Progressive failure analysis of a Pi joint and Delaminated Panel with uncertainties in fracture properties

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Collaborative work with Prof. Wooseok Ji, UNIST and Dr. Ravi Raveendran, Comet Tech.

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Motivation

- Accurate Failure Models leads to Large Cost Savings

- Require a validated high-fidelity, physics-based simulation framework
Two Examples

1. PI JOINT

2. CAI STRENGTH
Pi Joint Composite Structure

Conventional L-shape (Bolted) Composite Joints

- High peel and interlaminar shear
- High stress concentration

Pi Joint Composite Structure

- Distributed and non-concentrated stresses through Pi joint, resulting in reduction of peel stress

- Bonded interface is still the weakest link due to the large amount of load being transmitted over the region
Characterization of Pi Joint Performance

Shear test

Pulloff test

FE Model of Pi Joint Composite Structure

Discrete Cohesive Zone Model (DCZM)Element

- Decohesion process is discretized by successive failure of cohesive sub-elements governed by a traction separation law.
- Easily implemented into the conventional FE framework.
- Various failure modes (material failure, crack propagation, and local buckling) are tracked simultaneously, thus any potential interaction between the failure modes can be captured.
DCZM Element

Initial configuration before opening

Deformed configuration

2D

3D

Initial configuration before opening

Deformed configuration

\[ \Delta u^{(IJ)} \]

\[ \frac{\partial x}{\partial \eta} \] (Mode 3)
DCZM Element

\( F_1^{(mn)} = \begin{cases} \Delta a \tilde{K}_1^{(mn)} \delta_1^{(mn)} & \text{if } \delta_1^{(mn)} \leq \delta_1^{(1C)} \\ \Delta a \tilde{K}_1^{(mn)} \delta_1^{(1C)} \exp \left[ \alpha_1 \left( 1 - \frac{\delta_1^{(mn)}}{\delta_1^{(1C)}} \right) \right] & \text{if } \delta_1^{(mn)} > \delta_1^{(1C)} \end{cases} \)

\( F_2^{(mn)} = \begin{cases} \Delta a \tilde{K}_2^{(mn)} \delta_2^{(mn)} & \text{if } \left| \delta_2^{(mn)} \right| \leq \delta_2^{(2C)} \\ \Delta a \tilde{K}_2^{(mn)} \delta_2^{(2C)} \exp \left[ \alpha_2 \left( 1 - \frac{\delta_2^{(mn)}}{\delta_2^{(2C)}} \right) \right] & \text{if } \left| \delta_2^{(mn)} \right| > \delta_2^{(2C)} \end{cases} \)

Fracture toughness

\[
G_{IC} = \int_{0}^{\infty} \frac{F_1^{(mn)}}{\Delta a} \, d\delta_1 \\
G_{IIIC} = \int_{0}^{\infty} \frac{F_2^{(mn)}}{\Delta a} \, d\delta_2
\]

Cohesive strength

\[
\sigma_c = \tilde{K}_1^{(mn)} \delta_1^{(1C)} \\
\tau_c = \tilde{K}_2^{(mn)} \delta_2^{(2C)}
\]
DCZM Element

- **Direct-integration dynamic analysis**
  - Hilber-Hughes-Taylor integration scheme

\[
\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}
\]

\[
\mathbf{R}_{t+\Delta t} = -\mathbf{M}\ddot{\mathbf{u}}_{t+\Delta t} + (1 + \alpha)(\mathbf{F}_{t+\Delta t} - \mathbf{K}_{t+\Delta t}\mathbf{u}_{t+\Delta t}) - \alpha(\mathbf{F}_t - \mathbf{K}_t\mathbf{u}_t)
\]

\[
\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \Delta t\dot{\mathbf{u}}_t + \Delta t^2[(0.5 - \beta)\ddot{\mathbf{u}}_t + \beta\ddot{\mathbf{u}}_{t+\Delta t}]
\]

\[
\mathbf{v}_{t+\Delta t} = \mathbf{v}_t + \Delta t[(0.5 - \gamma)\ddot{\mathbf{u}}_t + \gamma\ddot{\mathbf{u}}_{t+\Delta t}]
\]

\[
\mathbf{u}_0 = \mathbf{u}(0) \quad \mathbf{v}_0 = \dot{\mathbf{u}}(0) \quad \mathbf{a}_0 = \mathbf{M}^{-1}(\mathbf{F}_0 - \mathbf{K}_0\mathbf{u}_0)
\]

