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Assuring Space Mission Success

Failure Predictions of Out-of-Autoclave Sandwich Joints with Delaminations under Flexure Loads

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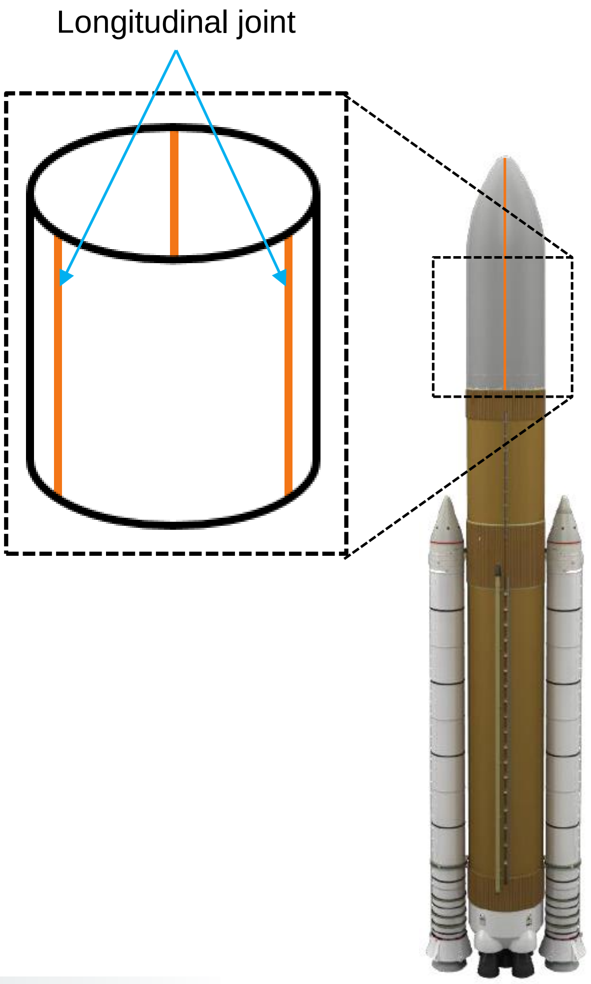
Overview

- Introduction
- Characterization of Material Systems
- Fabrication, Test Setup, and Results
- Finite Element Model
- Finite Element Results
- Summary and Conclusions

Introduction

Brief Background on Out-of-Autoclave Manufacturing; Research Motivation

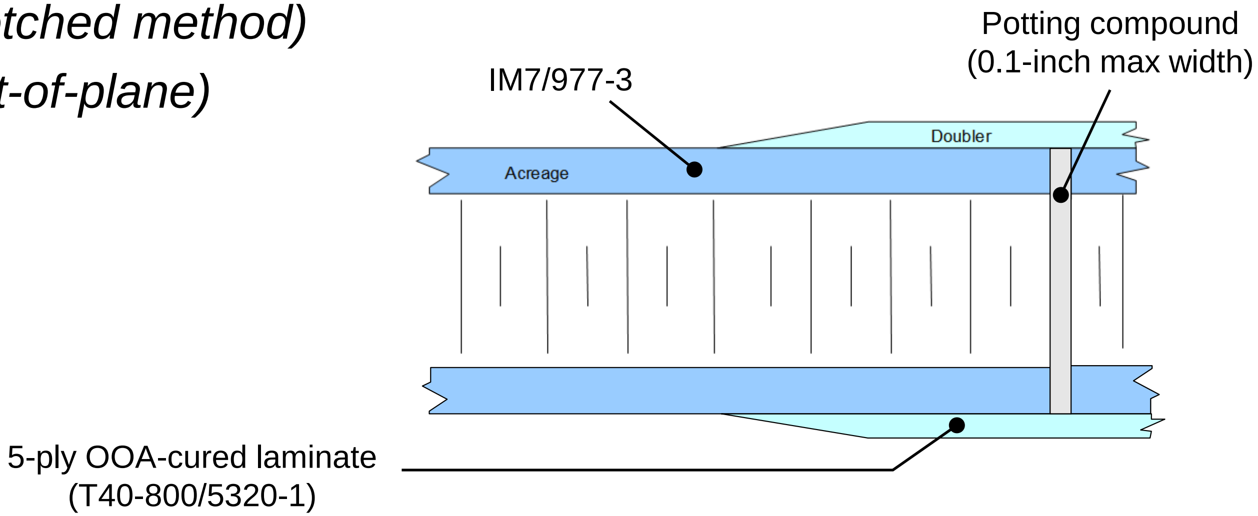
- Composite structures for heavy-lift launch vehicles projected to be largest composites ever built
  - *No autoclaves large enough to process large composite barrel section structures of this size*
- Approach considered is to join in-autoclave (IA) composite sections with bonded out-of-autoclave (OOA) doublers to achieve large full-barrel section
- Two aspects investigated:
  1. *Strength reduction associated with large flaw between OOA and IA materials*
  2. *Predictive capability of fracture methods to estimate failure load due to flaw in joint*



Characterization of Material Systems

Composite Descriptions

- Panels fabricated with IA curable unidirectional prepreg IM7/977-3 and OOA woven fabric T40-800/5320-1
  - *Both materials produced commercially*
- Mechanical tests performed to verify the T40-800/5320-1 material
  - *In-plane tension (panel 0-degree aligned with axial)*
  - *Compression (panel 90-degree aligned with axial)*
  - *In-plane shear (V-notched method)*
  - *Flatwise tension (out-of-plane)*

