Three-dimensional Modelling
of Multi-Bolt Composite Joints

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<u>Key words:</u> Bolted Joints, Composites, Clearance, Contact, Multi Bolt Joints.

Abstract
This paper focuses on the development of single lap, multi-bolt composite joints with clearance, with particular emphasis on load distribution within the joint. The models were developed in the non-linear finite element code MSC/MARC. Two models are presented: one is the control case with all three holes having a 'neat' fit clearance between the bolt and hole, while the other has a neat fit in two holes with the third hole having a large clearance. Results indicate that clearance has a significant effect on the load distribution in multi-bolt single lap joints.

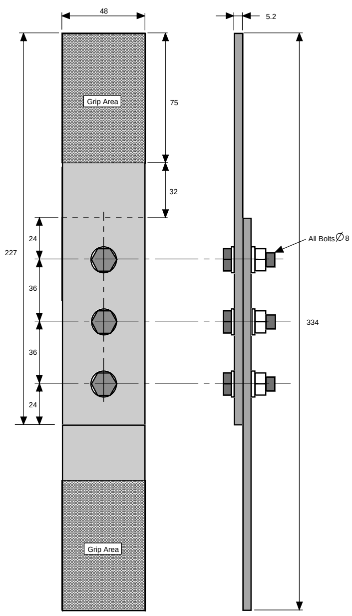
1. Introduction
An EU research project, "BOJCAS - Bolted Joints in Composite Aircraft Structures", is focusing on the development of improved design methods for bolted joints in composite aircraft structures, particularly primary structures. The methods will be based on finite element analysis, including global methods for preliminary design, and local methods for detailed design of critical joints. In this project, the University of Limerick is performing experimental analysis and three-dimensional finite element analysis of single and multi-bolt composite joints. The principal variable in the test series is bolt-hole clearance, which causes three-dimensional stress and strain variations which the models should be capable of quantifying.

2. Model Development
The single lap, multi bolt joint geometry being tested and modelled is shown in Figure 1. Four different clearances are being tested in a comprehensive test matrix, however only the case where all holes have a neat fit (coded "C1C1C1"), and the case where two holes have a neat fit with the third hole having a large clearance (coded "C4C1C1") are presented herein. The bolt numbering scheme and clearances used in each model are presented in Table 1.

Code	Hole 1 Clearance	Hole 2 Clearance	Hole 3 Clearance
C1C1C1	C1 (10 microns)	C1 (10 microns)	C1 (10 microns)
C4C1C1	C4 (240 microns)	C1 (10 microns)	C1 (10 microns)

Table 1 Clearances in multi-bolt models

2.1 Finite Element Mesh
The finite element model of the joint is shown in Figure 2. The meshing of the laminates was similar to that used by McCarthy *et al* [1], except there were three bolts and six washers spaced at a constant pitch. In order to keep the model to a manageable size only 5 elements were used through the thickness of the laminates. Eight-noded isoparametric hexahedral elements with a full integration scheme were used in the analysis. Wedge elements exist in the centre of the bolts.



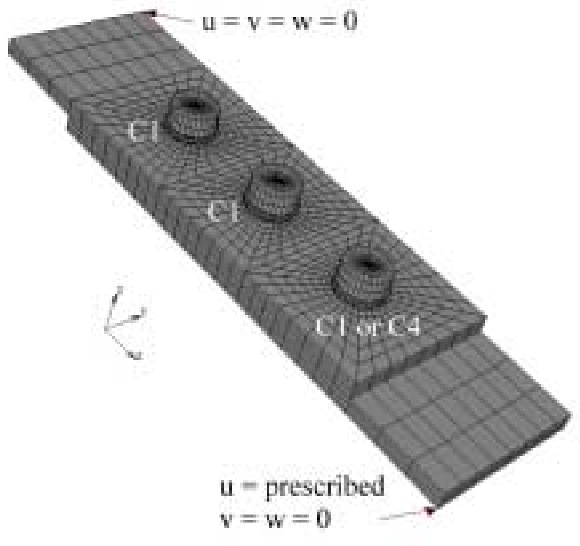


Figure 1. Joint Geometry **Figure 2. F.E. model with Boundary Conditions**

2.2 Boundary Conditions and Loading

Boundary conditions for the multi-bolt model were identical to that used in [1] where the gripped areas in Figure 1 were not modelled. Instead the ends of the top and bottom laminate were given prescribed displacement boundary conditions. Additionally, light springs were applied to the components which were not fully constrained, i.e. the bottom laminate and the bolt, in order to avoid potential rigid body modes.

