Durability of bonded aircraft structure

AMTAS Fall 2016 meeting
October 27th 2016
Seattle, WA
Durability of Bonded Aircraft Structure

• Motivation and Key Issues:
  – Adhesive bonding is a key path towards reduced weight in aerospace structures.
  – Certification requirements for bonded structures are not well defined.

• Objective
  • Improve our understanding of adhesive response under static and fatigue loading.
    – Effect of peel stress on static and fatigue response.
    – Response in tension and shear, in bulk and thin bonds.
    – Effect of joint toughness on fatigue life.
    – Visco-elastic response in static and cyclic loading.
    – Ratchetting in bulk tension and shear

• Approach
  – Coupons with varying amounts of peel stress
  – Bulk adhesives and thin bonds, plasticity models
  – Damage models
  – Non-linear viscoelasticity
Durability of Bonded Aircraft Structure

• Principal Investigators & Researchers
  – Lloyd Smith
  – Preetam Mohapatra, David Lemme, Reza Moheimani, Sayed Hafiz

• FAA Technical Monitor
  – Curt Davies

• Other FAA Personnel Involved
  – Larry Ilcewicz

• Industry Participation
  – Boeing: Will Grace, Peter VanVoast, Kay Blohowiak
Double Cantilever Beam (DCB)

ASTM D3433

\[ G_{IC} = \frac{4L^2 (\text{max})}{3E B^2h^3} \left[ 2 + a + \left( \frac{3}{a^2 + h^2} \right) \right] \]

Observations:
1. EA9696 – High toughness
2. FM300-2 \( \approx \) EA9380.05
3. EA9394 – Low toughness (adhesive failure)

Static test results

Fatigue test results: \( R = 0.1 \)
### Static:
1. EA9696 and EA9380.05 show more softening
2. FM300-2 strongest
3. Static strength does not correlate well with $G_{IC}$

### Fatigue:
1. EA9696 has highest fatigue life
2. EA9394 has shortest fatigue life
3. Fatigue life tends to correlate with $G_{IC}$
Wide Area Lap Shear - Static

Observations:
1. Higher toughness than scarf
2. Better correlation with $G_{IC}$ than scarf

Shims for bond line control

![Graph showing shear stress vs. extension for different materials.]

- **EA9696**
- **FM300-2**
- **EA9380.05**
- **EA9394**

Peak Shear Stress (psi):
- **EA9696**: 5138
- **FM300-2**: 4565
- **EA9380.05**: 5037
- **EA9394**: 4318

Adhesive failure
FEA Modeling of bulk adhesives and bonded joints

Characterization: Tough adhesive experiment

<table>
<thead>
<tr>
<th>Stress (psi)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
</tr>
<tr>
<td>2000</td>
<td>0.2</td>
</tr>
<tr>
<td>3000</td>
<td>0.3</td>
</tr>
<tr>
<td>4000</td>
<td>0.4</td>
</tr>
<tr>
<td>5000</td>
<td>0.5</td>
</tr>
<tr>
<td>6000</td>
<td>0.6</td>
</tr>
<tr>
<td>7000</td>
<td>0.7</td>
</tr>
<tr>
<td>8000</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Poisson's Ratio vs Axial Strain

- Bulk tensile experiment

Elastic properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Adhesive</th>
<th>Adherend</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (Psi)</td>
<td>277,000</td>
<td>10,600,000</td>
</tr>
<tr>
<td>(v_e)</td>
<td>0.43</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Yield criterion

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Linear elastic</th>
<th>Hardening curve</th>
<th>Drucker Prager yield constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>von Mises</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Drucker Prager</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Exponent Drucker Prager model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Psi(^{-1}))</td>
<td>0.00014</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
</tr>
<tr>
<td>(\psi)</td>
<td>3.50</td>
</tr>
</tbody>
</table>
**Observations:**

1. Not sensitive to yield criteria or hardening model.

**Observations:**

1. Pressure sensitive > elastic plastic (4% better) with isotropic
2. Kinematic > Isotropic (4% better) with von Mises yielding
3. Less sensitive to yield criteria and hardening model
FEA Modeling of bulk adhesives and bonded joints

**Stiff joint:**
1. Kinematic > Isotropic, by 65%, for both thin film and bulk input
2. Thin film > Bulk form, by 40%, for both hardening type
3. Hardening model > Input property type > yield criteria

**Compliant joint:**
1. Thin film > Bulk form, better by (5% with Kinematic) and (13% by Isotropic)
2. Kinematic > Isotropic, by 25% for both thin film and bulk form
3. Hardening model > input properties > yield criteria