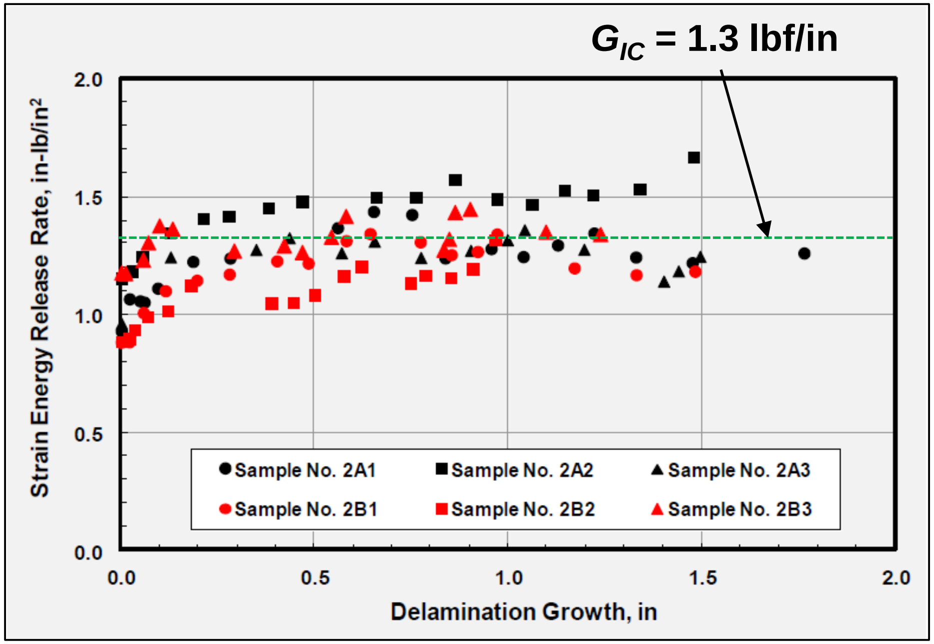


Characterization of Material Systems

Bond Property Characterization

- Two panels fabricated to measure Mode I interlaminar fracture toughness (G_{IC}) using double cantilever beam (DCB) test
  - *Finite element modeling used to size the stacking sequence to ensure bending stiffness of each cantilever arm was nearly equal*
- Six coupons tested
  - *2.5-inch flaw (x3)*
  - *3.5-inch flaw (x3)*
- GIC consistent between six coupons

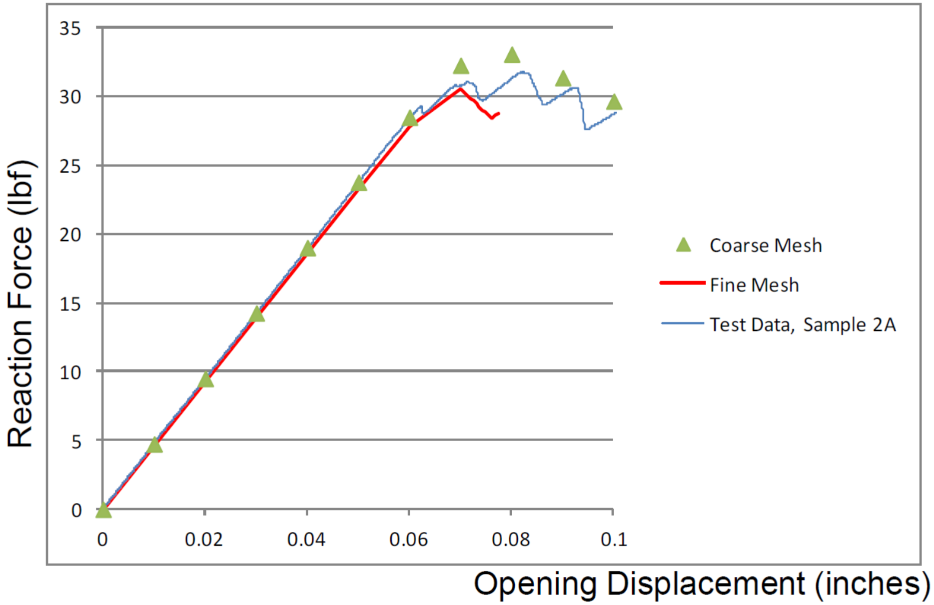
Test of DCB

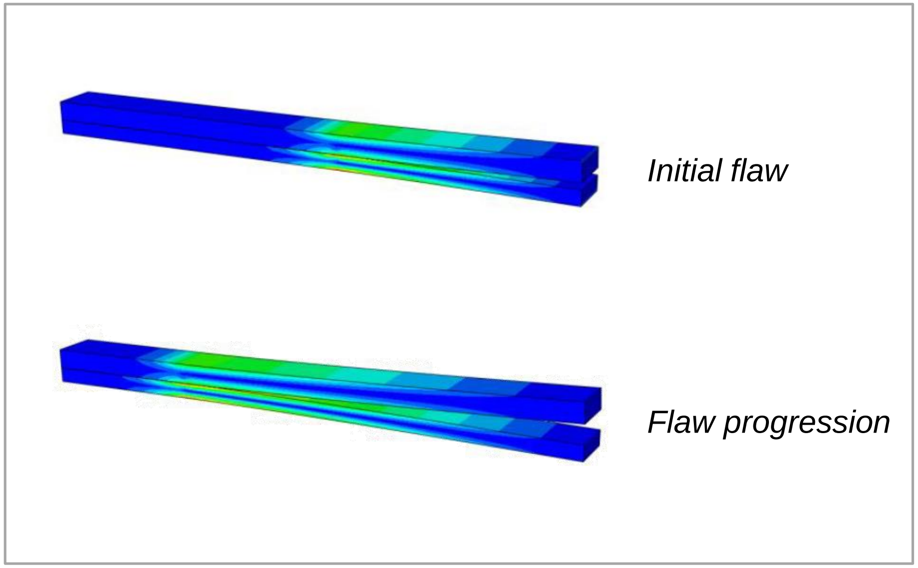


Characterization of Material Systems

Finite Element Model Predictions

- Load-displacement response from finite element simulations using cohesive elements showed good agreement with experimental response
- Response was relatively insensitive to mesh density



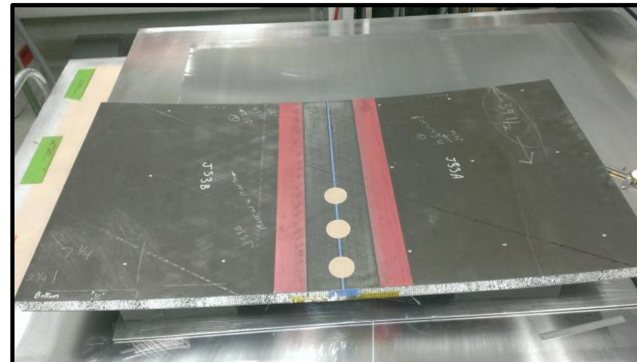


Simulations of DCB

Fabrication, Test Setup and Results

Panel Fabrication

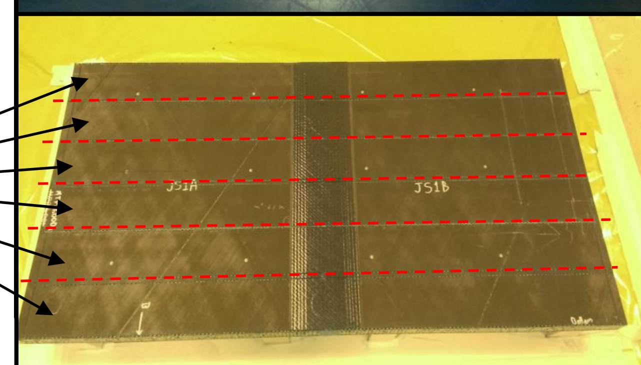
- Panel segments manufactured by NASA Light Spacecraft Structures and Materials program
  - *Radius of curvature = 198 inches*



