Durability of Bonded Aircraft Structure

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**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 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.

**Approach**
- Coupons with varying amounts of peel stress
- Bulk adhesives and thin bonds, plasticity models
- Bond thickness and temperature
- Non-linear viscoelasticity
Double Cantilever Beam (DCB)

ASTM D3433

\[ G_{1c} = \frac{4L^2(\text{max})[3a^2 + h^2]}{EB^2h^3} \]

Static test results

- **EA9696** – High toughness
- **FM300-2** ≈ **EA9380.05**
- **EA9394** – Low toughness (adhesive failure)
**Coupon Peel Stress**

**FEA Results:**
- Scarf has no load eccentricity
- Scarf has a uniform distribution of shear stress
- Scarf has minimal peel stress

Scarf Joint

![Graph showing shear stress versus normalized distance along gauge section.](image)

![Graph showing peel stress versus normalized distance along gauge section.](image)

**FEA Results:**
- Scarf has no load eccentricity
- Scarf has a uniform distribution of shear stress
- Scarf has minimal peel stress

Scarf Joint

![Graph showing average peel stress versus scarf angle.](image)

![Graph showing shear stress versus scarf angle.](image)
Scarf Joint - Static

- EA9696 and EA9380.05 show more softening
- FM300-2 strongest
- Static strength does not correlate well with $G_{IC}$

![Graph showing shear stress vs. extension for different materials with EA9696, FM300-2, EA9380.05, and EA9394]
Scarf Joint - Fatigue

- EA9696 has highest fatigue life
- EA9394 has shortest fatigue life
- Fatigue life tends to correlate with $G_{IC}$

![Graph showing shear strength/ultimate (%)](image)

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

Number of Cycles to Failure

Shear strength/Ultimate (%)

$R=0.1$
Wide Area Lap Shear - Static

- Higher toughness than scarf
- Better correlation with $G_{IC}$ than scarf

![Graph showing shear stress vs. extension for different materials: EA9696, FM300-2, EA9380.05, EA9394.](image)

![Shims for bond line control](image)
Wide Area Lap Shear – Bond Thickness

- Loaded at 70% of their respective peak static strength.
- Thickness affects peel stress more than shear stress
- 0.008” EA 9696 ≈ 0.014” FM 300-2 (comparable thickness)
Observations

- Increase in thickness increases ductility of the joint.
- Bond thickness had negligible effect on fatigue life
- In fatigue, adhesive toughness is more important than peel stress.
Wide Area Lap Shear: Temperature

- Static strength reduces as temperature increases
- Toughness is not significantly affected by temperature

![Graphs showing stress vs. extension for EA9696 and FM300-2 Static tests at different temperatures: 77F/25°C, 149F/65°C, and 212F/100°C.](image-url)
Fatigue life decreases as temperature increases.
Fatigue response strongly affected by static strength.

Wide Area Lap Shear: Temperature

- EA 9696
  - 77F/25°C
  - 149F/65°C
  - 212F/100°C

- FM 300-2
  - R=0.1
Observations from experiment

1. $G_{IC}$ tends to be a good indicator of fatigue performance

2. Joint toughness increases with peel stress and bond thickness, but not with increasing temperature

3. Fatigue response depends more on adhesive toughness than bond thickness or temperature.
**FEA adhesive models: EA9696**

- Model inputs

![Graph showing stress-strain relationship](image1)

<table>
<thead>
<tr>
<th>Linear Elastic</th>
<th>Adhesive</th>
<th>Adherend</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (Psi)</td>
<td>277000</td>
<td>10600000</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0.43</td>
<td>0.33</td>
</tr>
</tbody>
</table>

- Drucker Prager:
  - Sensitive to hydrostatic stress
  - Exponent > linear (better describes non associated flow of adhesive)

- Input:
  - Linear elastic properties
  - Tensile hardening curve
  - Drucker Prager parameters
  - Can use shear input (not usually done)
  - Did not improve correlation with current results

<table>
<thead>
<tr>
<th>Exponent Drucker Prager</th>
<th>Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>a ( )</td>
<td>0.0008</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
</tr>
<tr>
<td>$\psi$</td>
<td>3.5</td>
</tr>
</tbody>
</table>
FEA adhesive models: EA9696

- **Bulk adhesive in tension (input)**
  - Good agreement
  - von Mises and Drucker Prager predicted same result

