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Effects of Moisture Diffusion in Sandwich Composites

Mark Tuttle and

Hrishikesh ("Rishi") Pathak, Anirudh Ashok, Andrew King, Ritika Singh, Karen Harban, Balakumaran ("Bala") Gopalarethinam

Mechanical Engineering Dept

University of Washington

2017 Fall AMTAS Meeting

UW Center for Urban Horticulture

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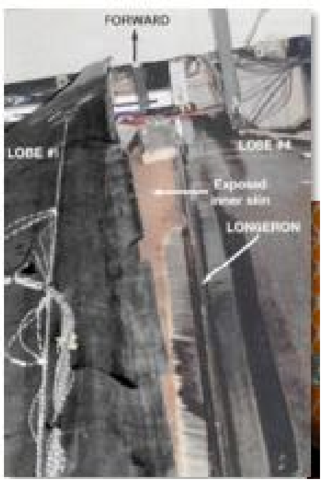
Effects of Moisture Diffusion in Sandwich Composites

<u>Motivation and Key Issues</u>:

- In-service bond failures between composite facesheets and honeycomb cores have been reported

X-33 Liquid Hydrogen Tank Failure



Boeing 747 upper skin disbonds

Airbus A-310 Rudder Failure

(Photos courtesy of Ronald Krueger, National Institute of Aerospace

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Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

- Core-to-skin disbond initiation and growth are thought to occur due to combination of factors:
  - Water ingression into core volume, followed by freeze-thaw cycles….water ingression may occur due to:
    - Wicking of liquidous water through facesheet microcracks, along fiber/matrix interfaces, and/or through improper design of edge closeouts
    - Diffusion of water *molecules* through (otherwise undamaged) facesheets, resulting in increased core humidity levels
  - Pressure differences between inside and outside of unvented honeycomb cores (Ground-Air-Ground or 'GAG' pressure cycles)

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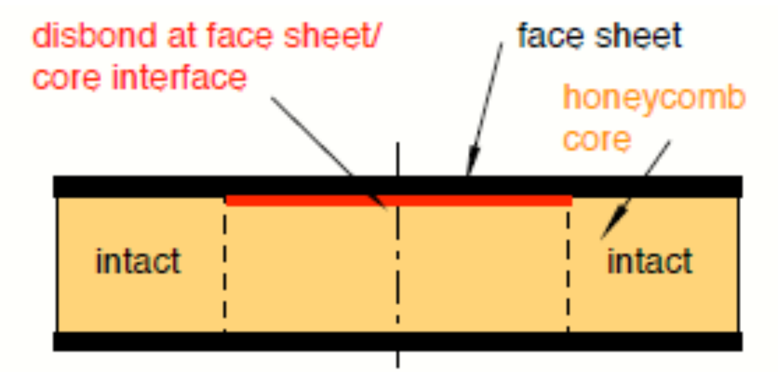
Effects of Moisture Diffusion in Sandwich Composites

- Pressure differences between inside and outside of unvented honeycomb structures (Ground-Air-Ground or 'GAG' pressure cycles)

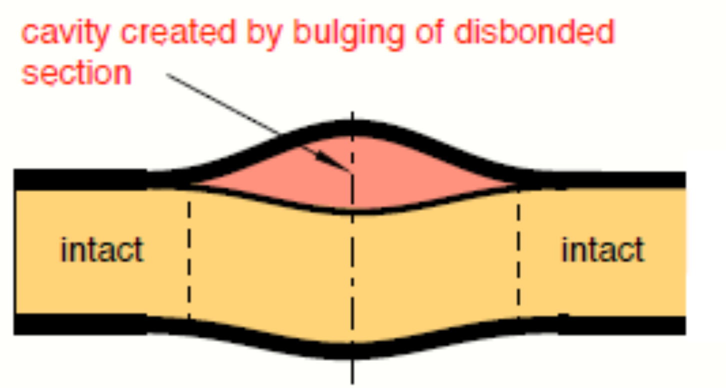
<u>Configuration at ground level</u>

P_o = 100 kPa = 14.7 psi



<u>Configuration at 35,000 ft</u>

P_o = 24 kPa = 3.5 psi



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Overall Program Objectives:

- (Initial objective): Determine if the condense-freeze-thaw-evaporate cycle of humidity within core region impacts the interfacial fracture toughness, G_c, of sandwich structures

- (Objective added in 2016): Develop experimental techniques to study/evaluate the GAG phenomenon

Effects of Moisture Diffusion in Sandwich Composites

- **Principal Investigator**
  - Mark Tuttle
- **Students**
  - Current: Hrishikesh ("Rishi") Pathak, Anirudh Ashok, Andrew King, Ritika Singh, Karen Harban, Balakumaran ("Bala") Gopalarethinam
  - Graduated: Will Smoot ('16), Sung Lin 'Jason' Tien ('16), Shuyu 'Frank' Xia ('17),
- **FAA Technical Monitor**
  - Lynn Pham, Zhi-Ming Chen
- **Industry Participation**
  - Bill Avery, Hamid Razi, and Adam Sawicki/The Boeing Company
  - Dan Holley and Chris Praggastis/3M
  - Bob Fagerlund/Bell Helicopter
  - Kevin Marshall/Hexcel Corporation
  - Shreeram Raj/Solvay Composites
- **Study Initiated in September 2015**

Effects of Moisture Diffusion in Sandwich Composites

Outline of Presentation

- Measurement of G_c associated with facesheet/core bond failures in sandwich structures:
  - Summary of the Single-Cantilever Beam (SCB) test geometry
  - Results obtained during 1st year of study (Sept '15-Sept '16)