1. Segments joined with splice adhesive

2. Teflon® inserts placed, doublers bonded to join panel segment

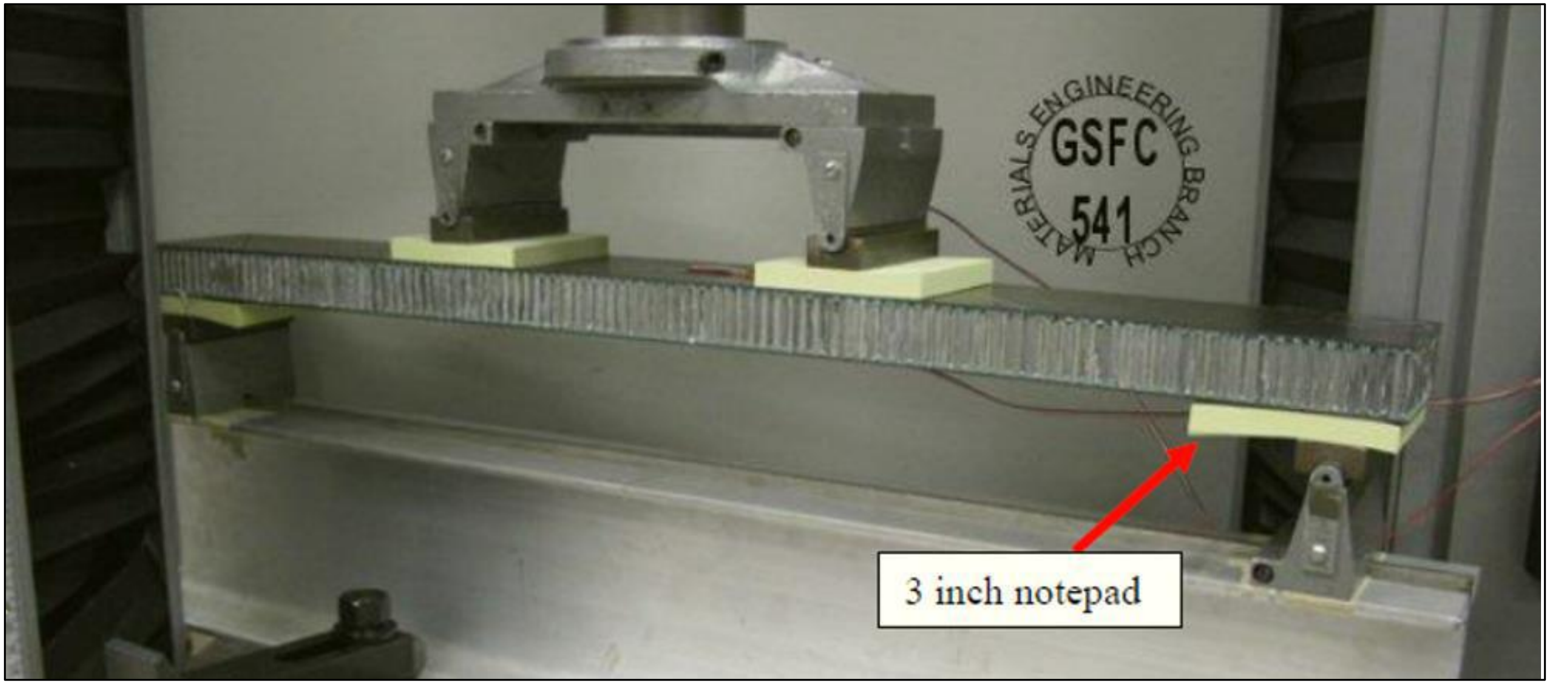
3. Individual four-point-bending (4PB) coupons excised from fabricated composite joint



Fabrication, Test Setup and Results

4PB Configurations

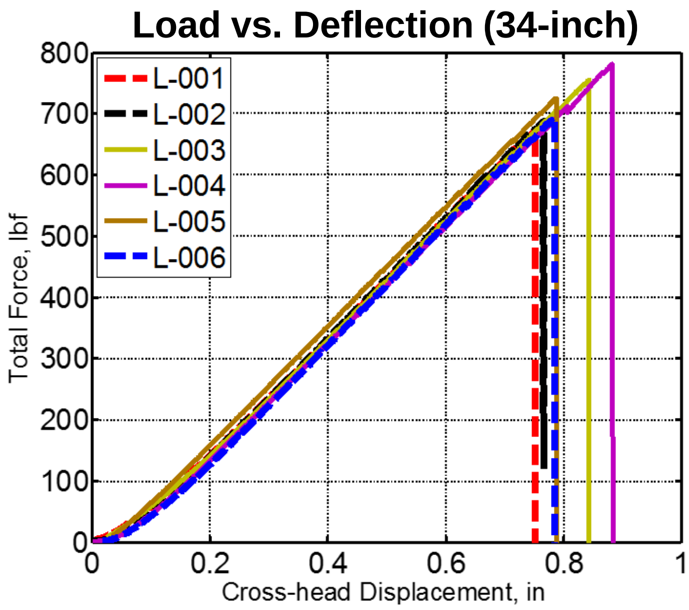
- Two different 4PB configurations used
  - *34-inch long (along zero degree ply; core ribbon direction)*
  - *38-inch long (transverse to zero degree ply; cross-ribbon direction)*
- Full panels manufactured then cut into separate samples