- **Thick adherend lap shear**
  - Good agreement only for linear elastic portion
  - Von Mises and Drucker Prager predicted similar results
FEA adhesive models: EA9696

- **Bulk shear specimen**
  - Good agreement
  - Drucker Prager exceeded von Mises by 4%

- **Scarf joint**
  - Good agreement
  - No non-linear response

- **WALS**
  - Good agreement
  - Von Mises and Drucker Prager predicted similar results
**FEA adhesive models: EA9696**

- **Bulk adhesive Material model**
  - Tensile Yield Stress (psi) vs. Tensile Plastic Strain
  - Experimental hardening
  - Extended hardening

- **Wide area lap shear**
  - Experiment
  - FEA DP using experimental hardening
  - FEA DP using extended hardening 2
  - FEA VM using extended hardening 2

- **Thick adherend lap shear**
  - FEA DP using experimental hardening
  - FEA DP using extended hardening 1
  - FEA VM using extended hardening 1


One tension hardening curve could not describe WALS and thick adherend shear.
Observations
1. Joints with low peel stress had low toughness and were readily modeled using elastic response
2. Joints with high peel stress could not be modeled from constituent properties
   - Required tailored hardening curve (extended) for each configuration
3. Drucker Prager model agreed slightly better than von Mises elastic plastic model
Progressive damage modeling

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

<table>
<thead>
<tr>
<th>Material degradation and failure (no pre-crack needs to be defined)</th>
<th>Adhesive type</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesive zone model: CZM</strong></td>
<td>High ductility</td>
<td>LEFM &amp; EPFM</td>
</tr>
<tr>
<td>• Uses traction separation law</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Based on interface Finite Element</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Continuum damage Model : CDM</strong></th>
<th>Brittle or moderately ductile</th>
<th>LEFM &amp; EPFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Material degradation occurs inside of solid element</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• when damage propagation onset &amp; path are not known a priori</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Advantages of CDM over CZM**

- Predict mode-mixity even when one of modes predominates
- Capture the influence of asymmetrical propagation and crack path along adhesive thickness
- Size and shape of fracture process zone (FZP) and its evolution during crack growth is well managed
Progressive damage modeling

Development of a numerical fracture model incorporating CZM, CDM - ABAQUS

✓ Use DCB and ENF (Damage for pure mode I & II)

<table>
<thead>
<tr>
<th>Constitutive softening law</th>
<th>$\sigma = (1-D)E\delta\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesive/Damage parameter</td>
<td>$D = \delta\delta_{um}(\delta_{1m} - \delta\delta_{1m})/\delta_{1m}(\delta_{1um} - \delta\delta_{1m})$</td>
</tr>
<tr>
<td>0&lt;D&lt;1</td>
<td></td>
</tr>
</tbody>
</table>

Critical Fracture Energy (mode I, II)

$$G_{\delta I} = \sigma \delta_{um}/2 \quad G_{\delta II} = \tau \delta_{um}/2$$

Future Work

✦ Fatigue damage of adhesives – experiments and models
✦ Composite adherends
  ✓ CDM and CZM can be used to simulate the failure of adherends and adhesive
  ✓ Failure is combination of cohesive and delamination of substrate
  ✓ Simulation of delamination development in fiber composites and failure of adhesive joints
Time Dependence

Aims:
- Identify the influence of toughening agents on adhesive time dependent response.
- Find nonlinear threshold.
- Determine if ratcheting behavior occurs under repeated loading.

Approach:
- Creep tests 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.

Ratcheting: cyclic accumulation of inelastic deformation.

Cyclic Loading

Input

<table>
<thead>
<tr>
<th>Stress</th>
<th>Time</th>
</tr>
</thead>
</table>

Output

<table>
<thead>
<tr>
<th>Strain</th>
<th>Time</th>
</tr>
</thead>
</table>
Linear Viscoelasticity

\[ \epsilon(t) = \int_{-\infty}^{t} D(t-\tau) \sigma(\tau) \, d\tau \]

\[ D(t) = D_0 + D_1 t^n \]

Input

Output

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Stress [psi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>1000</td>
<td>6000</td>
</tr>
<tr>
<td>2000</td>
<td>7000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Strain [ue]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>5000</td>
<td>15000</td>
</tr>
<tr>
<td>10000</td>
<td>20000</td>
</tr>
<tr>
<td>15000</td>
<td>25000</td>
</tr>
</tbody>
</table>

Linear Viscoelasticity Model

Experiment
Linear Viscoelasticity

- Adhesives behave nonlinearly
  - Initial compliance
  - Compliance over time

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**Standard Adhesive**

<table>
<thead>
<tr>
<th>Log Time [s]</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(t) \times 10^{-6} \text{ psi}^{-1}$</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

**Toughened Adhesive**

<table>
<thead>
<tr>
<th>Log Time [s]</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(t) \times 10^{-6} \text{ psi}^{-1}$</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
Linear Viscoelasticity: Temperature

- Strength decreases almost linearly with increasing temperature
Linear Viscoelasticity: Temperature

- EA 9696 increased nonlinearity and creep with increasing temperature.

