Durability of adhesive bonded joints in aerospace structures

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Durability of adhesive bonded joints in aerospace structures

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- Industry Participation
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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
  – Describe plastic adhesive response.
  – Develop time-dependent adhesive models.

• Approach
  – Experiments designed to clarify constitutive relations.
  – Develop FEA Models of adhesive bonds.
  – Compare models with experiments that are unlike constitutive tests.
Durability of adhesive bonded joints in aerospace structures

Nonlinearity in Bonded Joints

Time Dependence

Plasticity

Yield criterion

Hardening rule

Tension (closed form)

Shear (FEA)

1. Influence of yield criteria
2. Biaxial tests (Arcan)
3. Cyclic tests
4. FEA model

1. Creep, non-linear response
2. Ratcheting, experiment
3. Creep, model development
4. Ratcheting, model application
Plasticity: Hardening Rule: Challenges

What we found:
To quantify hardening in thin film adhesives we need to load and unload in a shear stress state.

Ref: Muransky O. et al [Metal Plasticity]
Plasticity: Hardening Rule: in Shear

- Initial size: \( V_0 = 2\tau_A \)
- Kinematic: \( V_k = \tau_B - \tau_C = 2\tau_A \)
- Isotropic: \( V_i = \tau_B - \tau_E = 2\tau_B \)
- Combined: \( 2\tau_A < V_c = (\tau_B - \tau_D) < 2\tau_B \)
- \( K = \frac{\tau_B + \tau_D}{2(\tau_B - \tau_A)} \)

Schematic presentation of cyclic shear loading
- tensile yield (\( n_{TY} \))
- tensile peak (\( n_{TP} \))
- compressive yield (\( n_{CY} \))
- compressive peak (\( n_{CP} \))

Size of yield surface at Nth cycle: \( n_{TP} - n_{CY} \)
Plasticity: Hardening Rule: Testing

Scarf fixture for tension-compression testing and assembly

Cyclic testing of scarf joint on an Instron to quantify adhesive hardening

Image analysis software (Vic 3D) used to analyze speckle images for strain calculation

Schematic locations of points tracked to calculate strain

\[ \tau_{avg} = \frac{F \cos \theta}{A} \]

\[ \gamma_{12} = \frac{dV'_{1-2} - \left( \frac{\tau_{avg}(D - t)}{G} \right)}{t} \]
Plasticity: Hardening Rule: Quantification

- 0.2% offset criterion used to determine yield point
- $Y_k \sim 43.1 \text{ MPa}$

**What we found:** Kinematic behavior dominated hardening mechanism of tough adhesive.

**Initial size:** $Y_o = 2\tau_A = 43.1$

$Y_k = \tau_B - \tau_C = 43.1$
0.2% offset criterion used to determine yield point

- 80 ksi (isotropic) > 60 ksi (actual size) > 58 ksi (kinematic)

\[ k = 91\% \]

(91% kinematic & 9% isotropic)

What we found:
Standard adhesive demonstrated combined hardening
Plasticity: Yield Criterion: Challenges

Schematic yield surface in normal-normal stress state:

- Solid line = von Mises (typically used for metals)
- Dotted line = Drucker-Prager (typically used for rocks, concrete, soil)

- Adhesive joints don’t soften at yield in compression.
- Consider normal-shear
Plasticity: Yield Criterion: Test Results

What we found:
von Mises: best fit
What we found:
von Mises: generally best fit
Plasticity: Numerical Modeling: Tensile Input Properties

Schematic butt joint with dimensions, load applied in the X direction

Butt joint being tested on an Instron load frame

Proposed locations of pins of uniaxial extensometer

Graph showing stress ($\sigma$) vs. strain ($\varepsilon$) for Thin Film Tension: Tough Adhesive and Thin Film Tension: Standard Adhesive.

Thin film Tension: Tough Adhesive

Thin film Tension: Standard Adhesive
Plasticity: Numerical Modeling: Tensile Input Properties

Tough (kinematic)

- Experiment
- linear
- non-linear

Standard (combined)

- Experiment
- Linear
- non-linear

\[ \sigma_y - \sigma_0 \] [MPa]

\[ \varepsilon_{pl} \]

Eqs. 2 and 4
Eqs. 3 and 5

Plasticity: Numerical Modeling: Tensile Input Properties

linear
non-linear

Advanced Materials in Transport Aircraft Structures

[Image]
Plasticity: Numerical Modeling: Shear Joints

Testing on Instron

Standard adhesive

Tough adhesive

FEA

Testing on Instron

Standard adhesive

Tough adhesive

FEA
What we found:
- use of mixed mode lap-shear joint
- von Mises criterion better explains adhesive yielding
- Adhesive yielding is not sensitive to hydrostatic pressure.
Plasticity: Numerical Modeling: Validation of Hardening Rule

Tough-Scarf

Tough-Lap Shear

Standard - Scarf

Standard - Lap Shear

\[ \tau [\text{MPa}] \]

\[ \gamma \]

\[ \text{Linear Isotropic} \]

\[ \text{Linear Kinematic} \]

\[ \text{Eq. 4} \]
Plasticity: Numerical Modeling: Validation of Hardening Rule

- **Tough-Scarf**
  - Non-Linear Isotropic
  - Non-Linear Kinematic
  - Eq. 5

- **Tough-Lap Shear**
  - Non-Linear Isotropic
  - Non-Linear Kinematic
  - Eq. 5

- **Standard-Scarf**
  - Non-Linear Isotropic
  - Non-Linear Kinematic
  - Eq. 5

- **Standard-Lap Shear**
  - Non-Linear Isotropic
  - Non-Linear Kinematic
  - Eq. 5

Underestimated fail strain for standard adhesive.
Plasticity: Numerical Modeling: Validation of Hardening Rule

Tough-Scarf

\[ \tau \text{ [MPa]} \]

- Non-Linear Kinematic
- Eq. 5

Tough-Lap Shear

\[ \tau \text{ [MPa]} \]

- Non-Linear Kinematic
- Eq. 5

Standard - Scarf

\[ \tau \text{ [MPa]} \]

- Linear Combined
- Non-Linear Combined
- Eqs 3 and 5

Standard - Lap Shear

\[ \tau \text{ [MPa]} \]

- Linear Combined
- Non-Linear Combined
- Eqs 3 and 5

Linear combined hardening underestimated experiment by 13% for standard adhesive.