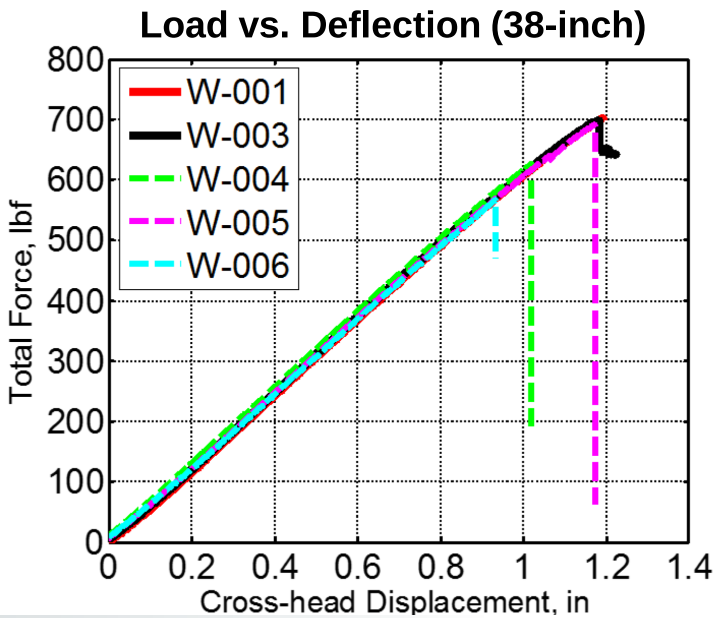


Fabrication, Test Setup and Results

4PB Test Results

- Six specimens of each configuration tested in 4PB
- For each configuration, only half the specimens included the 1.6-inch diameter Teflon® debond inserts
  - *Defect flaw size selected based on analysis to ensure failure in jointed region*
- Maximum deflections measured at centerline midspans





Overall strength reduction due to flaw inclusion was 9 to 10 percent

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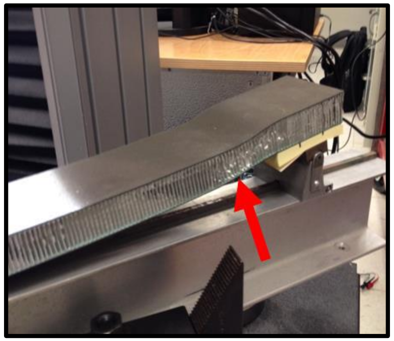
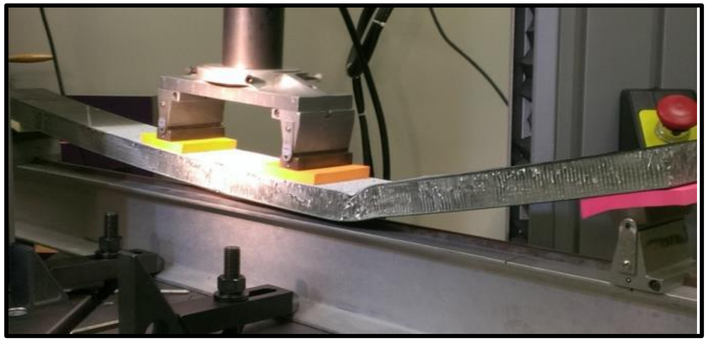
Fabrication, Test Setup and Results

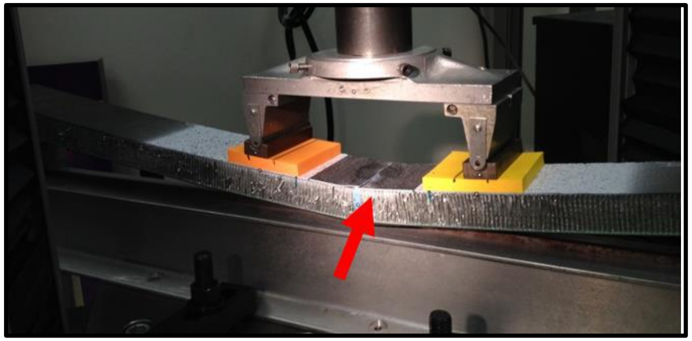
4PB Test Results (cont.)

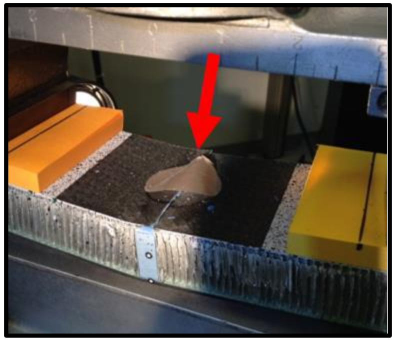
- Various failure modes observed in test as a result of whether flaw inserts were included
  - *Core shear failure (only observed in 38-inch <u>unflawed</u> samples)*





  - *Delamination at joint (observed in all <u>flawed</u> samples, and all 34-inch samples)*





Delamination growth at joint most likely failure mode encountered in tests

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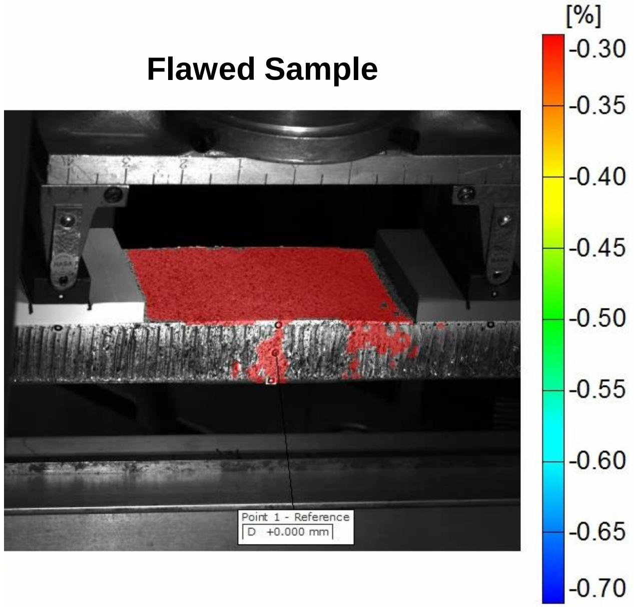
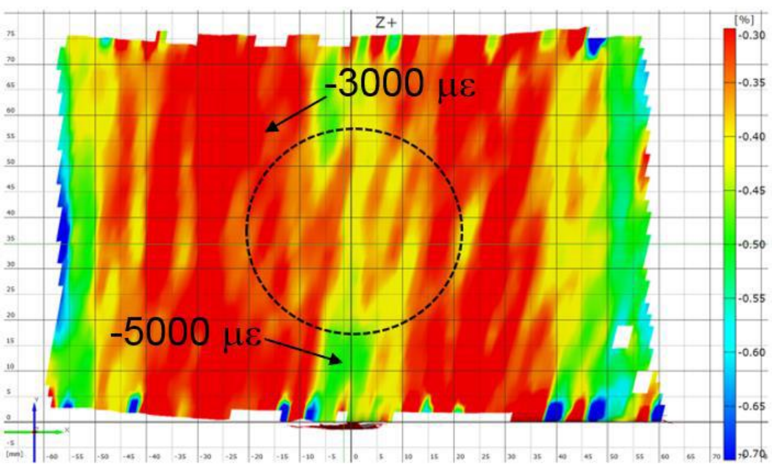
Fabrication, Test Setup and Results

4PB Test Results (cont.)