Graphs showing creep strain over time for different temperatures:
- 25°C/77F
- 65°C/149F
- 100°C/212F
Linear Viscoelasticity: Temperature

- FM300-2 increased nonlinearity and creep with increasing temperature.
Linear Viscoelasticity: Temperature

Strain input

\[ \varepsilon(t) = 9f \sigma_{\text{max}} / 5 \left\{ D_{\downarrow 0} t + D_{\downarrow 1} t^{\uparrow n+1} / n+1 \right. \\
\left. + \sum_{i=1}^{m} 2 (-1)^{i+1} \left[ D_{\downarrow 0} (t - t_{\downarrow i}) + D_{\downarrow 1} (t - t_{\downarrow i})^{\uparrow n+1} / n+1 \right] H(i-1) \right\} \]
Nonlinear Viscoelasticity

Nonlinear viscoelastic strain to an arbitrary stress input

\[ \varepsilon(t) = \int_0^t F_1 (t-\xi_1) \sigma(\xi_1) d\xi_1 + \int_0^t \int_0^t F_2 (t-\xi_1) \sigma(\xi_1) \sigma(\xi_2) d\xi_1 d\xi_2 \]

\[ + \int_0^t \int_0^t \int_0^t F_3 (t-\xi_1) \sigma(\xi_1) \sigma(\xi_2) \sigma(\xi_3) d\xi_1 d\xi_2 d\xi_3 \]

For uniaxial creep, this becomes

\[ \varepsilon(t) = F_1 \sigma + F_2 \sigma^2 + F_3 \sigma^3 \]

\( F_1, F_2, \) and \( F_3 \) are found from creep tests at three stress levels, \( \sigma_A, \) \( \sigma_B, \) and \( \sigma_C, \)

\[ D_{\downarrow A} + D_{\downarrow 1\downarrow A} t^{\uparrow n\downarrow A} = F_1 + F_2 \sigma A + F_3 \sigma A^2 \]

\[ D_{\downarrow B} + D_{\downarrow 1\downarrow B} t^{\uparrow n\downarrow B} = F_1 + F_2 \sigma B + F_3 \sigma B^2 \]
Nonlinear Creep

Good agreement under creep

---

**Standard Adhesive**

- **Graph 1**: Strain vs. Time for Standard Adhesive.
  - Experiment.
  - Nonlinear Viscoelastic Model.
  - Linear Model.

- **Graph 2**: Strain vs. Time for Toughened Adhesive.
  - Experiment.
  - Nonlinear Viscoelastic Model.
  - Linear Model.

**Initial Creep Strain**

- **Graph 3**: Initial Creep Strain vs. Stress.
  - Standard Adhesive.
  - Standard Adhesive Nonlinear Model.
  - Standard Adhesive Linear Model.
  - Toughened Adhesive.
  - Toughened Adhesive Nonlinear Model.

**Total Creep Strain**

- **Graph 4**: Total Creep Strain vs. Stress.
  - Standard Adhesive.
  - Standard Adhesive Nonlinear Model.
  - Standard Adhesive Linear Model.
  - Toughened Adhesive.
  - Toughened Adhesive Nonlinear Model.
Nonlinear Ratcheting

