MMS11

Predicting Deformation and Failure in Adhesive and Bolted Joints

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- Creep Modelling of Rubber-Toughened Epoxy Adhesives
- Predicting Fatigue Behaviour of Bonded and Bolted Joints
- Discussion and Future Work
Creep Modelling of Rubber-Toughened Epoxy Adhesives

Greg Dean
Predicting Fatigue Behaviour of Bonded and Bolted Joints

Bill Broughton
Slotted T-Joint Configuration

Objective: Optimise design to produce high joint strength and stiffness, excellent fatigue/creep resistance, low weight and low cost.
Materials Selection

- Rubber Toughened Epoxy Adhesives
  - XD4601 (Dow Chemicals) and DP460 (3M)
- Adherends
  - 2014-T6 aluminium alloy
  - GRP – UD + biaxial woven fabric/epoxy (SP Systems)
- Surface Treatment
  - Aluminium – CAE/CAA/SIP (Permabond)
  - Composite - grit blasted
- Systems
  - Aluminium/XD4601 and GRP/DP460
## Basic Laminate Configuration

\[\{0 = 63.2\%, \; 90 = 10.5\%\; \pm 45 = 26.3\%\}\]

<table>
<thead>
<tr>
<th>Layer Number</th>
<th>Ply Orientation</th>
<th>Total Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>0</td>
<td>3.84</td>
</tr>
<tr>
<td>7-10</td>
<td>Biaxial Fabric</td>
<td>1.60</td>
</tr>
<tr>
<td>11-12</td>
<td>90</td>
<td>1.28</td>
</tr>
<tr>
<td>13-16</td>
<td>Biaxial Fabric</td>
<td>1.60</td>
</tr>
<tr>
<td>17-22</td>
<td>0</td>
<td>3.84</td>
</tr>
</tbody>
</table>
Tensile Loading Modes

- Direct tension (pull-off)
- Transverse and 45° tension
Aluminium T-Joint - Basic Geometry

- Adhesive thickness = 0.5 mm
- Base plate
- Flange
- Web

Dimensions:
- Width: 150 mm
- Height: 101.6 mm
- Depth: 35 mm
- Edge: 15 mm

Total length: 300 mm
Bonded T-Joints

Aluminium

GRP
Direct Tension of Bonded T-Joint
Aluminium Bonded T-Joints
Direct Tension

Vertical Displacement (mm)
Load (N)

Specimen 1 (CAE) Specimen 2 (CAA) Specimen 3 (CAA) Specimen 4 (SIPS) FE
### Aluminium Bonded T-Joints

**Direct Tension - Failure Load (kN)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cavitation</th>
<th>E-D-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum principal strain</td>
<td>32.10</td>
<td>B</td>
</tr>
<tr>
<td>Hydrostatic stress</td>
<td>31.16</td>
<td>B</td>
</tr>
<tr>
<td>Experimental</td>
<td>21.91 ± 1.73</td>
<td>B</td>
</tr>
<tr>
<td>Initial</td>
<td>30.83 ± 3.58</td>
<td></td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td>B</td>
</tr>
</tbody>
</table>

**Exponent Drucker-Prager (E-D-P)**

**B = bottom of flange-web interface**
Deformed Mesh Superimposed on Original Mesh Failure Locations

Failure Locations

A
B
C
### Aluminium and GRP Bonded T-Joints

**Failure Load (kN)**

<table>
<thead>
<tr>
<th>Loading Mode</th>
<th>Aluminium</th>
<th>GRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
<td>Experiment</td>
</tr>
<tr>
<td>Direct Tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-linear Ultimate</td>
<td>31.16</td>
<td>21.91 ± 1.73</td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td>30.83 ± 3.58</td>
</tr>
<tr>
<td>Transverse Tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-linear Ultimate</td>
<td>6.80</td>
<td>-</td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Bolted Aluminium T-joint – Starting Geometry

A = flange
B = base plate
C = web plate
D = bolt

15

300

51.6

10

35

50

25.8

12*

150

25.8

40.9

15

300

NPL
Bolted T-Joints

Aluminium

GRP
Loading Arrangement for Bolted T-Joints

Direct Tension

Transverse Loading
Aluminium Bolted T-Joint
Direct Tension

Vertical Displacement (mm)
Load (N)

Specimen 1  Specimen 2  Specimen 3  Specimen 4  FEA
Aluminium Bolted T-Joint
Lateral Tension

Transverse Displacement (mm)

Load (N)

Specimen 2  Specimen 3  FEA
## Aluminium and GRP Bolted T-Joints

### Failure Load (kN)

<table>
<thead>
<tr>
<th>Loading Mode</th>
<th>Aluminium</th>
<th>GRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
<td>Experiment</td>
</tr>
<tr>
<td><strong>Direct Tension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-linear</td>
<td>51.97</td>
<td>48.72 ± 2.91</td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td>78.34 ± 3.69</td>
</tr>
<tr>
<td><strong>Transverse Tension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-linear</td>
<td>18.46</td>
<td>15.26</td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td>20.36</td>
</tr>
</tbody>
</table>
Progressive Failure of Bolted Aluminium T-Joint