  } Presented at Oct '16 AMTAS meeting

  - 2nd year of study:
    - Expanded test matrix
    - As-produced measurements (completed)
    - Humidity measurements (ongoing)
    - Thermal cycling (planned)
- Design and fabrication of GAG specimens
  - Initial measurements

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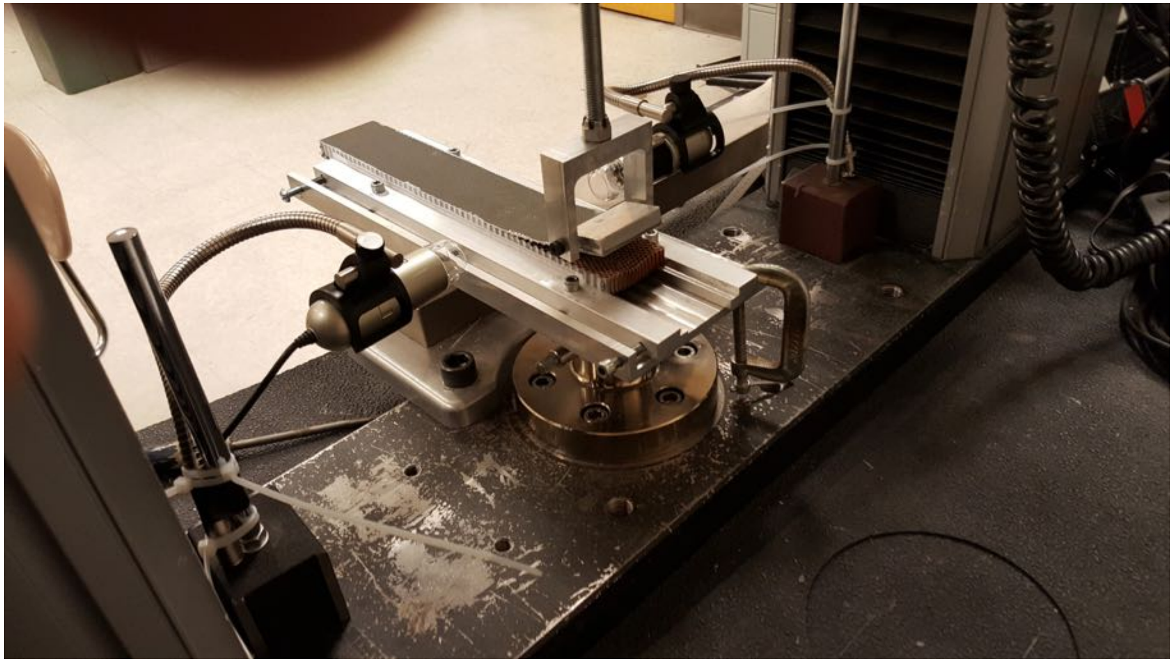
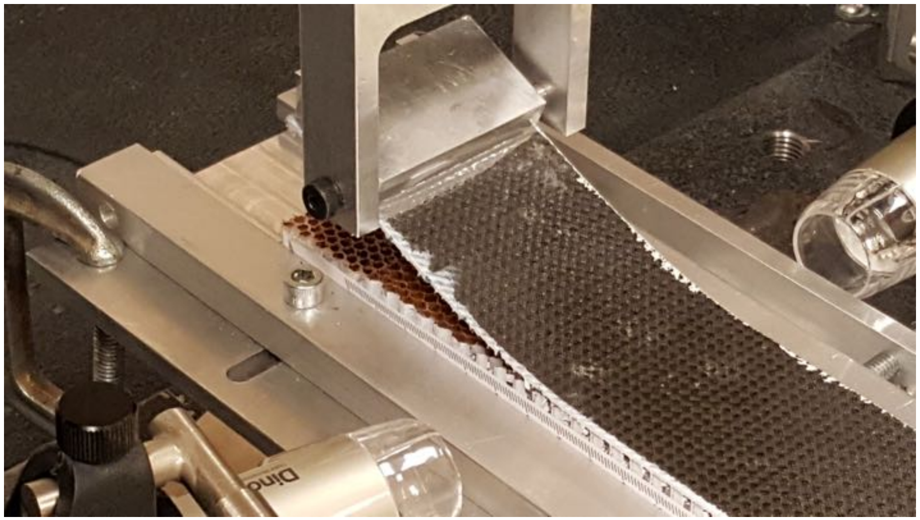
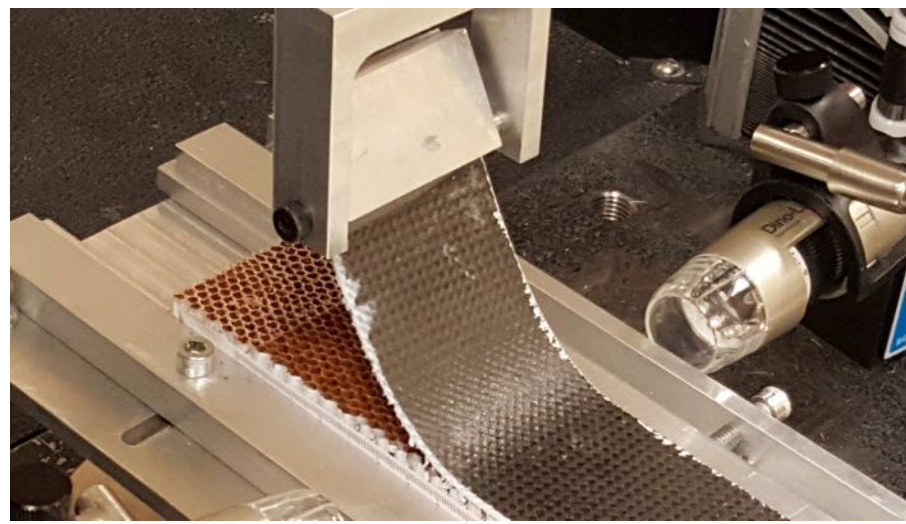
SCB Tests Conducted During 1st Year of Study