Plasticity: Numerical Modeling: Validation of Hardening Rule

Non-Linear	Kinematic

Non-Linear	Combined

Linear	Combined

Linear combined hardening underestimated experiment by 13% for standard adhesive.
Plasticity: Summary

- Assuming plastic properties can lead to error in numerical modeling.
  - Little has been done to characterize adhesive plastic response

- Arcan fixture was effecting in creating uniform shear with minimal peel stress.

- Adhesives considered here followed von Mises yielding
  - not influenced by hydrostatic pressure.

- Adhesives in this work tended to follow kinematic hardening
  - Isotropic hardening is commonly assumed
  - Nonlinear kinematic hardening governed the tough adhesive behavior.
  - Nonlinear combined hardening (90% kinematic) described standard adhesive.
Time dependence (viscoelasticity/viscoplasticity)

Background

- The time-dependent behavior of adhesives is important for durability
- Little work has been done on adhesive ratcheting effects
- Shear response tends to be more important than normal stress

Objectives

The final objective is to build a shear viscoelastic modeling on bonded joints for ratcheting

- FEA viscoelastic model of **bulk adhesives** under cyclic normal stress (07/31/2019)
- FEA viscoelastic model of **bonded joints** under shear (12/31/2020)
Measuring Adhesive Strain in Bonded Joints
Rosette Strain Gages

- Divide each strain component by 0.13
  - Fraction of the gage covering the adhesive
  - Strain in adherend was 2% of the adhesive and neglected

\[ \gamma = 2\varepsilon_2 - \varepsilon_1 - \varepsilon_3 \]

![Graph of Stress vs. Shear Strain](image)

- \( G = 107.2 \text{ ksi} \)
10000 Cycle Ratchet Test

- EA9696 Scarf Joint

50% UTS, R=0.1, 0.5 Hz

Recovery
### Approach: Time dependence (viscoelasticity/viscoplasticity)

- Comparisons of viscoelastic analytical/numerical models

<table>
<thead>
<tr>
<th>Model</th>
<th>Calibration</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Triple Integral Nonlinear (TIN)</strong></td>
<td>Extended Boltzmann superposition integral, nonlinear</td>
<td>From creep tests under load of 20%, 50% and 80% UTS, general</td>
</tr>
<tr>
<td><strong>Specific Linear Model (SLM)</strong></td>
<td>Boltzmann Superposition integral, single term</td>
<td>From creep tests under load of 20%, 50% and 80% UTS, tailored</td>
</tr>
<tr>
<td><strong>Prony</strong></td>
<td>Linear viscoelastic model in ABAQUS, summation</td>
<td>From creep tests under load of 20%, 50% and 80% UTS, tailored</td>
</tr>
<tr>
<td><strong>Parallel Rheological Framework (PRF)</strong></td>
<td>Nonlinear viscoelastic model in ABAQUS</td>
<td>From long term creep test data under load of 50% and 80% UTS, general</td>
</tr>
</tbody>
</table>
Modeling on Bulk resin

Approach: Time dependence (viscoelasticity/viscoplasticity)

- EA9696 Creep

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**Graph 1:**
- Test results for 20%, 50%, and 80% UTS.
- Models: PRF, Prony, TIN.

**Graph 2:**
- Recovery strain vs. time.
- 0 to 100,000 time scale.

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AMTAS
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PRF

- The **viscous** part in PRF model: 
\[
\dot{\varepsilon}^{cr} = \{Aq^n [(m + 1)\varepsilon^{cr}]^m \}^{\frac{1}{m+1}}
\]

- Taking the log of both sides we have: 
\[
\ln \dot{\varepsilon}^{cr} = \ln a + \frac{m}{m+1} \ln \varepsilon^{cr}, \quad \text{where } a = A^{\frac{1}{m+1}} q^n (m + 1)^{\frac{m}{m+1}}
\]

- But, experiment is only linear at 80% UTS

- Log of \( a \) and \( \bar{q} \) should also be linear
  - But they are not experimental

- Therefore, PRF is not well suited for EA9696
Approach: Time dependence (viscoelasticity/viscoplasticity)

Modeling on Bulk resin

- EA9696, 0.5 Hz, R=0.1
- EA9696, 0.025 Hz, R=0.1
Summary & Future Work

- 80% UTS has large experimental variation in creep and cyclic stress
- PRF FEA model cannot describe strain response from applied creep and cyclic stress
- Damage from cyclic stress appears to depend on both stress magnitude and rate, but could be due to batch differences

- Perform additional tests at 80% UTS
  - Creep, 1 ks and 10 ks
  - Cyclic tests, $R=0.1, 0.025 - 5$ Hz.
Summary & Future Work

- Another non-linear model (NPL)
  
  \[ D(t) = D_0 e^{\left(\frac{t}{t_0}\right)^m}, \quad \text{where } t_0 = Ae^{-\alpha \sigma^2} \]

Next step is to input it as a User Subroutine into ABAQUS PRF model.

- Enable plasticity in PRF model