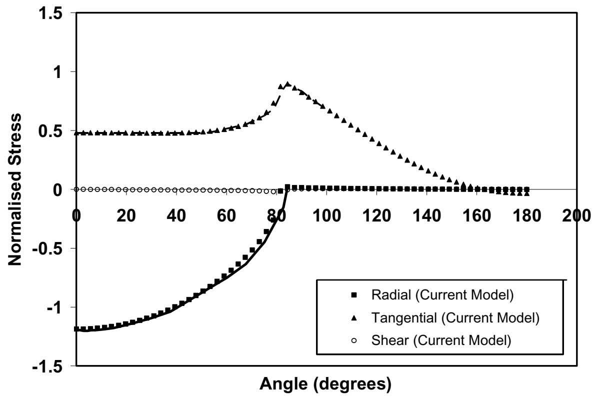
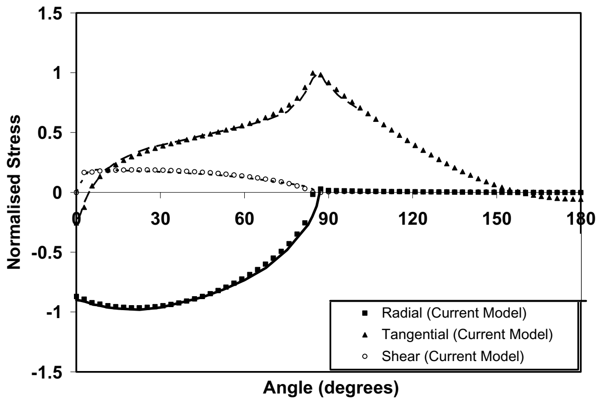


FIG 20 Load transfer in a single-lap, single-bolt joint with a C4 clearance



(a)



(b)

FIG 21 Stress distributions in a Pin-loaded laminate (a) without friction, (b) with friction

4.3 Modelling Damage in Composite Bolted Joints

In all the models presented thus far the material properties have been linear elastic, without any material damage or failure. In order to predict the failure of composite bolted joints progressive damage analysis (PDA) is often used. Since most finite element codes do not have inbuilt composite damage models, it is generally necessary to implement PDA using user defined material subroutines and a general procedure for doing this in the ABAQUS code is shown in FIG 22, where the user subroutine in USDFLD was used. In general, a failure criterion that can predict the failure mode as well as the failure load in the individual constituents that form the composite (i.e. matrix and fibre) is needed so that the appropriate material properties can be degraded according to the degradation law imposed. Reference [12] outlines one such progressive damage model that has been successfully implemented at the University of Limerick to predict damage in both single-bolt and multi-bolt composite joints. FIG 23 shows the extent of compressive matrix failure in a single-bolt, single-lap joint loaded to failure. As can be seen, extensive damage is evident at the bolt-hole throughout the laminate thickness, thus highlighting the need for detailed three dimensional analyses.

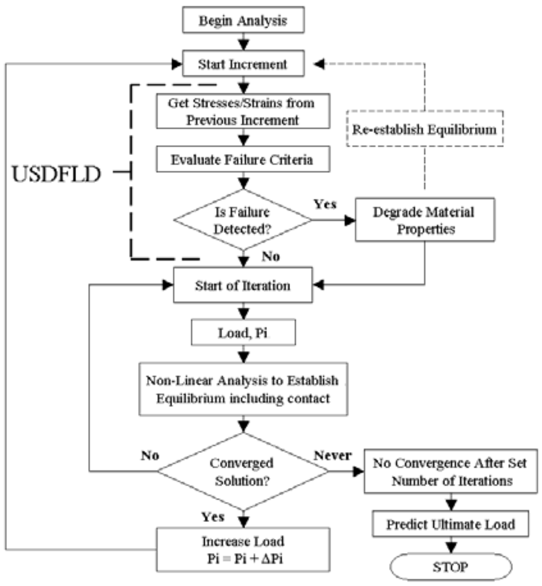


FIG 22 A general procedure for carrying out progressive damage analysis in ABAQUS