- The interfacial fracture toughness, G_c, was measured in accordance with the single-cantilever-beam (SCB) test standard being developed by a CMH-17 working group



SCB Tests Conducted During 1st Year of Study





SCB Tests Conducted During 1st Year of Study

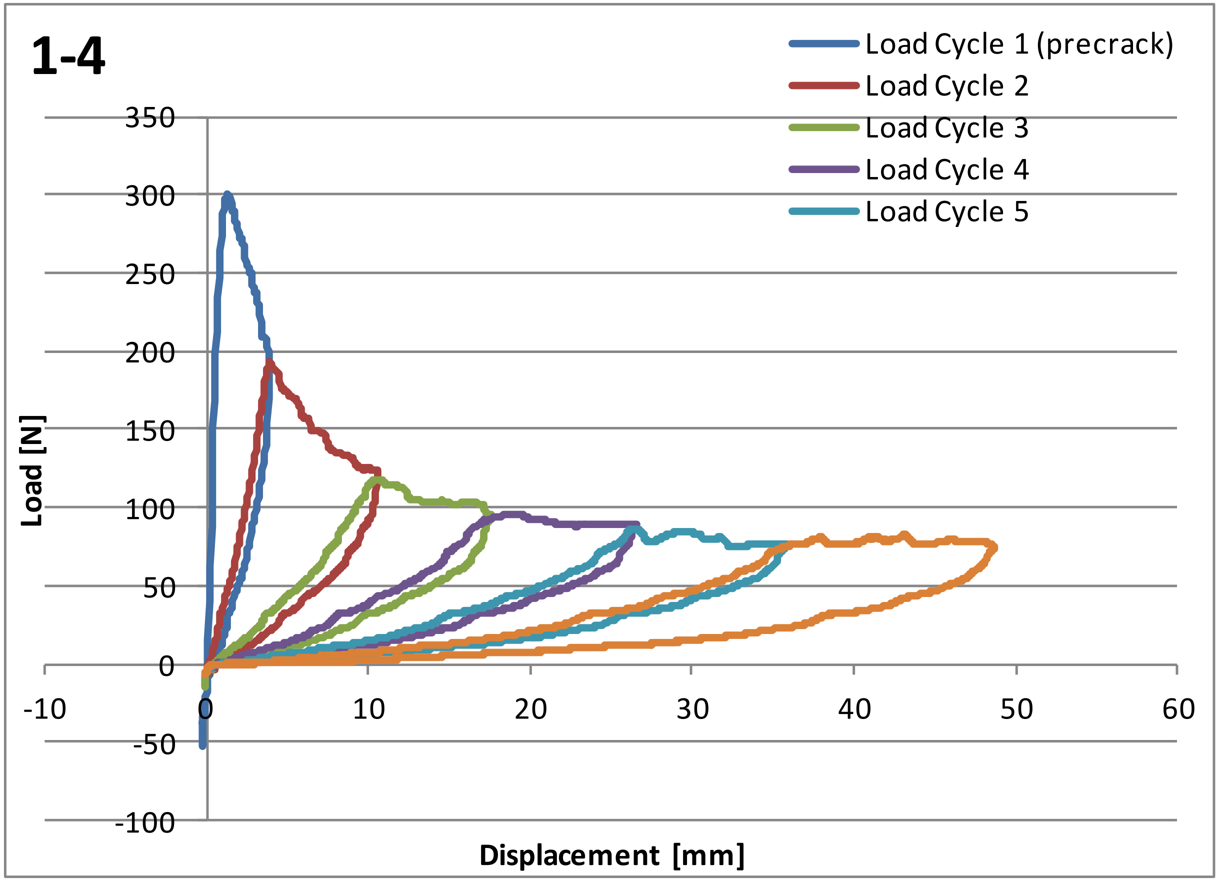
SCB specimens were machined from sandwich panels with 4-ply *woven* facesheets and $[45/0/0/45]_T$ stacking sequence:

Type	Manufacturer/Material Designation
Facesheet	Cytec T300/970 3k plain weave fabric
Core	Hexcel HRH-10 – 1/8 – 3.0 (0.50 in thick)
Adhesive	3M Scotch-Weld Structural Film AF 163-2K

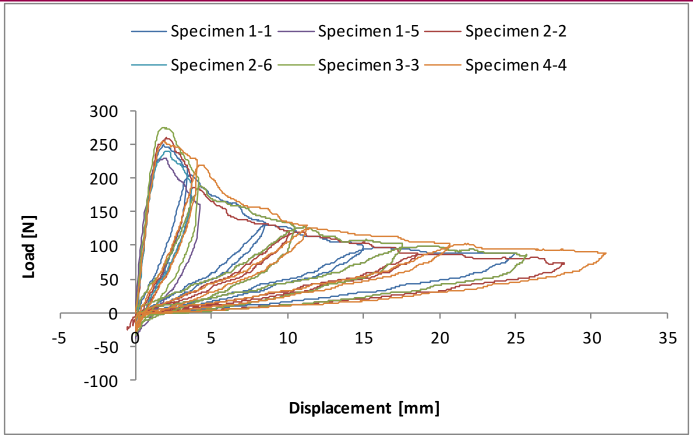
A sawcut was used to initiate a “crack” between facesheet and core

