Buckling of a Longitudinally Jointed Curved Composite Panel Arc Segment for Next Generation of Composite Heavy Lift Launch Vehicles: Verification Testing and Analysis

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Overview

The objective of this work was to exercise an out-of-autoclave all-bonded joint design concept for a Space Launch System (SLS) fairing during the Composites for Exploration (CoEx) effort.

This presentation aims to:

• Report the buckling test and analysis correlation results for the 54” x 29” CoEx IM7/977-3 jointed panel. The analyses include:
  ▪ Pre-test analyses to obtain a baseline buckling load and the stress state
  ▪ A trade study to look at design changes to lower the panel ends/corners stresses
  ▪ Correlating the buckling test data:
    o Using linear vs. non-linear analysis
    o Investigating surface (shape) imperfections on the jointed panel buckling behavior

• Present a summary results of the damaged jointed panel buckling and edge-supported compression tests, and to discuss the next steps to correlate the observed behaviors.
Background

- The parent material:
  - The Hitco demonstration HC sandwich panel, 1/16\textsuperscript{th} arc segment of 33-ft diameter cylinder, made under the CoEx program
  - 8-ply $[45^\circ/90^\circ/-45^\circ/0^\circ]_s$ face-sheets (IM7/977-3) with 1 in thick 3.1 pcf Al honeycomb core

Note: The final trimming reduced the overall size of the “jointed panel” to 52 in. x 27.8 in. (The panel still to be referred to as 54 in x 29 in)
Bonded Joint Configuration

- Cured ply thickness: 0.008 in
- Dominant mechanical properties were obtained through testing
- Joint out-of-autoclave cured to H/C panel in a co-bond operation
- The joint was made and inspected without any flaws
The Baseline FE Model Description

- ~0.5-in. element size with finer mesh at the joint region and at the fixed ends
  - Total of 61,146 elements and 56,444 nodes
- Face-sheets and bonded joint were modeled using 2-D elements (CQUAD4/PCOMP) with proper offsetting
- RBE2s were used to apply load and boundary conditions at the top and bottom
  - Top: Applied nodal load/displacement while constraining all degrees of freedom except for the axial translation
  - Bottom: Fixed
- Core was modeled using solid elements (5 elements through the thickness)
  - 2-D plate elements share nodes with the most inner/outer core solid elements
- Potting region and the Al frame (fixture) were modeled using solid elements
- Cut (potting) was modeled ~0.24 in wide to avoid a very fine mesh
Buckling and Strength Baseline Analyses

NASTRAN linear SOL 105
Euler eigenvector buckling contour
$P_{\text{critical}} = 85.1$ kips

Hexcel Core Stress Allowables:
Shear (xz): $\sim 145$ psi
Compressive stabilized strength: 215 (min) - 300 (typ) psi
Crush strength: 130 psi

Note: For stress components: x indicates axial, y hoop, and z through thickness directions.

Core Through Thickness Stress, psi

Max. Failure Index, Max. Strain Failure Criterion

Strength (SOL 101):
- Stress concentration in F/S and core at ends/corners
- $FI = 1$ indicates failure
Panel End-Condition Improvement

To address the high stress concentration issue at the ends/corners the following modifications were examined:

- Adding doublers to panel ends
- Including stress relief features into the potting compound
- Having both, the end-doublers, and the stress relief features
Adding End Doublers

Doublers
- Plain weave
- A 4-ply laminate
- Co-bonded to panel at same time as joints
Adding Stress Relief Features

• The potting compound at the corners was removed, as shown, to release the stresses at the corners/edges
Face-sheet/Joint/Doubler Failure Index

Failure Index Contour (Max. Strain Failure Criterion) at the critical buckling load, for each configuration:

- **Base-line Configuration**
  - Max FI = 0.61
  - P critical = 85.1 kips

- **with End-doublers (only)**
  - Max FI = 0.50
  - P critical = 88.7 kips

- **with Stress Relief Features (only)**
  - Max FI = 0.54
  - P critical = 84.9 kips

- **with End-doublers and Stress Relief Features**
  - Max FI = 0.49
  - P critical = 88.4 kips

**Selected Design**
### Core Stresses

**Core Through Thickness Stress at Panel Ends, psi**

- **Base-line Configuration**
  - Potted: Min: -289, Max: 301 psi
  - with End-doublers (only): Min: -255, Max: 149 psi
  - with Stress Relief Features (only): Min: -287, Max: 115 psi
  - with End-doublers and Stress Relief Features: Min: -217, Max: 135 psi

**Face-Sheet and Joint**

- **Buckling Critical Load (kips)**
  - Base-line: 85.1
  - with End-doublers: 88.7
  - with Stress Relief Features: 84.9
  - with End-doublers and Stress Relief Features: 88.4