For a cycled stress input in ratcheting, nonlinear strain is given by,

\[\varepsilon(t) = 9 f \sigma_{\text{max}} \frac{1}{5} (\sigma_{\text{A}} - \sigma_{\text{B}})(\sigma_{\text{A}} \sigma_{\text{B}} - \sigma_{\text{A}} \sigma_{\text{C}} - \sigma_{\text{B}} \sigma_{\text{C}} + \sigma_{\text{C}} \sigma_{\text{A}}) \begin{bmatrix} \Ldown1 \ (A) (\sigma_{\text{B}} \sigma_{\text{C}} \sigma_{\text{A}} \sigma_{\text{B}}) \Ldown1 \ (B) (\sigma_{\text{C}} \sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{C}}) \Ldown1 \ (C) (\sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{C}}) \Ldown1 \ (D) (\sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{C}}) \end{bmatrix} + 81 f \sigma_{\text{max}} \frac{1}{25} (\sigma_{\text{A}} - \sigma_{\text{B}})(\sigma_{\text{A}} \sigma_{\text{B}} - \sigma_{\text{A}} \sigma_{\text{C}} - \sigma_{\text{B}} \sigma_{\text{C}} + \sigma_{\text{C}} \sigma_{\text{A}}) \begin{bmatrix} \Ldown2 \ (A) (\sigma_{\text{C}} \sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{B}}) \Ldown2 \ (B) (\sigma_{\text{A}} \sigma_{\text{C}} \sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{C}}) \Ldown2 \ (C) (\sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{C}} - \sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{C}} + \sigma_{\text{C}} \sigma_{\text{A}}) \Ldown2 \ (D) (\sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{A}} \sigma_{\text{B}} \sigma_{\text{C}}) \end{bmatrix} + 729 f \sigma_{\text{max}} \frac{1}{125} (\sigma_{\text{A}} - \sigma_{\text{B}})(\sigma_{\text{A}} \sigma_{\text{B}} - \sigma_{\text{A}} \sigma_{\text{C}} - \sigma_{\text{B}} \sigma_{\text{C}} + \sigma_{\text{C}} \sigma_{\text{A}}) \begin{bmatrix} \Ldown3 \ (A) (\sigma_{\text{C}} - \sigma_{\text{B}}) \Ldown3 \ (B) (\sigma_{\text{A}} - \sigma_{\text{C}}) \Ldown3 \ (C) (\sigma_{\text{B}} - \sigma_{\text{A}}) \end{bmatrix} \]

\[\Ldown1 = D \downarrow 0 \ t + D \downarrow 1 \ t \uparrow n+1 /n+1 + \sum i=2 \uparrow m \boxplus 2 (-1) \uparrow i+1 \begin{bmatrix} D \downarrow 0 \ (t-t \downarrow i) + D \downarrow 1 \ (t-t \downarrow i) \uparrow n+1 /n+1 \end{bmatrix} \]

\[\Ldown2 = D \downarrow 0 \ t \uparrow 2 \ L \downarrow 1 \ t \uparrow n+2 /n+1 + \sum i=2 \uparrow m \boxplus 2 (-1) \uparrow i+1 \begin{bmatrix} D \downarrow 0 \ t(t-t \downarrow i) + D \downarrow 1 \ t(t-t \downarrow i) \uparrow n+1 /n+1 + D \downarrow 1 \ (t-t \downarrow i) \end{bmatrix} \]

\[\Ldown3 = D \downarrow 0 \ t \uparrow 3 \ L \downarrow 1 \ t \uparrow n+3 /n+1 + \sum i=2 \uparrow m \boxplus 2 (-1) \uparrow i+1 \begin{bmatrix} D \downarrow 0 \ t(t-t \downarrow i) + D \downarrow 1 \ t(t-t \downarrow i) \uparrow n+1 /n+1 + \cdots \end{bmatrix} \]
Nonlinear Ratcheting

Nonlinear viscoelastic model over predicts strain at high stress

![Graphs showing the comparison between experimental results and model predictions for Standard and Toughened Adhesives.](image-url)
Permanent Strain

- Max strain: strain after 9000s of recovery
- Both adhesives showed lower permanent strain from ratcheting
Time Dependence

Observations
- Both adhesives show a nonlinear creep and ratcheting response.
- Creep experiments can be used to predict ratcheting response.
- Nonlinearity appears to begin after 50% which corresponds to permanent formation.
- Permanent strain is small (3% of the total strain).
- A nonlinear model improves correlations, but becomes unstable after 400 cycles.

Next Steps
- Test 10,000 second creep and 10,000 cycle ratcheting.
- Develop strategies to improve nonlinear model.
- Consider effect of low temperature creep.
Looking forward

• Benefit to Aviation
  – Improved (accelerated) certification procedures for bonded structure
  – Guidance for adhesive joint design under fatigue loading

• Future needs
  – Improved understanding of adhesive non-linear adhesive response
    ▪ Viscoelastic, plastic/damage, environment.