SCB Tests Conducted During 1st Year of Study

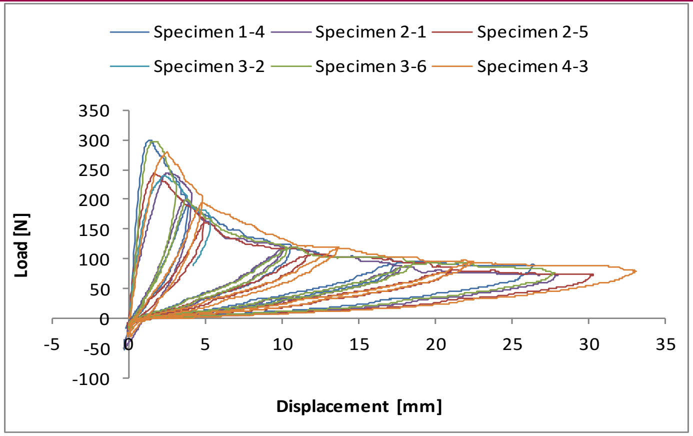
- A typical SCB test involved six load cycles
- Crack length is measured after each cycle
- G_c can be calculated using data collected during any one of the six cycles (data from cycle 1 is normally discarded)



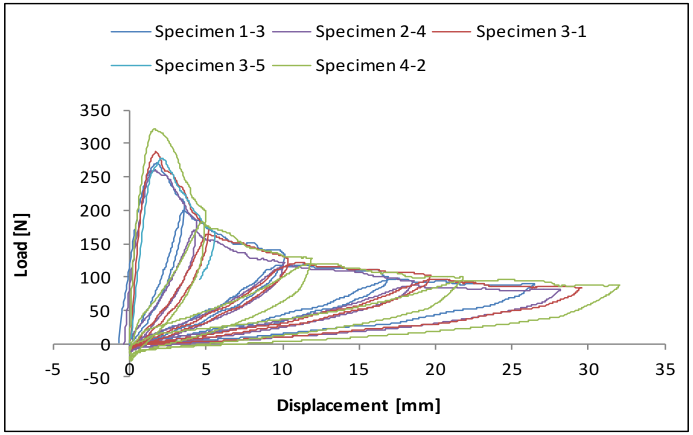
SCB Tests Conducted During 1st Year of Study