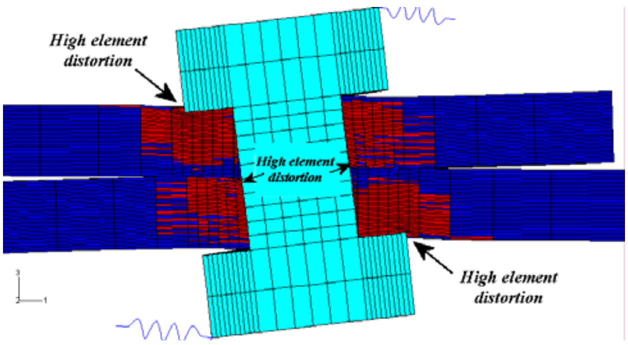


FIG 23 Compressive matrix damage in a single-bolt, single-lap composite joint

Bolt-hole clearance has been shown to have a significant effect on the stress state around the hole boundary with the stresses increasing with increasing clearance. These increased stresses lead to damage initiating earlier in joints with clearance. However, clearance has been found *not* to have a significant effect on the damage state in the laminate prior to ultimate failure. This can be explained by examining the extent of damage in the matrix and fibres in both a C1 and C4 clearance joint prior to ultimate failure, as shown in FIG 24. While there is evidently slightly more damage in the C4 clearance joint, both joints have sustained similar levels of damage. This damage softens the material around the bolt-hole which allows the bolt to press into the laminate more easily, thus masking any initial clearance effect.

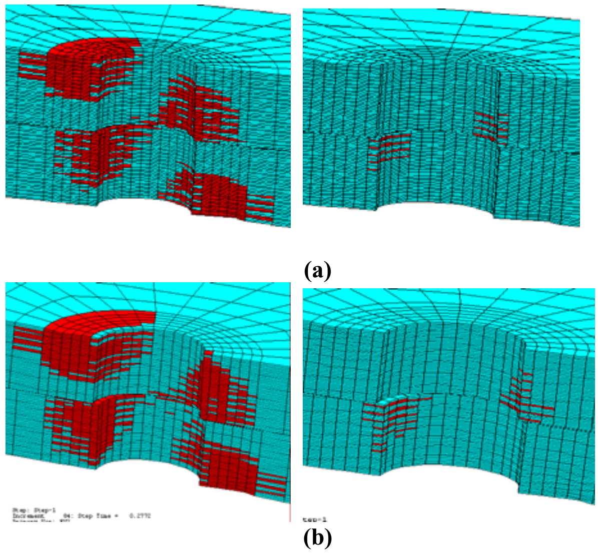


FIG 24 Damage in (a) C1 clearance joint and (b) a C4 clearance joint. Note: Left pictures show compressive matrix damage while right pictures show compressive fibre damage

4.4 Modelling Load Distribution in Multi-bolt joints

Another interesting application of finite element modelling of composite bolted joints is the prediction of load distribution in multi-bolt joints. For the three-bolt joint shown in FIG 25, a simple spring-mass model can accurately predict that the two outer bolts sustain a higher percentage of the applied load than the middle bolt [16]. However, while simple spring-mass models are useful for preliminary design and can also predict joint response in the presence of varying bolt-hole clearances, more detailed three-dimensional finite element models are needed to predict load distribution in joints where friction and material damage are present.

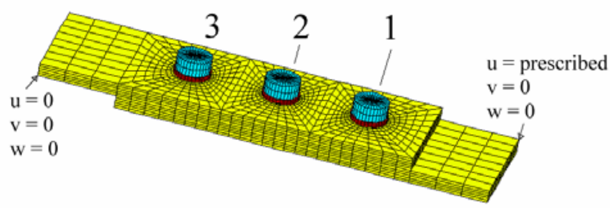
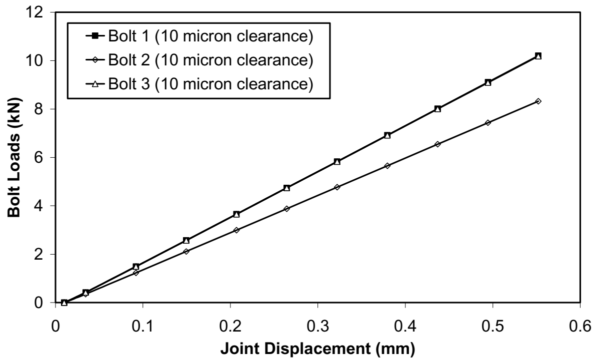


FIG 25 A three-dimensional finite element of a three-bolt, single-lap joint

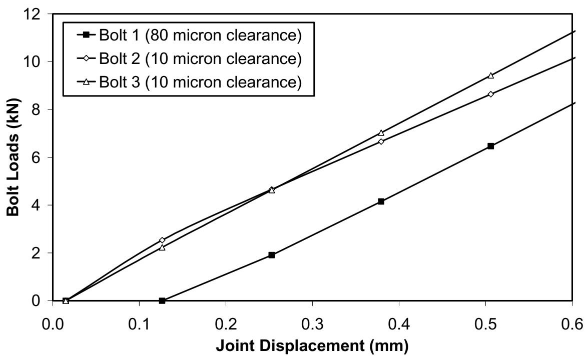
FIG 26(a) shows the load distribution in a joint with neat-fit clearances at each bolt-hole. As can be seen the two outer bolts sustain higher loads than the middle bolt. However, once a C2 (i.e. 80 µm) clearance is introduced to one of the outer bolts (with the other two having neat-fit clearances) the load distribution is significantly affected, as shown in FIG 26(b).

