Experimental Measurement and Finite Element Analysis of Load Distribution and Strength in Multi-Bolt Composite Joints with Variable Bolt Hole Clearances

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Content

• Context for work
• Quasi-static loading
• Fatigue loading
• Finite Element Analysis
Context – BOJCAS project

BOLTED JOINTS IN COMPOSITE AIRCRAFT STRUCTURES
EU FRAMEWORK V
COMPETITIVE AND SUSTAINABLE GROWTH

Partners:

IRELAND: University of Limerick (Project Co-ordinator)
UNITED KINGDOM: Airbus UK, QinetiQ (formerly DERA)
SWEDEN: SAAB, FOI, Royal Inst of Tech Stockholm
GERMANY: Airbus Germany
ITALY: CIRA
THE NETHERLANDS: NLR
GREECE: ISTRAM
SWITZERLAND: SMR
Why Study Clearance?

- Bolt-hole clearance results in 3D variations in stress/strain distributions
  - Good parameter to study for validation of 3D FE
- Clearance is inevitable in any practical manufacturing process
  - cannot be avoided, so effects should be understood
- Has not been studied experimentally in multi-bolt joints before
- Previous models of effects of clearance have been analytical or 2D FE
Quasi-Static Loading
Joint Geometries

- Single-lap joint
- HTA/6376 carbon/epoxy
- Quasi-isotropic lay-ups
- Titanium alloy bolts

- Double-lap joint
Controlling Clearance

Bolts (8 mm) obtained from SAAB (f7 tolerance)

Four different size holes obtained with reamers specially manufactured to a tight (h6) tolerance

Possible 24 µm variation for each nominal clearance

Four nominal clearances

<table>
<thead>
<tr>
<th>Clearance Code</th>
<th>Nominal Clearance (µm)</th>
<th>Drill Reamer Diameter Min (mm)</th>
<th>Drill Reamer Diameter Max (mm)</th>
<th>Bolt Diameter Min (mm)</th>
<th>Bolt Diameter Max (mm)</th>
<th>Possible Clearance Min (µm)</th>
<th>Possible Clearance Max (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0</td>
<td>7.985</td>
<td>7.994</td>
<td>7.972</td>
<td>7.987</td>
<td>-2</td>
<td>22</td>
</tr>
<tr>
<td>C2</td>
<td>80</td>
<td>8.065</td>
<td>8.074</td>
<td>&quot;</td>
<td>&quot;</td>
<td>78</td>
<td>102</td>
</tr>
<tr>
<td>C3</td>
<td>160</td>
<td>8.145</td>
<td>8.154</td>
<td>&quot;</td>
<td>&quot;</td>
<td>158</td>
<td>182</td>
</tr>
<tr>
<td>C4</td>
<td>240</td>
<td>8.225</td>
<td>8.234</td>
<td>&quot;</td>
<td>&quot;</td>
<td>238</td>
<td>262</td>
</tr>
</tbody>
</table>
## Clearance Cases

<table>
<thead>
<tr>
<th>Case Code</th>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1_C1_C1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C1_C1_C2</td>
<td>0</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>C1_C1_C3</td>
<td>0</td>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>C1_C1_C4</td>
<td>0</td>
<td>0</td>
<td>240</td>
</tr>
<tr>
<td>C1_C3_C1</td>
<td>0</td>
<td>160</td>
<td>0</td>
</tr>
<tr>
<td>C1_C3_C3</td>
<td>0</td>
<td>160</td>
<td>160</td>
</tr>
</tbody>
</table>
Centring/Aligning/Drilling Jigs

- Manufactured to very high precision

Measuring Load Distribution

Single-lap joints:
→ Instrumented bolts

Double-lap joints:
→ Strain gauges
SL Joints – Load Distr.

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SL Joints - Failure

No clear effect on ultimate strength

Load (kN)

Machine Stroke (mm)

Net Tension Failure

Bolt Failure

C1_C1_C1 (A)
C1_C1_C1 (B)
C1_C1_C1 (C)
C4_C1_C1 (A)
C4_C1_C1 (B)
C4_C1_C1 (C)
Most Interesting Failure

Two bolts failed simultaneously

Usual design rules (ignoring clearance) → middle bolt NOT under any threat of failure

But with clearance in one of the outer holes – failure of middle bolt becomes possible
SL Joints – Failure *Initiation*

C1_C1_C4 joint exhibits sharp losses in stiffness earlier than C1_C1_C1 joint.