**Honeycomb Out-of-Plane Stresses, psi**

- **Max. Fl:** 0.61, 0.50, 0.54, 0.49
- **Min $\sigma_z$:** -289, -255, -287, -217
- **Max $\sigma_z$:** 301, 149, 115, 135
- **$|\tau_{xz}|$:** 459, 472, 101, 75

P critical values:
- 85.1 kips
- 88.7 kips
- 84.9 kips
- 88.4 kips
Test Article

- Made to the recommended specifications
- The joint was inspected without any flaws (Also, made NDE standard)
Surface Non-uniformities to FE Model

- Prior to testing, surface imperfections were measured on both the IML and OML surfaces, individually.
- Used single feature point inspection to create point clouds on both the IML and OML surfaces.
- The point clouds were then traced along the length of the panel at six different width locations (two on each left, center and right sides) to obtain an imperfection profile on each surface.

- An estimate of the worst case profile with the maximum bow magnitude was incorporated into the FE model for FE analysis.
Buckling Test

- Test was Conducted (by S. Kellas) at LaRC

- The jointed panel reached buckling load of 79.3 K-pounds without joint failure
  - Panel buckled toward IML

- Test Details:
  - 600-kip test frame
  - Photogrammetry (VIC system) on both surfaces to obtain full-field strains/displacements
  - Four displacement transducers to measure end shortening
  - Total of 20 back-to-back strain gages on OML/IML for local strain measurements, specimen alignment and controlling the test
Surface Imperfection Affected Linear Buckling Response

Predicted buckling loads vs. test data

- ~11% over predicting the buckling load when surface imperfections are not included
- ~8% over predicting when the surface imperfections are included
- ~4% difference in stiffness between test and analysis
Surface Imperfection Affected Non-linear Buckling Response

- Out-of-plane deformation at 0.25” imposed axial displacement

Surface imperfection NOT included in FEM

Surface imperfection included in FEM

Panel buckles towards OML

Panel buckles towards IML

Consistent with experimental observation
Bow Affected Buckling Critical Load

**Surface imperfection NOT included in FEM**

![](chart1.png)

- ABAQUS: 84.8 kips
- NASTRAN SOL 106: 83.9 kips

**Surface imperfection included in FEM**

![](chart2.png)

- ABAQUS: 82.1 kips
- NASTRAN SOL 106: 81.2 kips

- Critical buckling load decreases as a result of including the surface imperfections
  - From within 5% the test value to about 2%
Onset of Buckling Determination

Monitoring back to back elements’ axial strains, in the panel’s middle edge to determine the onset of buckling analytically – Analogous to what determines when the buckling event has occurred during the experiment, prior to unloading the panel, without cartographically failing the specimen.
Axial Deformation/End Shortening Correlation

Test correlation at buckling load of ~79.3 kips

Buckling/post-buckling analysis results

OML VIC Results
OML FEA Results
IML VIC Results
IML FEA Results
Out-of-plane Deformation Correlation

Test correlation at buckling load of ~79.3 kips

OML VIC Results

OML FEA Results

IML VIC Results

IML FEA Results
Axial Strain Correlation

Test correlation at buckling load of ~79.3 kips

- Qualitative and qualitative comparison
- The ~4% stiffness difference causes the FEA to show slightly higher axial strains
Hoop Strain Correlation

Test correlation at buckling load of ~79.3 kips

OML VIC Results

OML FEA Results

IML VIC Results

IML FEA Results
Damaged Jointed Panel Buckling Test
Impacted OML – Off Joint Centerline

Buckling Test # 2

Jointed Area

Damage Site

Pre-Test Impact Damage - UT Inspection Results

Post Test - UT Inspection Results of the Same Damage Area

Joint damage does not grow after buckling Test (80K lbs-f)
- 5.5 ft-lbs Impact Energy

Impact and UT inspections by W. Jackson & M. Czabaj at NASA/LaRC
Objectives: To evaluate –
• Damage tolerance capability
• Ultimate strain capacity

The evolution of impacted damage with compressive load; the axial VIC strain at different loads/frames

The catastrophic failure at average center strain of +6000 με (~123 kips)

Ultrasound NDE Result After 5.5 ft-lb impact

Test, Un-damaged - to Buckling
Test, Damaged - to Buckling
Test - Damaged/Edge Supported, to Failure

End Shortening, in

Compressive Load, lb

Buckling Test # 3

2.5" Wide End-Doubler

4" Wide Bonded Joint

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Next Steps

• Correlate the edge-supported panel compression test to failure
  – Modeling the impacted initial damage
  – Study the panel’s response without and with the initial damage
  – And ultimately, model and analyze the damage propagation leading to the catastrophic failure at ~123 kips

• **Objective:** To adapt a practical/general analysis approach for analyzing similar progressive failures in composite joints
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