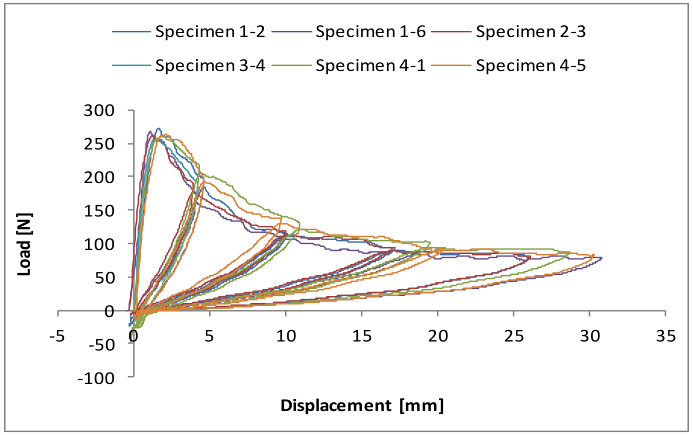
Type A – As Produced



Type B – Thermally Cycled

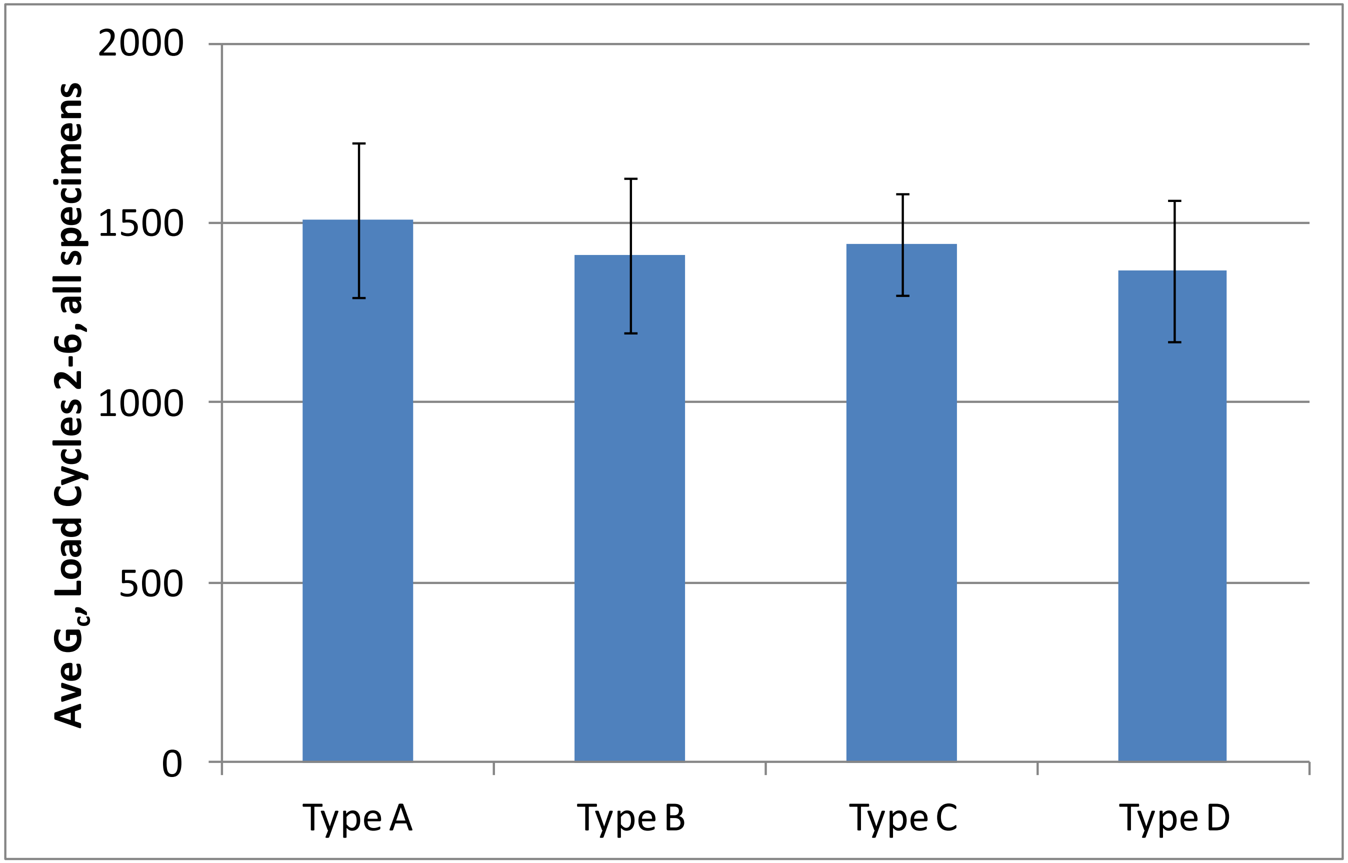


Type C– Humid



Type D– Humid & Thermally Cycled

SCB Tests Conducted During 1st Year of Study



SCB Tests Conducted During 1st Year of Study

Preliminary Conclusions

- Although significant scatter was evident, it appears that environmental factors (i.e., thermal cycling and/or elevated humidity levels) have a modest but measureable impact on interfacial fracture toughness, G_c,
- The most aggressive environmental conditions considered during this study (humid specimens exposed to 700 thermal cycles from RT to -50ºC) resulted in about a 10% reduction in G_c.

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Effects of Moisture Diffusion in Sandwich Composites

Expanded Test Matrix

Component	Description
Facesheet	Cytec T300/970 3k Plain Weave Fabric:
	$[0/45/0]_T$
	$[0/90/90/0]_T$
	$[0/45/90/45]_s$
Core Materials	Hexcel HRH-10-1/8-3.0 (0.50 in thick)
	Hexcel HRH-10-1/8-3.0 (1.00 in thick)
	Hexcel HRH-10-1/8-8.0 (0.50 in thick)
	Hexcel HRH-36-1/8-3.0 (0.50 in thick)
Adhesive	3M Scotch-Weld Structural Film AF 163-2K

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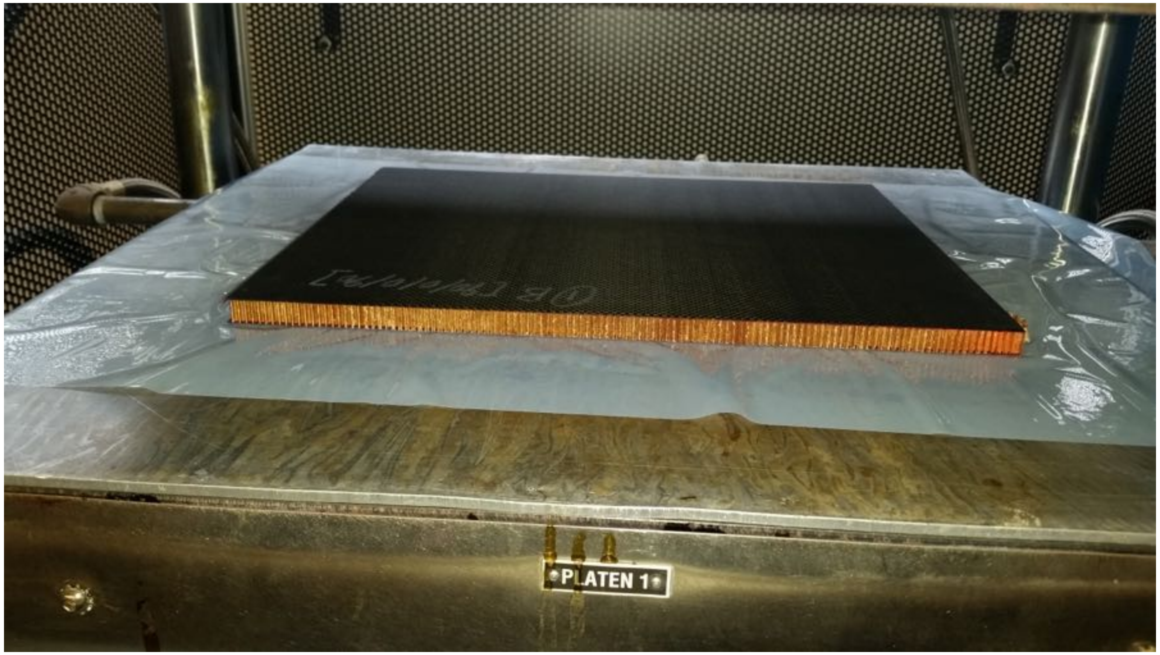
Effects of Moisture Diffusion in Sandwich Composites