Slope of load-deflection curve, i.e. joint stiffness
Measure of Failure Initiation

Load (kN)

Slope (kN/mm)

C1_C1_C1
C1_C1_C4

30% Loss

Load at 30% stiffness loss
C1_C1_C1 case

## Failure “Initiation” Loads

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Load at 30% stiffness drop (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1_C1_C1 (A)</td>
<td>51.06</td>
</tr>
<tr>
<td>C1_C1_C1 (B)</td>
<td>47.26</td>
</tr>
<tr>
<td>C1_C1_C1 (C)</td>
<td>51.00</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>49.77</strong></td>
</tr>
<tr>
<td>C1_C1_C4 (A)</td>
<td>48.25</td>
</tr>
<tr>
<td>C1_C1_C4 (B)</td>
<td>47.64</td>
</tr>
<tr>
<td>C1_C1_C4 (C)</td>
<td>46.20</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>47.36</strong></td>
</tr>
</tbody>
</table>

Failure initiated earlier in C1_C1_C4 joints
Double-Lap Joints

Again, no clear effect on ultimate strength

![Graph showing load vs. machine stroke for various joint configurations.](image-url)
DL Joints – Failure Initiation

- Strain gauge method of load distribution measurement much cheaper → can test to failure
- Strain gauge readings interrupted at a “significant” failure event

Load at 30% loss of stiffness matches load at interruption of strain gauge pattern very well
• Again load at 30% loss of stiffness matches load at interruption of strain gauge pattern very well (true for all six clearance cases)
• Load is significant lower in C1_C3_C1 case than C1_C1_C1
• From consideration of bearing yield allowable, the “first significant failure” was found to be bearing failure at one of the holes
**Effect of Clearance on first bearing failure**

<table>
<thead>
<tr>
<th>Code</th>
<th>Load at first bearing failure (kN)</th>
<th>Percentage Difference from C1_C1_C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1_C1_C1</td>
<td>50</td>
<td>0%</td>
</tr>
<tr>
<td>C1_C3_C1</td>
<td>44</td>
<td>12%</td>
</tr>
<tr>
<td>C1_C1_C4</td>
<td>44.3</td>
<td>11.4%</td>
</tr>
<tr>
<td>C2_C1_C1</td>
<td>43.2</td>
<td>13.6%</td>
</tr>
<tr>
<td>C4_C1_C1</td>
<td>40</td>
<td>20%</td>
</tr>
<tr>
<td>C3_C3_C1</td>
<td>37.2</td>
<td>25.6%</td>
</tr>
</tbody>
</table>
Conclusions – QS Loading

• Clearance:
  - No significant effect on ultimate tensile load
  - DID affect ultimate tensile mode
  - Small effect on failure initiation load in SL joints
  - LARGE effect on failure initiation load in DL joints (load at first bearing failure affected by 25%)

• Strain gauge load distribution method cheaper than instrumented bolts – can be used up to failure (cannot easily be used for SL joints though)

• Load at 30% loss in stiffness appears to be a good measure of first “substantial” failure
Fatigue Loading
Fatigue Cases

<table>
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<tr>
<th>Case Code</th>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1_C1_C1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C1_C1_C4</td>
<td>0</td>
<td>0</td>
<td>240</td>
</tr>
</tbody>
</table>

- Both Single-Lap and Double-lap joint
Test Set-up

- Constant amplitude fatigue loading, $R = -1 \left( \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = -1 \right)$
- Anti-buckling guides

- To avoid temperature rise, frequencies between 0.66 and 5 Hz
- Temperature of each bolt monitored – maintained $< 25^\circ\text{C}$
Failure Criterion

- Hole elongation criterion for failure (Starikov and Schon, 2002)
- Increase in peak-to-peak displacement $\Delta \delta$ of 0.8 mm
Ultimate Failure Modes

• However, in single-lap joints, other failure modes occurred on continuation of tests beyond the hole elongation failure point.

