An Engineering Approach for Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading

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Research Team

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An Engineering Approach for Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading

• Motivation and Key Issues
  • Thermo-mechanical loads during ground-air-ground (GAG) cycling result in localized mode I stresses that cause further delamination/disbond/core fracture growth.

• Objective
  • Develop an engineering approach for damage tolerance analysis of sandwich structures subjected to combined mechanical and pressure loads.

• Approach [Shown in the next slide]
  • Engineering Approach [Discussed in next slide]
    • SCB Testing (Obtain $G_{IC}$ fracture toughness values)
    • FEA Analysis on SCB Test and Validate modeling techniques
    • Develop a test method for GAG (Edgewise Compression) specimens.
    • Develop High Fidelity FEA models for GAG Specimens
    • Blind Predictions Comparing GAG FEA Data with Test Data
Accomplishments

★ Mode I (G1c) Fracture Toughness of Composite Sandwich Structures for Use in Damage Tolerance Design and Analysis
  • Volume 1: Static Testing Including Effects of Fluid Ingression (DOT/FAA/TC-16/23)
  • Volume 2: Fatigue Testing Including Effects of Fluid Ingression (DOT/FAA/TC-17/06)
  • Volume 3: Damage Growth in Sandwich Structures (DOT/FAA/TC-17/7)
  • Volume 4: Investigation of Face/Core Interface Debonding in Aircraft Sandwich Composites Subjected to Combined Pressure and In-plane Loading: An Engineering Approach (On Going)

★ Other Contributions to ASTM D30 & CMH-17
  • CMH-17 Rev. H chapters/sections (completed review)
  • SCB Fracture test standard development ASTM D30

★ Other Publications
  • Damage Initiation and Fracture Analysis of Honeycomb Core Single Cantilever Beam (SCB) Sandwich Specimen (submitted to JSSM)
  • Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading (Accepted for ASC 34th Technical Conference)
Analysis – Engineering Approach

• SCB ➔ GAG

SCB FE Model

SCB Experimental Setup

GAG Experimental Setup

GAG Loading Cycles

3-Ply Flat
Outline

• SCB Test Configuration
  • Materials & Test Setup (translatable base)
• Foundation Model Approach & Validation
  • Comparison of Analytical, FEA & Exp. Results
• Finite Element Model Description of SCB Specimens
  • Cohesive-based modeling approach
• GAG - Edgewise Compression (EWC) Test Configuration w/t Pressure Loading
  • Test Setup & Loading
  • Static and fatigue testing
• Finite Element Model description for GAG Specimens
  • Modeling approach
  • Comparison to test data
• Summary & Future Work
**SCB Test Configuration**

- **Materials**
  - Facesheet: T650 – 5320 PW
  - Core: Hexcel HRH-10
  - Adhesive: FM300 - 2
- **Prescribed Crack**
  - Teflon® inserts
  - $a_o = 50.8$ mm
- **Dimensions**
  - $L = 254$ mm
  - $b=50.8$ mm
- **Piano Hinge**
  - Bonded using EA9394

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**Test Matrix**

<table>
<thead>
<tr>
<th>Case</th>
<th>Facesheet Material</th>
<th>Plies</th>
<th>Cell Size (mm)</th>
<th>Core Density (kg/m³)</th>
<th>Core Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T650/5320-PW</td>
<td>4</td>
<td>3.2</td>
<td>48.0</td>
<td>25.4</td>
</tr>
<tr>
<td>2</td>
<td>T650/5320-PW</td>
<td>4</td>
<td>3.2</td>
<td>96.0</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>T650/5320-PW</td>
<td>4</td>
<td>9.5</td>
<td>48.0</td>
<td>12.7</td>
</tr>
<tr>
<td>4</td>
<td>T650/5320-PW</td>
<td>8</td>
<td>3.2</td>
<td>96.0</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Outline – Moving Forward

• SCB Test Configuration
  • Materials & Test Setup (translatable base)

• Foundation Model Approach & Validation
  • Comparison of Foundation, FE & Exp. Results