2.3 Material Properties

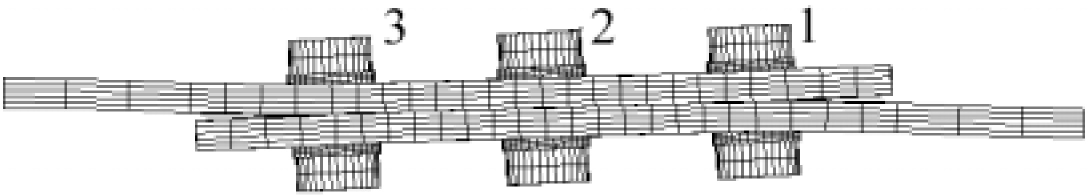
Material properties used in the analysis were developed in [1]. They are "equivalent" homogeneous, orthotropic properties, representative of a quasi-isotropic lay-up $[45/0/-45/90]_{5s}$ and are presented in Table 2.

	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (Gpa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
Equivalent Properties	54.25*	54.25*	12.59	20.72*	4.55	4.55	0.309*	0.332	0.332

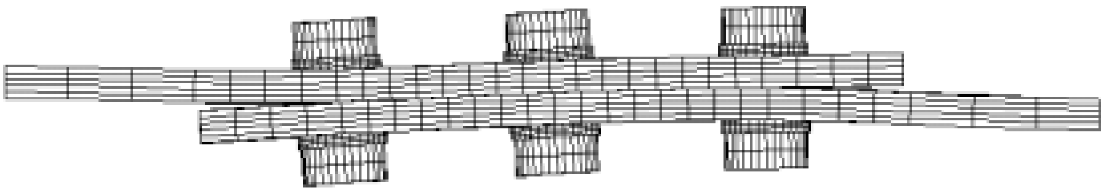
Table 2: "Equivalent" laminate material properties for quasi-isotropic layup
*** - verified by laminate theory**

3. Results

Figure 3 shows the deformed shape of the two joints at a displacement magnification factor of two. Model C1C1C1 shows an anti-symmetric deformation, but as would be expected anti-symmetry is lost in the C4C1C1 model. The bolts are numbered from right to left and the clearance at each hole corresponds to Table 1. In the C1C1C1 model all three bolts are tilted by approximately the same degree of rotation. The situation is different in the C4C1C1 joint, where Bolt 1 has not rotated as much as Bolts 2 and 3. The reason for this is that Bolt 1 is not contacted and hence, not rotated by the laminate, until the clearance at that hole is taken up. This has a significant effect on the load distribution among the other two fasteners as will be shown in Section 3.1.



(a) C1C1C1 deformed shape, showing anti-symmetric deformation



(b) C4C1C1 deformed shape, anti-symmetry is lost

Figure 3 Deformed shape of the multi-bolt models ($\times 2$ magnification)

3.1 Load Distribution Analysis

The method used to determine bolt load distribution in the FE models was to sum the x-components of the contact forces at each hole. Most of these forces were due to contact by the bolt on the inside of the hole, while components due to contact of the laminate surface with the washer were very small because the model is frictionless. It was confirmed that summing the three “bolt forces” obtained in this way equaled the total applied force which indicates that the lap was in static equilibrium at each solution step.

Figure 4 shows the load-deflection curve for the C1C1C1 and C4C1C1 joints. The C1C1C1 joint has an essentially linear load-deflection curve, however the C4C1C1 joint is only piecewise linear. The reason for this lies in the load distribution among the bolts in the presence of variable bolt-hole clearances. The load in the C1C1C1 joint is taken up by all three bolts after the first few increments. In contrast, the load in the C4C1C1 joint is only taken up by Bolts 2 and 3 until the clearance is taken up in Hole 1, which is why the stiffness of the C4C1C1 joint is initially lower.