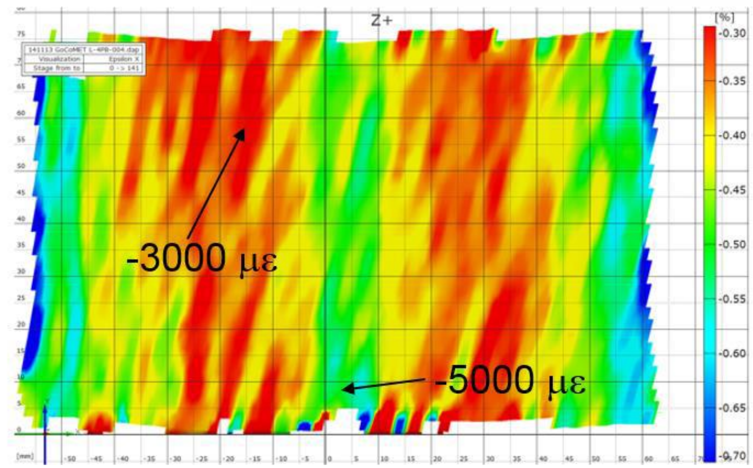
- Surface strains measured in joint region using Digital Image Correlation (DIC)
- Axial strain fields captured at last frame before failure
- Teflon® inserts observed to increase strain field on joint seam

Flawed Sample





Flawed Sample

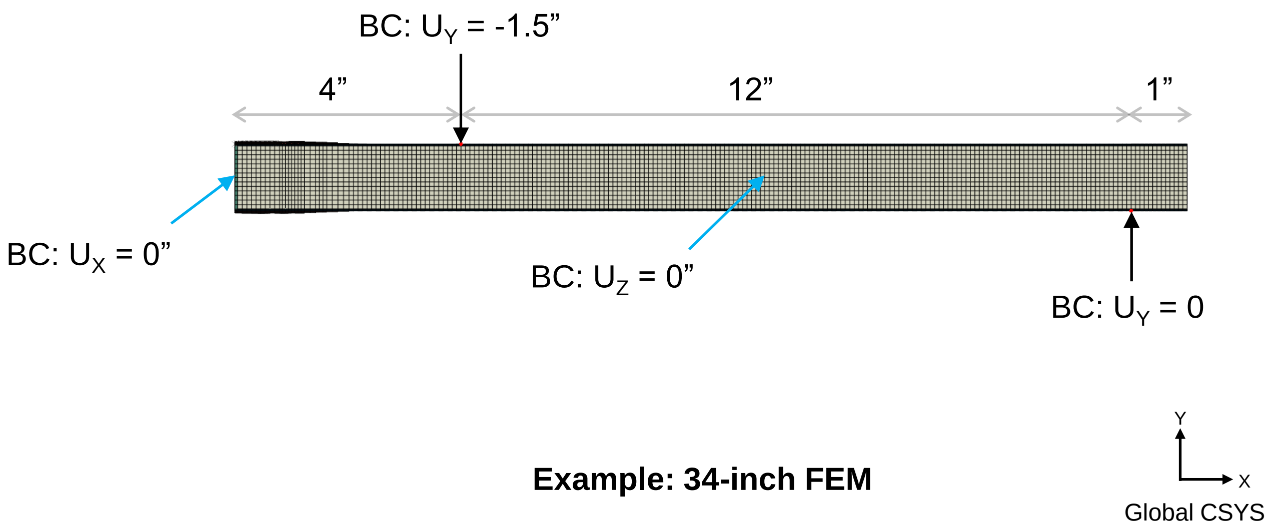


Unflawed Sample

Finite Element Model

Simulation Methodology

- Finite element models (FEMs) using Abaqus
- 34-inch and 38-inch specimens with and without flaws
- Two-way symmetry and displacement control utilized



Example: 34-inch FEM

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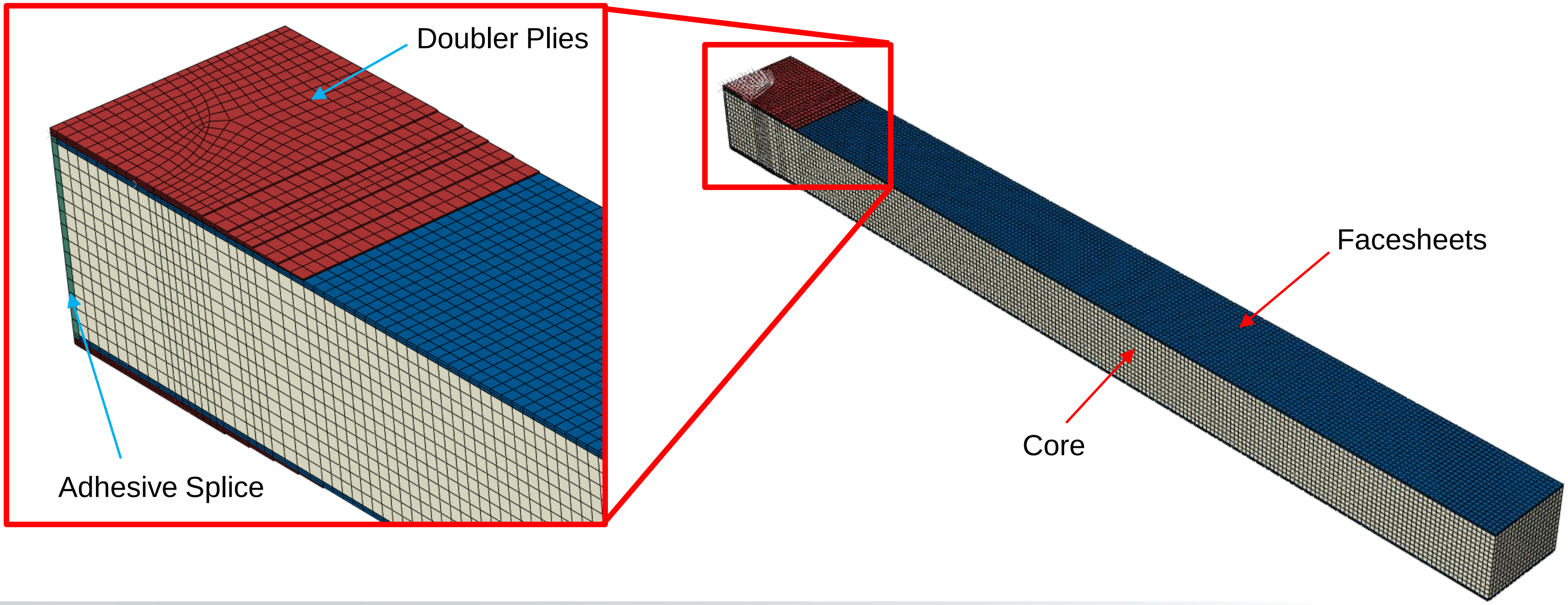
Finite Element Model

Simulation Methodology (cont.)