**Joint in pure shear:**
1. Toughened adhesive was linear in pure shear.
2. Independent of yield criteria or hardening model
3. Bulk input successful predictor.
Progressive damage modeling

**Aim:** Identify failure criterion for adhesive joints under cohesive damage and validate with experimental results in ABAQUS

**Considerations:**
- 2D, plane strain
- Cohesive zone damage model with a traction-separation description of the interface element
- Compare load-displacement response with experiment and analytical results
- Analytical results are plotted based on Timoshenko beam theory (E is the substrate modulus)

\[
P_{\text{Tim}} = \frac{b h}{2a} \sqrt{\frac{G_c E h}{3 \left(1 + \frac{(1+\nu)(h/a)^2}{5}\right)}}
\]

\[
y_{\text{Tim}} = 4a^2 \sqrt{\frac{G_c}{3 E h^3}} \sqrt{\frac{1 + \frac{3(1+\nu)(h/a)}{5}}{1 + \frac{(1+\nu)(h/a)^2}{5}}}
\]

**ABAQUS Inputs**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_y )</td>
<td>Interface Strength</td>
</tr>
<tr>
<td>( E )</td>
<td>Interface Stiffness</td>
</tr>
<tr>
<td>( G_{ic} )</td>
<td>Fracture Toughness</td>
</tr>
</tbody>
</table>
Damage modeling with cohesive elements in ABAQUS

Schematic damage process zone and corresponding bi-linear traction-separation law

von Mises stress Field

Displaying cohesive elements:
They are removed, while failing
SDEG (Scalar stiffness degradation)

$0 < D < 1$
Damage modeling with cohesive elements in ABAQUS

✓ CZM combines a strength based failure criterion to predict the **damage initiation** and a fracture mechanics-based criterion to determine the **damage propagation**.

✓ 2D meshing by using COH2D4(adhesive) and CPE4(adherends) four-node linear plane strain elements

• **Damage initiation**: (linear part)

- **Maximum nominal stress** (Pure Mode)
  Damage initiates when either of the peel or shear components of traction exceeds the respective critical value.

\[
\max \left\{ \frac{t_n}{t_n^0}, \frac{t_s}{t_s^0} \right\} = 1, \quad t_n^0 = \text{tensile strength}, \quad t_s^0 = \text{shear strength}
\]
Damage modeling with cohesive elements in ABAQUS

• Damage evolution: (Softening part)

Energy based evolution model:

- Pure Mode (Mode I or Mode II)

Damage propagates when either the normal or shear components of energy release exceeds the respective critical value.

\[
\left\{ \frac{G_I}{G_{IC}}, \frac{G_{II}}{G_{IC}} \right\} = 1 , \ \text{(Fracture energy is equal to the area under the traction-separation curve)}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Modulus E (ksi)</th>
<th>Tensile Strength (\sigma_0) (Psi)</th>
<th>Fracture Toughness (G_{IC}) (lb/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA 9696</td>
<td>277</td>
<td>6660</td>
<td>22-55</td>
</tr>
<tr>
<td>FM300-2</td>
<td>400</td>
<td>7450</td>
<td>12</td>
</tr>
<tr>
<td>EA9394</td>
<td>615</td>
<td>6675</td>
<td>3</td>
</tr>
<tr>
<td>EA 9380.05</td>
<td>290*</td>
<td>7000*</td>
<td>10</td>
</tr>
</tbody>
</table>

* Found through iteration
Static Test on DCB (2 coupons per Adhesive)

- EA9696 - Coupon #7
  - FEM $G_{IC} = 55$
  - Analytical $G_{IC} = 55$
  - FEM $G_{IC} = 22$
  - Exp

- EA 9696 Coupon #9
  - EXP
  - FEM $G_{IC} = 55$
  - FEM $G_{IC} = 22$
  - ANALYTICAL $G_{IC} = 55$

- FM300-2 Coupon #1
  - FEM $G_{IC} = 12$
  - Analytical $G_{IC} = 12$
  - Exp

- FM300-2 Coupon #2
  - EXP
  - FEM $G_{IC} = 12$
  - Analytical $G_{IC} = 12$
Static Test on DCB (2 coupons per Adhesive)
Fatigue Test on DCB – experiments and FEM models

- Paris law $\frac{da}{dN} = C G^m$

<table>
<thead>
<tr>
<th></th>
<th>FM300-2</th>
<th>EA9696</th>
</tr>
</thead>
<tbody>
<tr>
<td>(da/dN-G) Plot</td>
<td>EXP</td>
<td>EXP</td>
</tr>
<tr>
<td></td>
<td>C=3x10^{-5}, m=0.762</td>
<td>C=7x10^{-5}, m=1.0864</td>
</tr>
</tbody>
</table>
Time Dependence

**Aims:**
- Influence of toughening agents
- Find nonlinear threshold.
- Determine how ratcheting behavior occurs under repeated loading.