- Facesheets were cured in an autoclave
- Facesheets and core materials were machined to size and stored for 1 month at 50ºC (122ºF) at 8% RH in a humidity chamber, to insure components were as “dry” as possible

Effects of Moisture Diffusion in Sandwich Composites

- Parent panels were then produced using the facesheets and core using a hot press
- SCB specimens were machined from the "parent" panels



Effects of Moisture Diffusion in Sandwich Composites

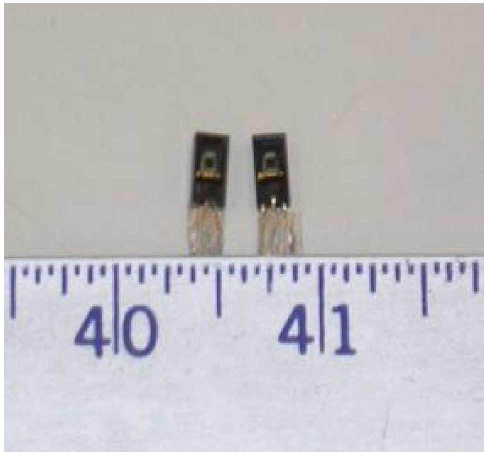
Parent Panels Used to Produce SCB Specimens

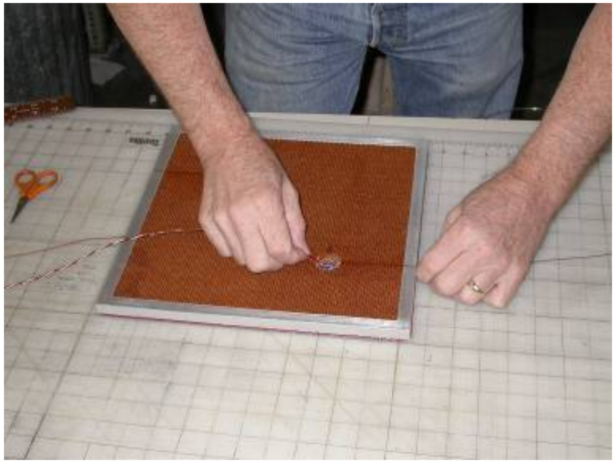
Facesheet Stacking Sequence	Core Material	Core Thickness (in)
$[0/45/0]_T$	Nomex HRH-10, 3 lb ft^3	0.5
	Nomex HRH-10, 8 lb ft^3	0.5
	Nomex HRH-10, 3 lb ft^3	1
	Kevlar HRH-36, 3lb ft^3	0.5
$[0/90/90/0]_T$	Nomex HRH-10, 3 lb ft^3	0.5
	Nomex HRH-10, 8 lb ft^3	0.5
	Nomex HRH-10, 3 lb ft^3	1
	Kevlar HRH-36, 3lb ft^3	0.5
$[0/45/90/45]_s$	Nomex HRH-10, 3 lb ft^3	0.5
	Nomex HRH-10, 8 lb ft^3	0.5
	Nomex HRH-10, 3 lb ft^3	1
	Kevlar HRH-36, 3lb ft^3	0.5

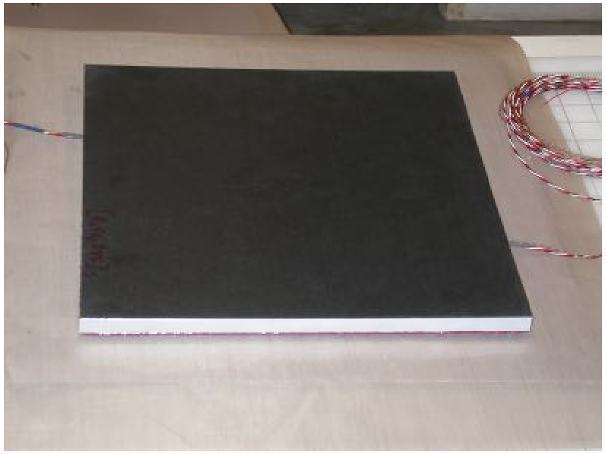
- SCB specimens machined from these panels will be at tested at room temperature, for two conditions:
  - (a) As produced (48 specimens)
  - (b) Following exposure to elevated humidity and thermal cycling (48 specimens)

Effects of Moisture Diffusion in Sandwich Composites

- "Witness" panels were produced with an Ohmic Instruments Model HC-610 capacitive humidity sensors embedded within the core volume
- The humidity sensors are used to monitor core humidity levels during subsequent environmental exposures







Effects of Moisture Diffusion in Sandwich Composites

8 Witness Panels Used to Monitor Core Humidity Levels

Panel No	Facesheet	Core
1	$[90/45/90/45]_s$	HRH-10-3-0.5
2	$[0/45/0]_T$	HRH-10-3-0.5
3	$[0/90/90/0]_T$	HRH-10-3-1.0
4	$[90/45/90/45]_s$	HRH-10-3-1.0
5	$[0/90/90/0]_T$	HRH-10-8-0.5
6	$[0/90/90/0]_T$	HRH-36-3-0.5
7	$[0/45/0]_T$	HRH-36-3-0.5
8	$[0/90/90/0]_T$	HRH-10-3-0.5

Effects of Moisture Diffusion in Sandwich Composites

- 48 tests of “as-produced” SCB specimens performed without mishap during June 2017