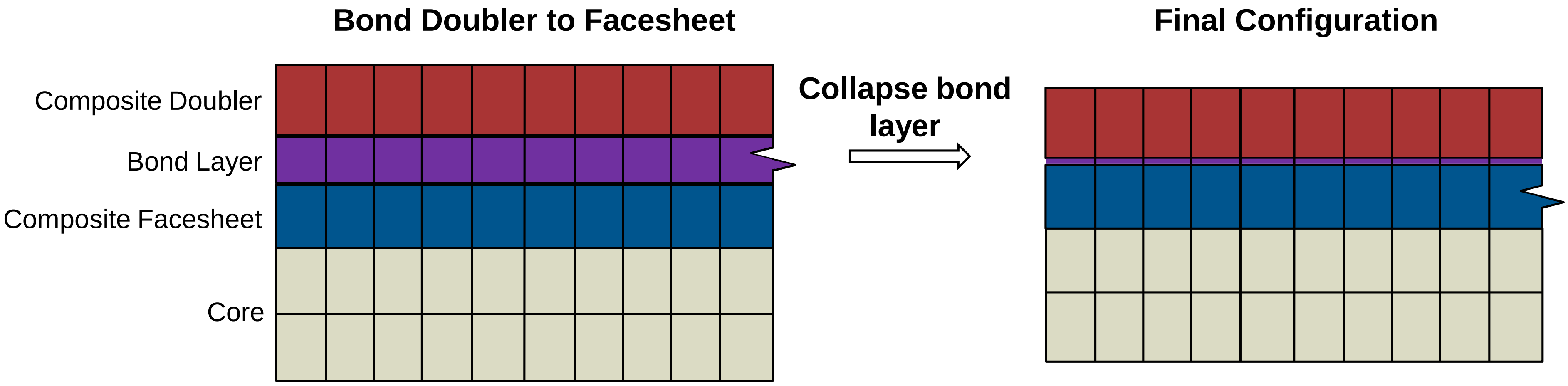
- 4PB loading creates a mixed-mode failure; therefore, necessary to formulate some basis for determining appropriate values of Mode II and Mode III fracture energies (G_{IIC} and G_{IIIC})
  - *Analyses run for (1) $G_{IIC} = 1*G_{IC}$, (2) $G_{IIC} = 2*G_{IC}$, (3) $G_{IIC} = 3*G_{IC}$*
  - $G_{IIC} \approx G_{IIIC}$



Finite Element Model

Cohesive Element Formulations – Abaqus UEL

- First cohesive layer modeling methodology simulates an irreversible exponential constitutive law for the interface
- Solid elements collapsed to zero thickness
- Flaw (or “debond”) region uses UEL while bonded region uses Abaqus built-in solid cohesive elements



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Finite Element Model

Cohesive Element Formulations – Surface-based Cohesion

- Second cohesive layer modeling methodology utilizes surface-based cohesive behavior using built-in Abaqus contact formulation
- Flaw region utilizes frictionless tangential behavior coupled with hard contact normal behavior
- Bond region used cohesive behavior to transfer stresses across the interface using arbitrarily high stiffness
  - *Assumptions made on max bond strength due to lack of experimental data*
  - *Delamination initiation predicted with strength-based criterion and propagation based on fracture criterion (power law)*

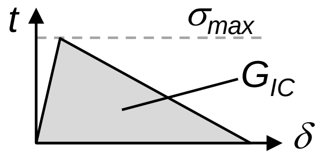
Elastic Behavior:

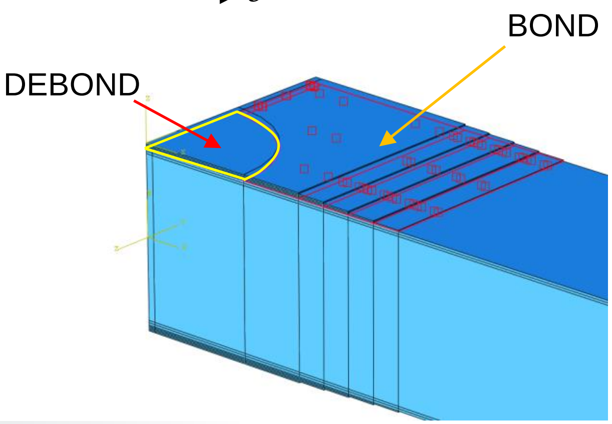
$$\boldsymbol{t} = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix} = \boldsymbol{K\delta}$$

Damage Initiation:

$$\left\{\frac{\langle t_n \rangle}{t_n^o}\right\}^2 + \left\{\frac{t_s}{t_s^o}\right\}^2 + \left\{\frac{t_t}{t_t^o}\right\}^2 = 1$$

Damage Propagation:





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Finite Element Model

Failure Criteria

- One metric of modeling procedure was to identify likely failure mode for each simulation
- Five types of potential failure criteria:

1. Doubler bond failure (debond)

   Damage initiation criterion = 6,000 psi

2. Core shear failure in ribbon direction (L)

   Damage initiation criterion: 155-210 psi (transverse shear strength)

3. Core shear failure transverse to ribbon direction (W)

   Damage initiation criterion: 90-130 psi (transverse shear strength)