**Ratcheting:** Increase in peak strain per cycle with repeated loading.

**Approach:**
- Bulk adhesives
- Creep at different durations and stress levels.
- Fit response to linear and nonlinear viscoelastic models.
- Compare load response with linear model to find nonlinear and ratcheting thresholds and determine how nonlinear model predicts strain.
Nonlinear Ratcheting

- Nonlinear viscoelastic model over predicts strain at high stress, while linear model under predicts strain.
- Why is nonlinearity higher in creep than ratcheting?
The difference in ratcheting is not due to variation in coupons but a difference in how the material behaves in static versus cycled loading.
Power Law Model

Both creep and ratcheting were fit to a viscoelastic power law.

- Elastic compliance, $D_0$, was constant across all stress levels and for both creep and ratcheting.
- Creep and ratcheting showed a different time dependent response, shown by the coefficients $D_1$ and $n$, which was more significant in the toughened adhesive.

$$D(t) = D_0 + D_1 t^n$$
Nonlinear Strain

• Nonlinear strain was observed to increase linearly with total strain.
• Ratcheting had a smaller increase in nonlinear strain with total strain than creep
  – Why?

\[ \varepsilon_{\text{nonlinear}} = \varepsilon_{\text{exp}} - \varepsilon_{\text{linear}} \]
Permanent Strain

- The toughened adhesive showed significantly more permanent strain than the standard adhesive.
- Both adhesives showed lower permanent strain from ratcheting, and a linear relationship between permanent and total strain.

![Graphs showing the relationship between Permanent Strain and Max Strain for FM300-2 and EA9696.]

- FM300-2: $y = 0.0748x - 1294.2$
- EA9696: $y = 0.1413x - 3407.1$
A different approach to nonlinear viscoelasticity is being investigated.

**Current Approach:**

\[
\varepsilon(t) = \int_0^t F_1(t - \xi_1)\sigma(\xi_1)d\xi_1 + \int_0^t \int_0^t F_2(t - \xi_1)\dot{\sigma}(\xi_1)\dot{\sigma}(\xi_2)d\xi_1d\xi_2 + \int_0^t \int_0^t \int_0^t F_3(t - \xi_1)\dot{\sigma}(\xi_1)\dot{\sigma}(\xi_2)\dot{\sigma}(\xi_3)d\xi_1d\xi_2d\xi_3
\]

where \( F_1, F_2, \) and \( F_3 \) define the nonlinearity.

**Schapery Approach, single integral with more nonlinear coefficients:**

\[
\varepsilon(t) = g_0D_0\sigma_0 + g_1 \int_0^t \Delta D(\varphi - \varphi')\frac{d(g_2\sigma_0)}{d\tau}d\tau
\]

\[
\varphi = \int_0^t \frac{dt'}{a_\sigma} \text{ and } \varphi' = \varphi(t) = \int_0^\tau \frac{dt'}{a_\sigma}
\]

where \( g_0, g_1, g_2, \) and \( a_\sigma \) define the nonlinearity.
Viscoelastic Response in Shear

**Bulk Tension**

**End Notch Flexure** (unnotched)

**Wide Area Lap Shear**

![Graphs showing strain, time, and cycles for different tests](image-url)
Viscoelastic Response in Shear

- Damage occurred in the WALS ratchet coupons while bulk resin coupons showed very little damage.
Observations

• $G_{IC}$ tends to be a good indicator of fatigue performance
• Fatigue response depends more on adhesive toughness than bond thickness or temperature.
• Toughest adhesive (EA9696) did not have constant $G_{IC}$
  – Could not describe crack growth with linear fracture mechanics
• DCB crack growth followed Paris and were reproduced from FEA
• von Mises stress describes adhesive yield behavior
• Adherend void bridging increases plastic strain over bulk
• Adhesives tend to follow a kinematic hardening law
• Linear viscoelasticity under predicts ratchet strain while nonlinear model over predicts it.
• Nonlinear viscoelastic strain increased with total strain similar to permanent strain.
• Ratcheting in shear is more severe than bulk tension
Next Steps:

- Measure elastic and strength of EA 9380.05
- Static and Fatigue ENF simulation
- Consider a combined isotropic/kinematic hardening law
- Investigate ratcheting response in shear, numeric modelling
- Compare the nonlinear Schapery model with the triple integral model to determine if it fits the response in ratcheting better