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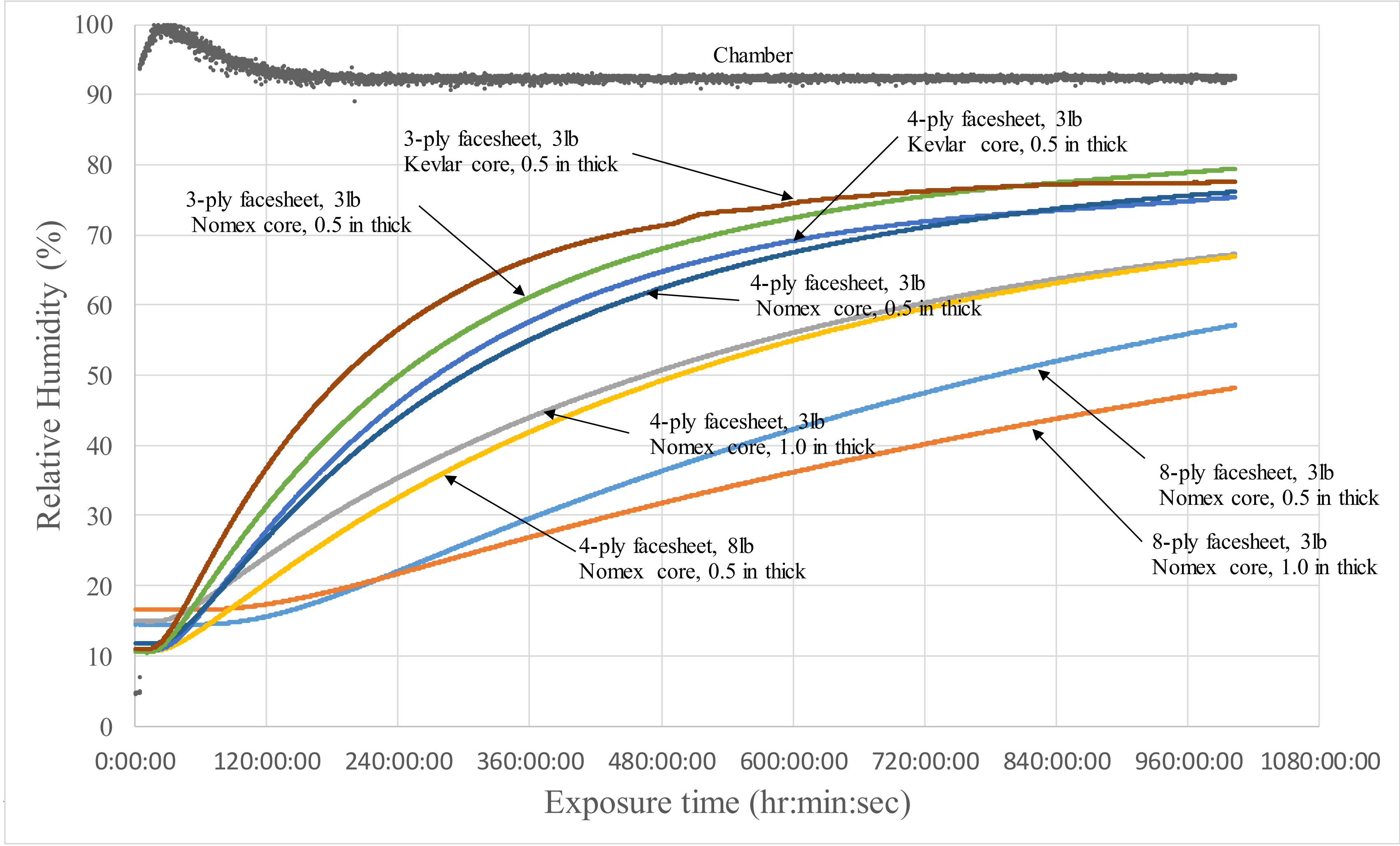
Effects of Moisture Diffusion in Sandwich Composites

- 48 tests of "as-produced" SCB specimens performed without mishap during June 2017
- Murphy's law re-discovered:
  - Remaining 48 SCB Specimens and 8 witness panels were placed in the humidity chamber on 29 June
  - Initial panel core humidity ~9%RH
  - Elevated environmental conditions imposed on 3 July: 65°C and 90%RH
  - Sometime over the weekend of 4-6 August (about 4 weeks later) the control system of the humidity chamber failed, flooding the SCB specimens and witness panels….
  - SCB specimens and witness panels were placed in a separate test oven with desiccant and "dried out" for ~ 6 weeks while the humidity chamber was repaired (humidity levels within witness panels reduced to 10-15% RH)
  - Exposure to 65°C and 90%RH re-started on 21 September

Effects of Moisture Diffusion in Sandwich Composites



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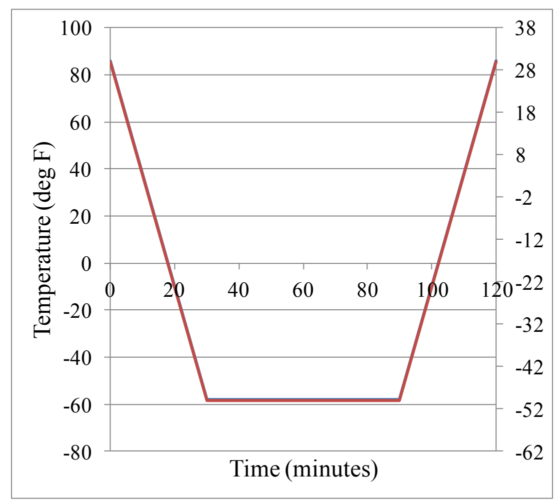
- 3-ply laminates approaching 80%RH; thermal cycling will begin soon.
- Thermal cycling of 4- and 8-ply laminates will begin when core humidity ~80%RH
- SCB tests of environmentally-conditioned specimens performed after ~100 thermal cycles