- **ABAQUS implementation**

\[
\text{AMATRIX} = \mathbf{M}^{\text{el}}\frac{\partial\ddot{\mathbf{u}}}{\partial\mathbf{u}} + (1 + \alpha)\frac{\partial\mathbf{K}_t^{\text{el}}}{\partial\ddot{\mathbf{u}}}\frac{\partial\ddot{\mathbf{u}}}{\partial\mathbf{u}} + (1 + \alpha)\mathbf{K}_t^{\text{el}}
\]

\[
\text{RHS} = \mathbf{R}_t^{\text{el}}
\]
Performance of 2D Pi Joint under pulloff loading

Note: Peak load and its corresponding displacement value of Base G$_2$C are used to normalize the axes.

Failure mode of Pi joint with base G$_2$C at the peak load

Experimental data
- Mean: 0.9091
- STD: 0.0106
Performance of 3D Pi Joint under pulloff loading

\[ G_{\text{mix}} = \frac{G_1}{G_{1C}} + \frac{G_2}{G_{2C}} + \frac{G_3}{G_{3C}} \]
Performance of 3D Pi Joint under pulloff loading
Performance of 3D Pi Joint under shear loading
Probability Analysis with NESSUS – in the spirit of ICME

Probability Analysis with NESSUS

- Cumulative probability of peak load response of 2D Pi joint subject to pulloff loading

![Graph showing cumulative probability vs. peak load]
Probability Analysis with NESSUS

- Important factors affecting the peak load response
Composite Plate with an Initial Delamination

Laminated composite degradation – Schapery theory (ST)

• Thermodynamics based, work potential theory for the progressive damage growth in a lamina, capable of capturing the effects of microdamage mechanisms, responsible for macroscopic, orthotropic material nonlinearity.

• Matrix microcracks induce degradation in properties of the laminae including changes in strengths, effective moduli, Poisson’s ratios, and other material properties.

• The use of these modeling strategies computes lamina degradation evolution during the damage process using the physics of the failure mechanisms.

• ST can account for fiber direction damage -- an additional internal state variable associated with the fiber direction response is used.

Laminated composite degradation – Schapery theory (ST)

Damage at lamina level

*Thermodynamics-based work potential model*

\[
W_{TOTAL} = W_E + W_S
\]

\[
\frac{\partial W_T}{\partial S_i} = 0
\]

\[
f_i = \frac{\partial W_S}{\partial S_i}
\]

\[
f_i \dot{S}_i \geq 0
\]
Composite Plate with an Initial Delamination

Distribution of degraded $G_{12}$ at 5$^{th}$ layer (Interface 2)
Composite Plate with an Initial Delamination

Distribution of degraded $G_{12}$ at 5th layer

Full view

Section views for delamination pattern growth
Composite Plate with an Initial Delamination

- Distribution of degraded $G_{12}$ at 5th layer (Interface 2)
- Distribution of degraded $G_{12}$ at 6th layer (Interface 2)
- Delamination pattern growth over the DCZM region with $G_{\text{mix}}$ distribution
  
- X-ray photographs of the final delamination pattern (Reeder et al. 2002)
Composite Plate with an Initial Delamination

- PFA is coupled with the probabilistic analysis using NEESUS.
- Geometrical as well as material uncertainties are accounted for.
- A computationally efficient methodology is developed to consider the geometric variability on large nodal data.

Mean value, standard deviation (STD) value, and distribution type of the variable parameters

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<th>Parameter</th>
<th>Mean</th>
<th>STD</th>
<th>Type</th>
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<td>$E_{11}$ (ksi)</td>
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<td>$E_{22}$ (ksi)</td>
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<td>$G_{12}$ (ksi)</td>
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<td>radius (in)</td>
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<td>$\sigma_{2c}$ (psi)</td>
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</tr>
<tr>
<td>$\sigma_{3c}$ (psi)</td>
<td>120</td>
<td>20</td>
<td>Normal</td>
</tr>
</tbody>
</table>
Composite Plate with an Initial Delamination

Cumulative probability distribution for peak load
Composite Plate with an Initial Delamination

Importance levels of modeling parameters on peak load

![Importance levels chart](chart.png)
Concluding remarks

- Numerical framework for delaminations through the discrete cohesive zone model.
- Each fracture mode behavior and interactions of the modes can be captured.
- Probability analysis implemented to assess the reliability and quantify uncertainty in input properties and how these affect performance – using NEESUS
- Two example problems demonstrated in a unified numerical framework to predict interactive failure mechanisms.
Questions and Suggestions

Thank you!