Bolt failure

Net tension failure

Extreme hole elongation

• Double-lap joints exhibited only extreme hole elongation.
Ultimate Failure Cycles

• Cycles to “ultimate failure” were also recorded

• “Ultimate failure” – displacement to + or – 10 mm

• Reached suddenly in catastrophic failure modes and gradually in extreme hole elongation cases
SL Joints – Hole Elong

Joints with loose-fit bolt have shorter fatigue life in general
Joints with loose-fit bolt have shorter fatigue life in general.
Temperature and Displ. History

Single-lap joint

Hole elongation initiates here

C1_C1_C1 +/-27 kN
Temperature and Displ. History

Single-lap joint

Hole elongation initiates earlier

C1_C1_C4 +/-30 kN

No. of cycles

Delta_Pk_Pk (mm)

Temperature (deg C)

Temperature - Bolt 1
Temperature - Bolt 2
Temperature - Bolt 3
Delta_Pk_Pk
SL - Cycles to small hole elong

- Clearer distinction between clearance cases

**Cycles to \( \Delta P_{k,Pk} = 0.2 \text{ mm} \)**

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Joints with loose-fit bolt have shorter fatigue life in general.
• Again - clearer distinction between clearance cases
Load distribution during Fatigue

C4_C1_C1 200th Cycle

C4_C1_C1 20000th Cycle

- Due to hole wear, clearance has less effect as wear progresses (load distribution evens out) ➞ clearance most affects **initiation** of failure, less effect on final failure
Conclusions – Fatigue Loading

• Joints with a loose-fit bolt had shorter fatigue lives than joints with all neat-fit bolts (SL and DL)

• Clearance had a particularly strong effect on failure initiation, i.e. cycles to a small hole elongation

• Effect of clearance less pronounced as failure progresses since failure causes elongation of the neat-fit holes in the C1_C1_C4 joint causing the clearance to even out over time
Finite element Analysis
Model Creation Tool: BOLJAT

Contact Analysis

Contact analysis performed between all parts
Contact Area Development

Single-Bolt, Single-Lap Joint

C1 Clearance (Contact Area)

C4 Clearance (Contact Area)
Model of Double-Lap Joint

Quarter Symmetry assumed

Fixed in X, Y and Z
(U, V and W = 0)

Fixed in Y and Z
(V and W = 0)

Prescribed X displacement
Point A

Y-Symm
(V = 0)

Z-Symm
(W = 0)

Point B

Composites Research Centre
University of Limerick
Stress Distribution

Stresses vary through thickness of each laminate even in DL joint (due to bolt bending)

Net tension stresses in central laminate highest at this hole (i.e. bypass stresses correctly accounted for)
Progressive Damage Analysis

USDFLD

Begin Analysis

Start Increment

Get Stresses/Strains from Previous Increment

Evaluate Failure Criteria

Is Failure Detected?

Yes

Degrade Material Properties

No

Start of Iteration

Load, Pi

Non-Linear Analysis to Establish Equilibrium including contact

Converged Solution?

Yes

Increase Load

Pi = Pi + ΔPi

No

No Convergence After Set Number of Iterations

Predict Ultimate Load

STOP

Re-establish Equilibrium
Bolt Loads (C1_C1_C1)

Experiment

Simulation

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Bolt Loads (C4_C1_C1)

Experiment

Simulation

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## Compressive Matrix Damage (C1_C1_C1)

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Hole 1 (0 μm)</th>
<th>Hole 2 (0 μm)</th>
<th>Hole 3 (0 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kN</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>30 kN</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>50 kN</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
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# Compressive Fibre Damage

## (C1_C1_C1)

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<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
</tbody>
</table>
## Compressive Matrix Damage (C3_C3_C1)

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Hole 1 (160 µm)</th>
<th>Hole 2 (160 µm)</th>
<th>Hole 3 (0 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kN</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>30 kN</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>50 kN</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
</tbody>
</table>
## Compressive Fibre Damage (C3_C3_C1)

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Hole 1 (160 µm)</th>
<th>Hole 2 (160 µm)</th>
<th>Hole 3 (0 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kN</td>
<td><img src="image1" alt="Image" /></td>
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<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
</tbody>
</table>
Conclusions – FEA

• 3D FEA with contact can account for: variable contact in each hole and through thickness; bypass stresses; non-uniform bearing stresses through thickness

• PDA gives insight into failure processes at each hole and gives prediction of initial failure (bearing failure in one hole)