While the bolt-loads significantly contribute to failure, it is the combination of bolt loads and by-pass loads that govern failure in multi-bolt joints. FIG 27 shows a bearing-bypass diagram that was generated numerically using a three-dimensional finite element model. The failure envelopes were however determined experimentally. As can be seen from the diagram, both bearing and by-pass stresses contribute to joint failure. The bearing/by-pass stress state at each hole in the joint is plotted and Hole 1 crosses the failure envelope first. Hence, a net-tension failure is predicted to occur at Hole 1 in the joint. This finding agrees with experiments and a detailed analysis can be found in Reference [17].

Finally, the effects of friction and material damage on the load distribution in a three-bolt joint is shown in FIG 28(a) and FIG 28(b), respectively. As can be seen, friction causes a delay in load been taken by any of the bolts for a significant portion of the loading history. Once static friction between the joint plates is overcome, the bolts start to transfer load but the distribution of load is no longer the same as the no-friction case, shown in FIG 26(a). The effect of damage is to cause a redistribution and equalisation of load at each bolt-hole, once a significant failure event (such as bearing failure at one bolt-hole) occurs in the joint. All the numerical predictions of load distribution presented in this paper have been fully validated experimentally and a detailed description can be found in Reference [18].



(a)



(b)

FIG 26 Load distribution in multi-bolt joints (a) Neat-fit clearances at each bolt-hole, (b) 80 μm clearance at bolt-hole 1 with the other two having neat-fit clearances

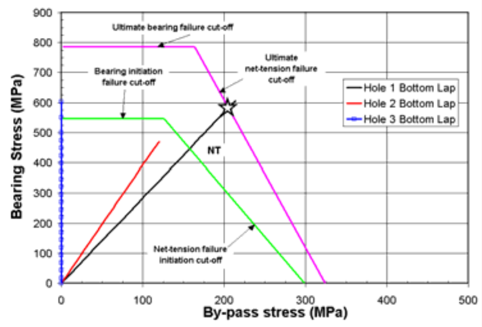
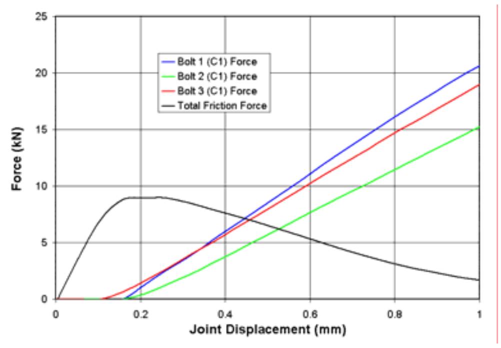
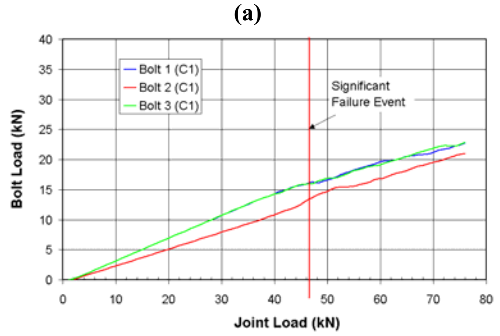


FIG 27 Bearing-bypass diagram for a three-bolt joint



(a)



(b)

FIG 28 Finite element predictions of bolt load distribution in a three-bolt joint (a) with friction (b) with material damage

5. WAY FORWARD

From the extensive body of work carried out during the BOJCAS project, a number of key future developments have been identified. An important area for research is to develop simplified joint models so that large joints (200+ bolts) can be analysed efficiently. The experiments and models presented herein could be used to benchmark such methods. For detailed three-dimensional joint analysis, more powerful model generation tools are needed to cut down on the large overhead associated with meshing and debugging contact and the University of Limerick is currently developing such tools. The most important future step to consider is the development of highly accurate damage models for composites. The PDA presented in this paper should only be considered as a starting point and more powerful Continuum Damage Models are available. However, there is as yet no one model that has found universal acceptance. Accurate prediction of damage in composite materials may lie in the ability to perform multi-scale analysis, where micromechanical damage can be captured in large scale models of joints.

6. CONCLUSIONS

This paper has presented an overview of the many issues involved in testing and modelling composite bolted joints. The study has concentrated on bolt-hole clearance as it provides an interesting and practical test case. It has been found that clearance affects the stress state around the hole, and severely interrupts the bolt load distribution in multi-bolt joints. This leads to a significant influence on the initial (bearing) failure load in multi-bolt joints, although the influence on final failure load is minimal. Clearance affects joint fatigue life in a similar fashion.

7. ACKNOWLEDGMENTS

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