Direct Tension

25.46 kN  
29.66 kN  
39.11 kN
Failure Mechanisms

Initial regions of through thickness tensile failure - near supports

Initial region of through thickness tensile failure - inside of base plate bolt hole

Direct Tension

Transverse and 45° Tension

Problem: Interpreting Failure

♦ Onset of damage (used in FEA study)
♦ Degree of damage (i.e. hole elongation)
♦ Separation between flange and base plate
Stress Concentrations in Isotropic Plates

\[ K_T^\infty = 1 + \frac{2}{\lambda} \]

where

\[ \lambda = \frac{a}{b} = 1; \text{ circular hole} \]

\[ \implies K_T^\infty = 1 + 2 = 3 \]

**FHW CORRECTION**

\[ \frac{K_T^\infty}{K_T} = \frac{3(1 - 2a/w)}{2 + (1 - 2a/w)^3} \]
Example:

\[ a = b = 12.2 \text{ mm}; \ w = 50 \text{ mm} \]

\[
\frac{K_T^\infty}{K_T} = \frac{3\left(1 - \frac{12.2}{50}\right)}{2 + \left(1 - \frac{12.2}{50}\right)^3} = 0.933
\]

\[ \Rightarrow K_T = 3 / 0.933 = 3.22 \]
Isotropic Plate with Circular Hole Stress Distribution

\[ \frac{\sigma_y}{\overline{\sigma}} = 1 + \left( \frac{a}{x} \right)^2 + \frac{3}{2} \left( \frac{a}{x} \right)^4 \]

\[ K_T \approx 1; \text{yielding} \]
Orthotropic Plate with Circular Hole

\[
\frac{K_T^\infty}{K_T} = \frac{3(1 - 2a/w)}{2 + (1 - 2a/w)^3} + \frac{1}{2} \left(\frac{2a}{w} M\right)^6 \left(K_T^\infty - 3\right) \left[1 - \left(\frac{2a}{w} M\right)^2\right]
\]

\[
M^2 = \frac{\sqrt{1 - 8 \left[\frac{3(1 - 2a/w)}{2 + (1 - 2a/w)^3} - 1\right]}}{2(2a/w)^2}
\]

\[
K_T^\infty = 1 + \sqrt{\frac{E_{xx}}{E_{yy}} - \nu_{xy}} + \frac{E_{yy}}{G_{xy}}
\]
GRP Plate with Circular Hole
Predicted Stress Concentration

\[ a = b = 12.2 \text{ mm}; \, w = 50 \text{ mm}; \, t = 12.08 \text{ mm} \]

\[
\begin{align*}
E_{xx} &= 38.8 \text{ GPa} \\
E_{yy} &= 18.0 \text{ GPa} \\
G_{xy} &= 7.17 \text{ GPa} \\
\nu_{xy} &= 0.28 \\
\nu_{yx} &= 0.12 \\
\end{align*}
\]

\[
\begin{align*}
E_{xx} &= 33.5 \text{ GPa} \\
E_{yy} &= 17.9 \text{ GPa} \\
G_{xy} &= 6.50 \text{ GPa} \\
\nu_{xy} &= 0.30 \\
\nu_{yx} &= 0.16 \\
\end{align*}
\]

\[
\frac{K_T^\infty}{K_T} = 0.935; \quad K_T^\infty = 5.49; \quad K_T = 5.87 \quad \text{(Experimental)}
\]

\[
\frac{K_T^\infty}{K_T} = 0.935; \quad K_T^\infty = 5.59; \quad K_T = 5.98 \quad \text{(CoDA)}
\]
Orthotropic Plate with Circular Hole Stress Distribution

\[ \frac{\sigma_y(x,0)}{\sigma} = \frac{1}{2} \left( 2 + \left( \frac{a}{x} \right)^2 + \frac{3}{2} \left( \frac{a}{x} \right)^4 - \left( K_T^\infty - 3 \right) \left[ 5 \left( \frac{a}{x} \right)^6 - 7 \left( \frac{a}{x} \right)^8 \right] \right) \quad x > a \]

POINT STRESS CRITERION

\[ \frac{\sigma_N^\infty}{\sigma_o} = \frac{2}{2 + \xi_1^2 + 3 \xi_1^4 - \left( K_T^\infty - 3 \right) \left( 5 \xi_1^6 - 7 \xi_1^8 \right)} \]

\[ \xi_1 = \frac{a}{a + d_o} \]

\[ d_o = \text{characteristic length} \]
Orthotropic Plate with Circular Hole
Open Hole Tension/Pin Bearing Strength

\[ S_{XX}(T) = 889 \pm 33 \text{ MPa} \]
\[ S_{XX}(C) = 975 \text{ MPa} \]
\[ S_{XX}(OHT) = 510 \pm 11 \text{ MPa} \]
\[ S_{XX}(PB) = 446 \pm 4 \text{ MPa} \]
\[ S_{XX}(PB) = 711 \pm 11 \text{ MPa (T = 3 Nm)} \]