• Finite Element Model Description of SCB Specimens
  • Cohesive-based modeling approach

• GAG - Edgewise Compression (EWC) Test Configuration w/t Pressure Loading
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  • Static and fatigue testing

• Finite Element Model description of GAG Specimens
  • Modeling approach
  • Comparison to test data

• Summary & Future Work
Foundation Model Approach & Validation

Python Based Suite

SCB Fracture Tests
Compliance, \( C = \delta/P \)
crack length, \( a \)

SCB FE-Model
Compliance & energy-release rate validation

Foundation model
Compliance & energy-release rate validation

Winkler-based foundation model

Closed – Form Expressions

Compliance vs. crack length

(a)

(b)

(c)

(d)

Python Suite

Core properties:
- Gibson-Ashby model

Gibson model

Energy release rate validation

Gibson-Ashby model
Foundation Model Approach & Validation

Python Based Suite

Foundation model: Gibson-Ashby model
Initiation fracture toughness: Modified Beam Theory (MBT)

SCB Fracture Tests
Compliance, $C = \frac{\delta}{P}$
Crack length, $a$
Initiation fracture toughness: Modified Beam Theory (MBT)

SCB FE-Model
Compliance & energy-release rate validation

Energy-release rate vs. crack length

(a) (b) (c) (d)

Python Suite

Closed – Form Expressions

Closed – Form Expressions

Winkler-based foundation model

Core properties: Gibson-Ashby model

Compliance, $C = \frac{\delta}{P}$
Crack length, $a$

Normalized energy-release rate vs. 
Normalized crack length, $a / h_y$
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FEA – SCB Model Description and Approach

- **Cohesive zone** to model the damage in the core.

- Four configurations considered:
  - Core density (48.96 kg/m³) & Thickness (12.7, 25.4 mm)
  - Cell size (3.2, 9.5 mm)
  - Face-sheet thicknesses (4, 8-ply)

- Failure modeled in core using cohesive elements (located beneath meniscus layer)

**Boundary Conditions and Loading Introduction Point**

**Damage in the core**

**Core - Homogenous medium (Gibson-Ashby Approach)**

**G1c**

\[

t_0 = \frac{4}{27} \sqrt{\frac{12E_G u}{h_{\text{eff}}}}
\]

\[
K = \frac{E_G}{h_{\text{eff}}}
\]

Comparison of FE & Exp. Results

Critical Load and Displacement Comparison

<table>
<thead>
<tr>
<th>Case</th>
<th>Facesheet Material</th>
<th>Plies</th>
<th>Cell Size (mm)</th>
<th>Core Density (kg/m³)</th>
<th>Core Thickness (mm)</th>
<th>Exp. Load (N)</th>
<th>Predicted Crack Initiation Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T650/5320-PW</td>
<td>4</td>
<td>3.2</td>
<td>48.0</td>
<td>25.4</td>
<td>97.7</td>
<td>FEA Load (N) 96.0, Error (%) -1.8</td>
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<td>T650/5320-PW</td>
<td>4</td>
<td>3.2</td>
<td>96.0</td>
<td>12.7</td>
<td>120.7</td>
<td>FEA Load (N) 106.8, Error (%) -1.5</td>
</tr>
<tr>
<td>3</td>
<td>T650/5320-PW</td>
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<td>9.5</td>
<td>48.0</td>
<td>12.7</td>
<td>77.2</td>
<td>FEA Load (N) 68.5, Error (%) -11.3</td>
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<tr>
<td>4</td>
<td>T650/5320-PW</td>
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<td>3.2</td>
<td>96.0</td>
<td>12.7</td>
<td>258.2</td>
<td>FEA Load (N) 281.3, Error (%) 8.9</td>
</tr>
</tbody>
</table>
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GAG - Edgewise Compression (EWC) Test Setup

- DIC speckle pattern on front and back sides
- 3D printed (Ultem) pressure port
- Hysol EA9309.3NA Epoxy

Damage Growth monitoring
- Digital Image Correlation (DIC)
- Distributed fiber optic strain sensors