4. Facesheet ply failure

   Damage initiation criterion: 9,200 $\mu\varepsilon$ maximum strain

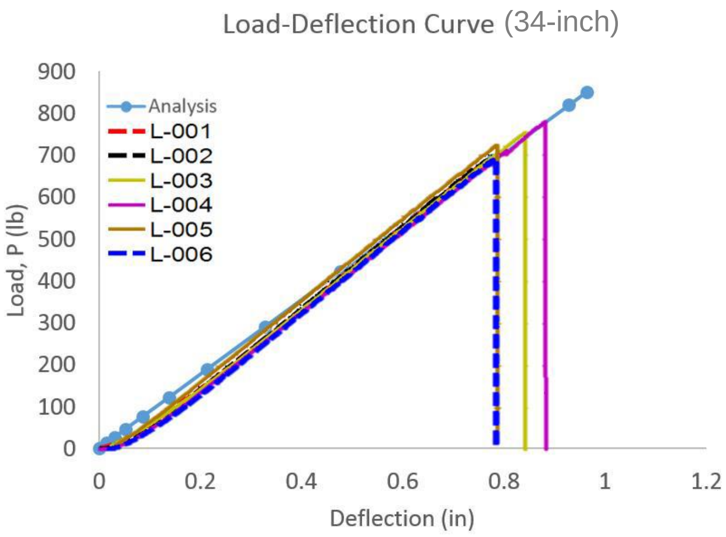
5. Doubler ply failure

   Damage initiation criterion: 10,000 $\mu\varepsilon$ maximum strain

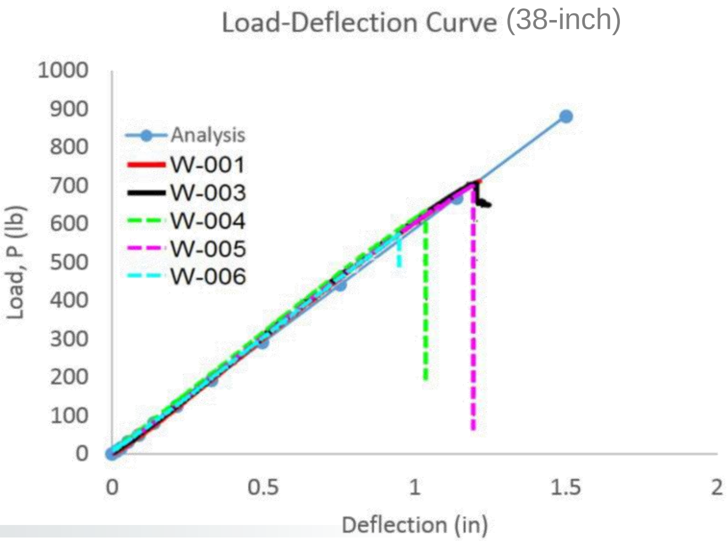
Finite Element Results

Unflawed Samples

- Analysis of 34-inch samples predicted joint failure at peak load of 852 lbf
  - *Max load seen in test = 781 lbf*
  - *Model prediction within 10 percent*



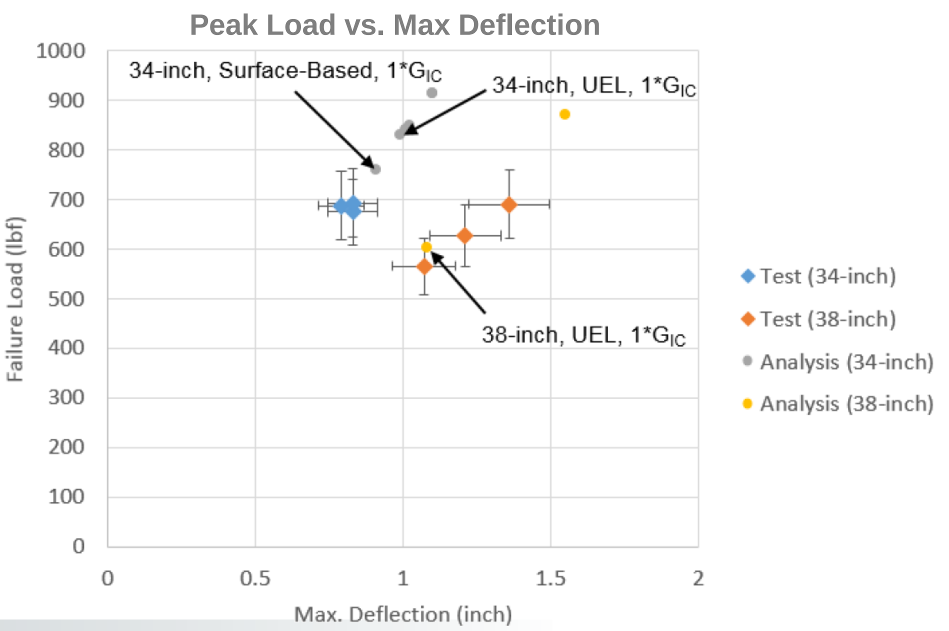
- Analysis of 38-inch samples predicted core shear failure at peak load of 724 lbf
  - *Max load seen in test = 702 lbf*
  - *Model prediction within 3 percent*



May indicate that core strength properties were lower than used in analysis

Finite Element Results
Flawed Samples

- All failures for flawed specimens occurred by joint failure due to debonding
  - *No models predict ply failure in facesheet and doubler plies*
  - *No models predict core shear failure in honeycomb core*
- For 34-inch specimens, best match to tests is surface-based cohesive elements with $G_{IIC} = 1*G_{IC}$
  - *Peak load of 759 lbf within 11 percent of average test peak load*
- For 38-inch specimens, best match to tests is the UEL cohesive elements with $G_{IIC} = 1*G_{IC}$
  - *Peak load of 604 lbf within 4 percent of average test peak load*