For \( a = 6 \text{ mm}, w = 36 \text{ mm} \) and \( t = 6.08 \text{ mm} \)

\[ K_T = 1.74 \ (d_o = 1.55) \]
\[ S_{XX}(PB, T = 3 \text{ Nm}) \approx 1.60 \ S_{XX}(PB) \]
Failure Modes

(a) Shear Out   (b) Tension   (c) Bearing
(d) Tension/Shear Out   (e) Bearing/Shear Out
(f) Bearing/Tension/Shear Out   (g) Cleavage
$S(OHT) \approx 21.3 + 0.55S(T)$
Comparison of Fatigue Performance

- **2014-T6 Aluminium**
- **Unidirectional T300/924**
- **Unidirectional E-glass/913**
2014 Unnotched ($K_t = 1.0$) Aluminium Alloy Military Handbook MIL-HDBK-5H Fatigue Data
2014 Aluminium Alloy
S-N Curve ($R = \sigma_{MIN}/\sigma_{MAX} = 0.0$)

$\sigma_{MAX} = AN^m = 1319N^{-0.11}$

Fatigue Limit

Cycles to Failure ($N_f$)
2014 Aluminium Alloy
Log-Linear S-N Curve (R = 0.0)

\[ \sigma_{\text{MAX}} = AN^m = 1319N^{-0.11} \]

\[ \sigma_{\text{MAX}} = AN^{-0.11} \text{ where } A \approx 1277 + 482R \]
2014 Aluminium Alloy
Fatigue Life

![Graph showing the relationship between normalised maximum stress and R ratio for different cycles.](image-url)
Universal Curve for Metallic Materials

\[ \sigma_{\text{MAX}} = A n^{-0.11} \quad (R = 0.0) \]

- Ti-6Al-4V
- 300M STEEL
- 2014-T6
- 2024-T4
- 6061-T6

A = 407 + 2.06 \sigma_{\text{UTS}}
2014 Notched ($K_t = 3.4$) Aluminium Alloy
Military Handbook MIL-HDBK-5H Fatigue Data
Notched 2014 Aluminium Alloy

$m$ versus $K_t$

\[ m = 0.088 + 0.019K_t \]

\[ \sigma_{\text{MAX}} = AN^{-m} \text{ where } A \approx 1277 + 482R \]
Normalised S-N Curve
Unidirectional E-glass/F922 (R = 0.1)

\[
\frac{\sigma_{\text{MAX}}}{\sigma_{\text{UTS}}} = 1 - 0.1 \log_{10}N_f
\]

Cycles to Failure (\(N_f\))
Normalised Maximum Stress (\(\sigma_{\text{MAX}}/\sigma_{\text{UTS}}\))
run-out
Normalised S-N Curves
Unidirectional E-glass/913

Normalised Stress Range ($\Delta \sigma /\sigma_{UTS}$) vs. Cycles to Failure ($N_f$) for different values of $R$:

- $R = 0.10$
- $R = 0.50$
- $R = 0.75$
GRP Laminates

- Universal relationship ($R = 0.1$):
  \[
  \frac{\sigma_{\text{MAX}}}{\sigma_{\text{UTS}}} = 1 - 0.1\log_{10}N_f
  \]

  - Unidirectional, multidirectional, random mat and woven fabrics
  - In-plane and T-T tension, compression and shear
  - OHT, OHC and pin-bearing
  - Wet and dry, low and high temperature

- Reduction factor applied to undamaged strength to determine initial strength of damaged/notched material

- Universal relationship ($0 \leq R \leq 1$):
  \[
  \frac{\sigma_{\text{MAX}}}{\sigma_{\text{UTS}}} = 1 - k\log_{10}N_f; \quad \text{where } k = 0.11 - 0.07R
  \]
Joint Efficiency of Adhesively Bonded Joints

Tension-Tension Cyclic Fatigue

<table>
<thead>
<tr>
<th>Joint Configuration</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scarf joint (aluminium with 30° taper)</td>
<td>0.055</td>
</tr>
<tr>
<td>Double-lap (titanium alloy)</td>
<td>0.075</td>
</tr>
<tr>
<td>Double strap joint (aluminium with tapered straps)</td>
<td>0.088</td>
</tr>
<tr>
<td>Single-lap (mild steel)</td>
<td>0.093</td>
</tr>
<tr>
<td>Double-lap (PMC)</td>
<td>0.097</td>
</tr>
<tr>
<td>T-Peel (mild steel)</td>
<td>0.130</td>
</tr>
</tbody>
</table>
Publications/Smart Manual Modules

- Publications
  - Finite Element Assessment of Geometric and Material Property Effects on the Strength and Stiffness of Bonded and Bolted Joints, NPL Report MATC(A)124.
- Smart Manual Modules
  - Deformation and Failure of Rubber-Toughened Adhesive Joints
Future Work

- Experimental validation of FEA predictions
  - Boundary conditions
  - Bolt pre-stress and friction coefficient
  - Materials models and failure criteria
- Optimise joint through investigation of the effects of
  - Laminate lay-up
  - 4 bolt array
  - Clamping force
  - Geometry of clamping washer
- Validate fatigue and creep models