Pressure Simulation

Ability to accommodate various specimen sizes
• 10x12 (shown) and 18x20 (test size)
GAG (EWC) Quasi Static Testing w/t Pressure Loading

- Test rig developed for combined compression (in-plane) & pressure loading
- Face sheet & core parameters altered
- Ability to accommodate various specimen sizes

Loading Condition

Test Matrix

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</tr>
</tbody>
</table>
GAG - Edgewise Compression (EWC) Specimen Configuration

Pressure Port: 3D Printed

Honeycomb Core: HRH-10

Film Adhesive: FM300-2

Disbond: Release Film

Facesheet:

FM300-2 5320 PW

Disbond

HRH-10 Core
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FEA – GAG (EWC) FE-Model Description and Approach

- Cohesive based FE analysis – combined static & pressure loading.
- Cohesive parameters from SCB analysis.
  - $G_{1c}$, Penalty parameters (stiffness, $K_n$, & strength, $\tau_n$)
- Damage modeled in the core (similar to SCB specimens)
FEA – GAG (Model Description: Loading and Boundary Conditions)

- Displacement applied at top surface
- Constant pressure (13.1 Psi) applied
- BCs applied on specimen edges to closely replicate the test setup

Test Setup

Boundary Conditions and Load Introduction

Pressure thought the pressure port.
# GAG Test Data Comparison Summary

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<th>FEA Load (kN)</th>
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<td>81.8</td>
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<td>3.2</td>
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<td>118</td>
<td>18.6</td>
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<td>70.9</td>
<td>73.7</td>
<td>3.9</td>
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<td>96.0</td>
<td>12.7</td>
<td>215.7</td>
<td>248.9</td>
<td>15.4</td>
</tr>
</tbody>
</table>
GAG Test Data Comparison Summary

Load Vs Displacement               Out of plane Displacement

Load Vs Displacement               Out of plane Displacement
GAG Test Data Comparison Summary

- Out-of-plane displacement plots (*disp. inches, force in lbf*)
- Crack initiation monitored by deletion of Cohesive elements

8-ply facesheet; 0.5” core
GAG Test Data Comparison Summary

• Out-of-plane displacement plots (*disp. inches, force in lbf*)
• Crack initiation monitored by deletion of Cohesive elements
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• Summary & Future Work
Summary & Future Work

• An engineering approach to study debonding presented
  • SCB fracture tests on typical honeycomb core sandwich specimens validated & benchmarked against analytical expressions
  • A test setup capable of applying combined pressure and in-plane loading developed (GAG-cycle)
  • A cohesive zone based FE-model of GAG tests developed
    • FE-model over-predicted for the thicker core; thinner core prediction within the range 3-18%

• Future work
  • The engineering approach can be expanded to study configurations w/t attachments/connections
Thank You

References


2. Tomblin JS, Seneviratne W, Denning S. Fatigue Damage Growth Rate of Sandwich Structures DOT/FAA/TC-17/6. New Jersey, 2018


T650-5320 PW / Nomex® HRH-10 core: Energy-release rate Evaluation & Comparison

• A brief introduction to the CSDE method:
  • Solely based on relative crack flank displacements
  • Utilizes closed-form expressions for both ERR and mode-mixity proposed by Suo & Hutchinson (1990)
  • The numerical error zone close to the near-tip plastic zone avoided by linear extrapolation
  • Can be applied in 2-D and 3-D specimens (SCB studied here using a 2D model)

\[
G = \frac{\pi}{8H_{11} r} \left( \frac{H_{11}}{H_{22}} \delta_y^2 + \delta_x^2 \right)
\]

\[
\psi = \tan^{-1} \left( \frac{H_{11} \delta_x}{H_{22} \delta_y} \right) - \varepsilon \ln \left( \frac{r}{h} \right) + \tan^{-1}(2\varepsilon)
\]

\[
\varepsilon = \frac{1}{2\pi} \ln \left( \frac{1 - \beta}{1 + \beta} \right)
\]

\[
\beta = \frac{S_{12} + \sqrt{S_{11} S_{22}}}{\sqrt{H_{11} H_{22}}}
\]