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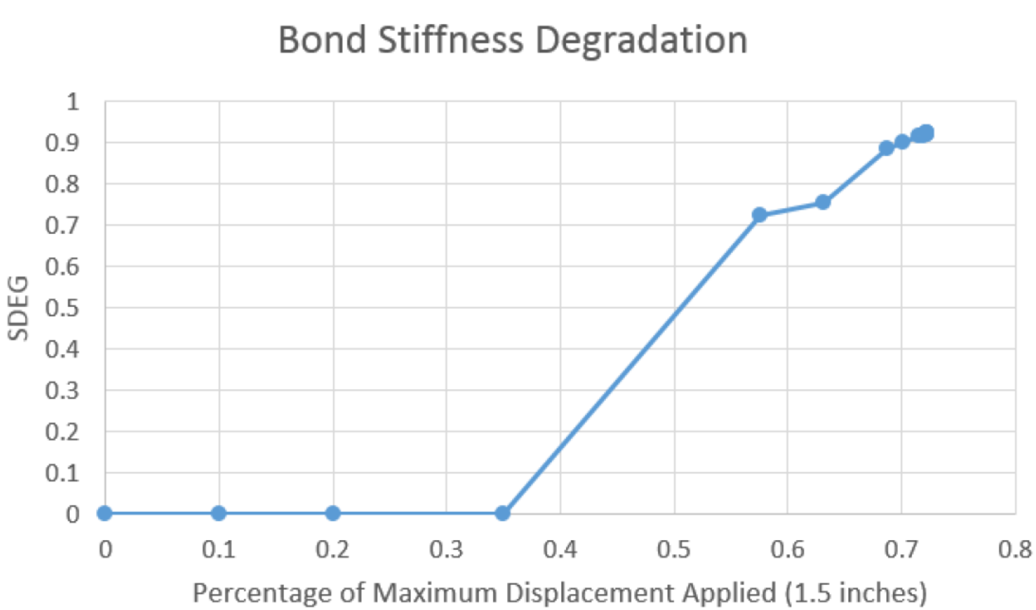
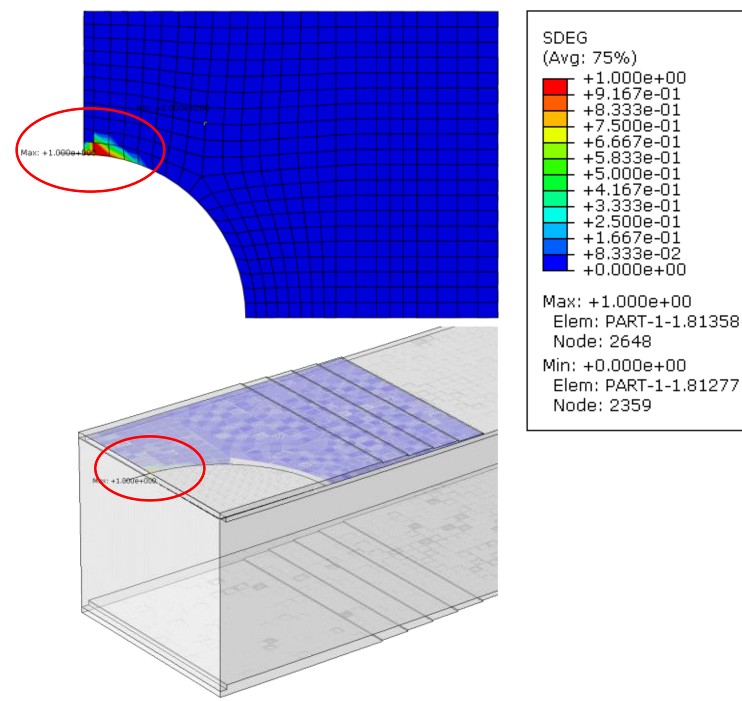
Finite Element Results

Bond Damage Propagation

- Analysis closest to tests: 38-inch sample with UEL bond and $G_{IIC} = 1*G_{IC}$
- Results inspected for damage propagation at joint doubler interface to panels
- Scalar stiffness degradation (SDEG) monitored through analyses
  - *Bond failure initiates at ~35 percent of maximum displacement applied (~308 lbf)*



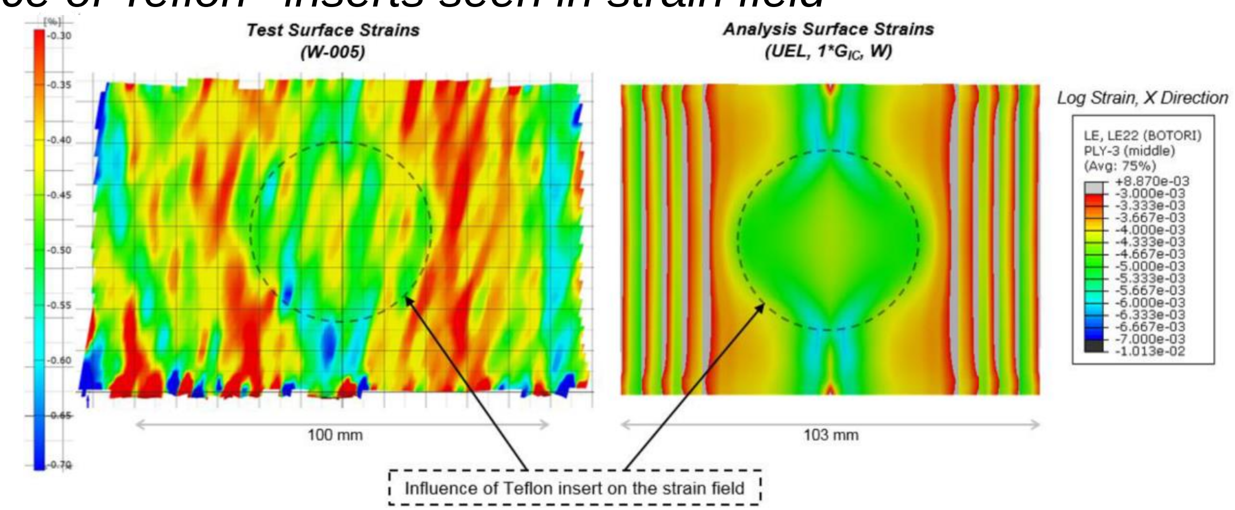


Finite Element Results

Surface Strains

- 34-inch specimens show strain in circular debond region ~5-10 percent higher in analysis than in test
  - *Corresponds to the ~11 percent higher peak load predicted in analysis over test*
- 38-inch specimen analysis show strain values matching very well with tests
  - *Correspond to within ~1 percent*
  - *Influence of Teflon® inserts seen in strain field*

38-inch



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Summary

- 4PB configuration with and without flaws tested and analyzed
- Mechanical properties of joint material characterized
- Relative to unflawed samples, test and analysis demonstrated at least a 10 percent strength reduction due to 1.6-inch flaw between IA material (IM7/977-3) and OOA material (T40-800/5320-1)
- Analysis in reasonable agreement with test results both with and without flaws

Conclusions

- Investigation demonstrates OOA joint is robust to a flaw of a size that is a significant percentage of the width of the sample
- Concerns of bonding an OOA material to an IA material is mitigated for the geometries, materials, and load configurations considered
- OOA processing a good potential option
- Investigation demonstrated predictive capability of state-of-the-art analytical tools available in commercial software for assessing effects of defects at joint interface

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