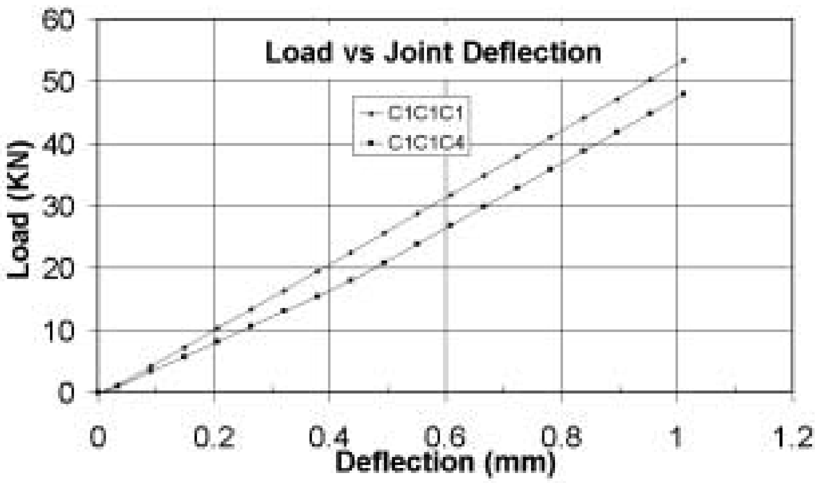
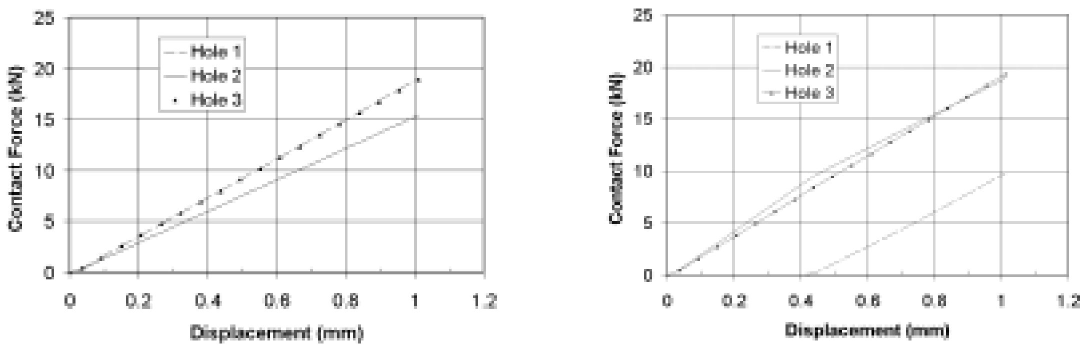


Figure 4 Load-deflection curve for the C1C1C1 and C4C1C1 joints

Although the load-displacement curve for the C1C1C1 joint is linear, the load transferred through the joint is not distributed equally among each bolt as is illustrated in Figure 6a. The load taken at Hole 1 and 3 is approximately the same due to the anti-symmetric nature of the joint. Considerably less load is taken at Hole 2, so Hole 2 is therefore not a critical area in the joint to be considered in a failure analysis. However, when clearance is introduced into Hole 1 (in the C4C1C1 model), Hole 2 becomes the most highly loaded hole until the clearance is taken up in Hole 1 as illustrated in Figure 6b. As the load is increased further, the load taken by each bolt starts to level off and would theoretically approach that of the control case (C1C1C1 model) eventually. However the joint would fail long before this would happen. This suggests that all three holes are of equal importance when considering a damage analysis since it is highly unlikely that a joint could be manufactured to have all perfect-fit bolt holes as in the control case analysed here.



(a) C1C1C1 joint **(b) C4C1C1 joint**

Figure 6 Load taken at each bolt hole

4. Discussion and Conclusion

It was found that load transfer in multi-bolt composite joints is a complex problem which is highly dependent on joint parameters such a bolt-hole clearance. The stiffness and anti-symmetry properties of single lap joints are also affected by varying clearances. In the case of a failure analysis, three dimensional finite element models are needed to give valuable information on the load transfer, and stress and strain distributions in multi bolt joints.

5. References

McCarthy, C.T., McCarthy, M.A. and Padhi, G.S., "Three Dimensional Modelling of Single-Bolt Composite Joints", Proceedings of the 9th ACME conference, University of Birmingham, U.K., 8-10 April 2001.

6. Acknowledgments

BOJCAS - Bolted Joints in Composite Aircraft Structures 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.