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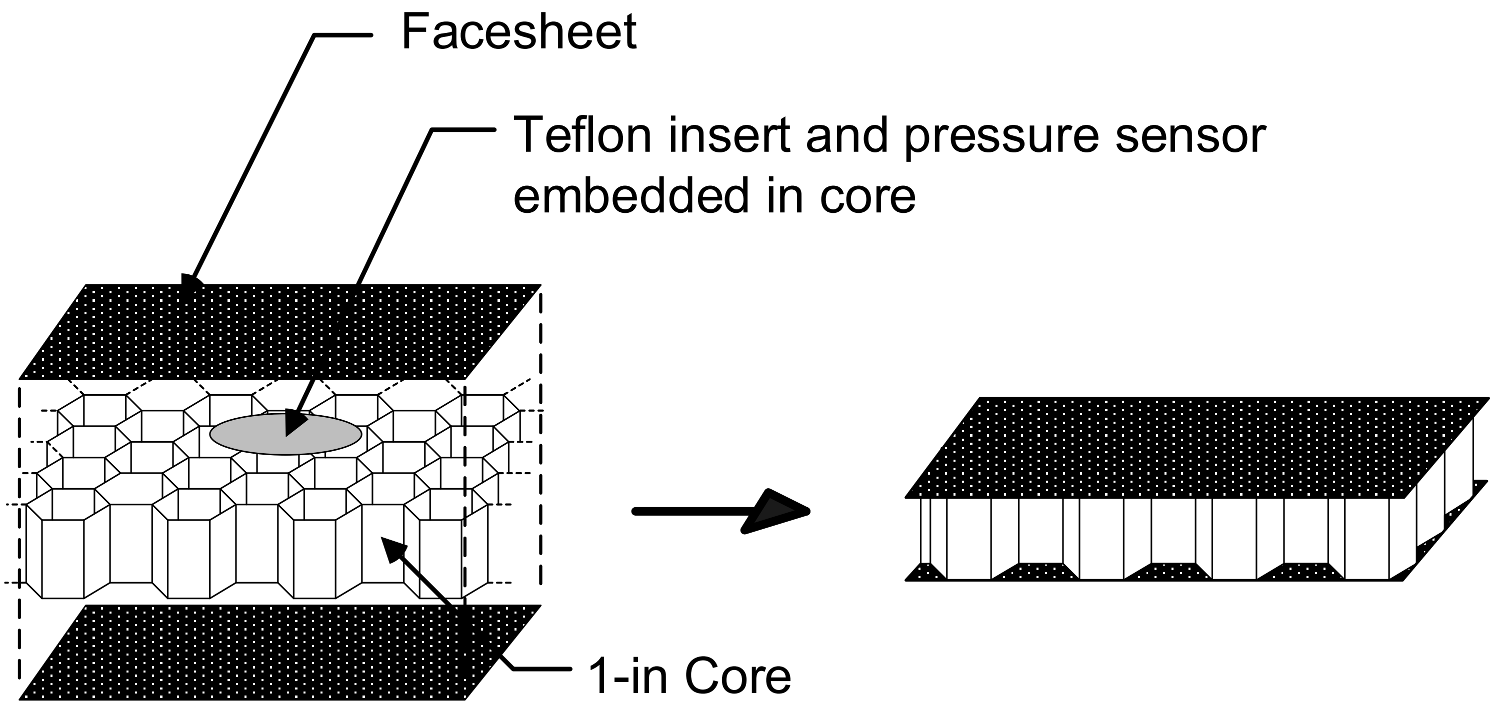
Design and Fabrication of GAG Specimen and Test Setup

GAG Specimen:



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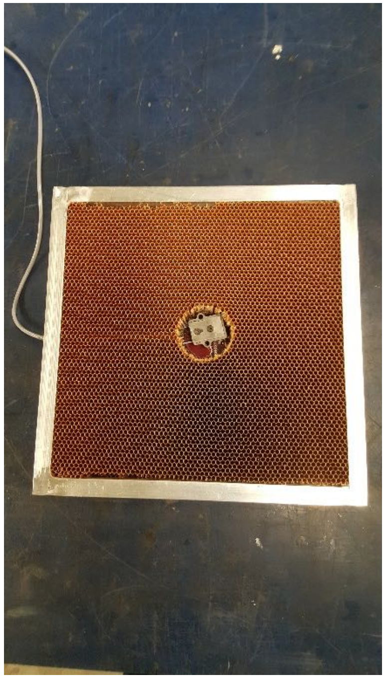

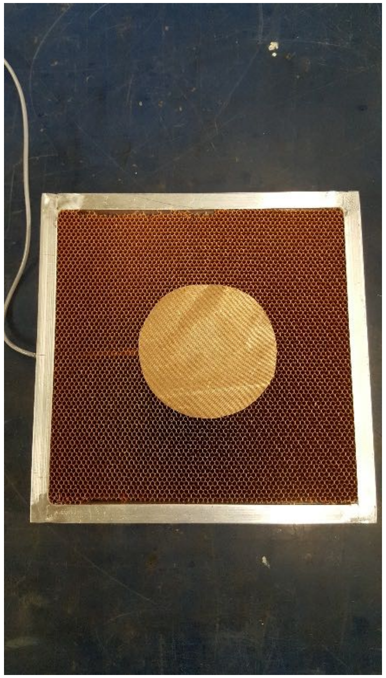

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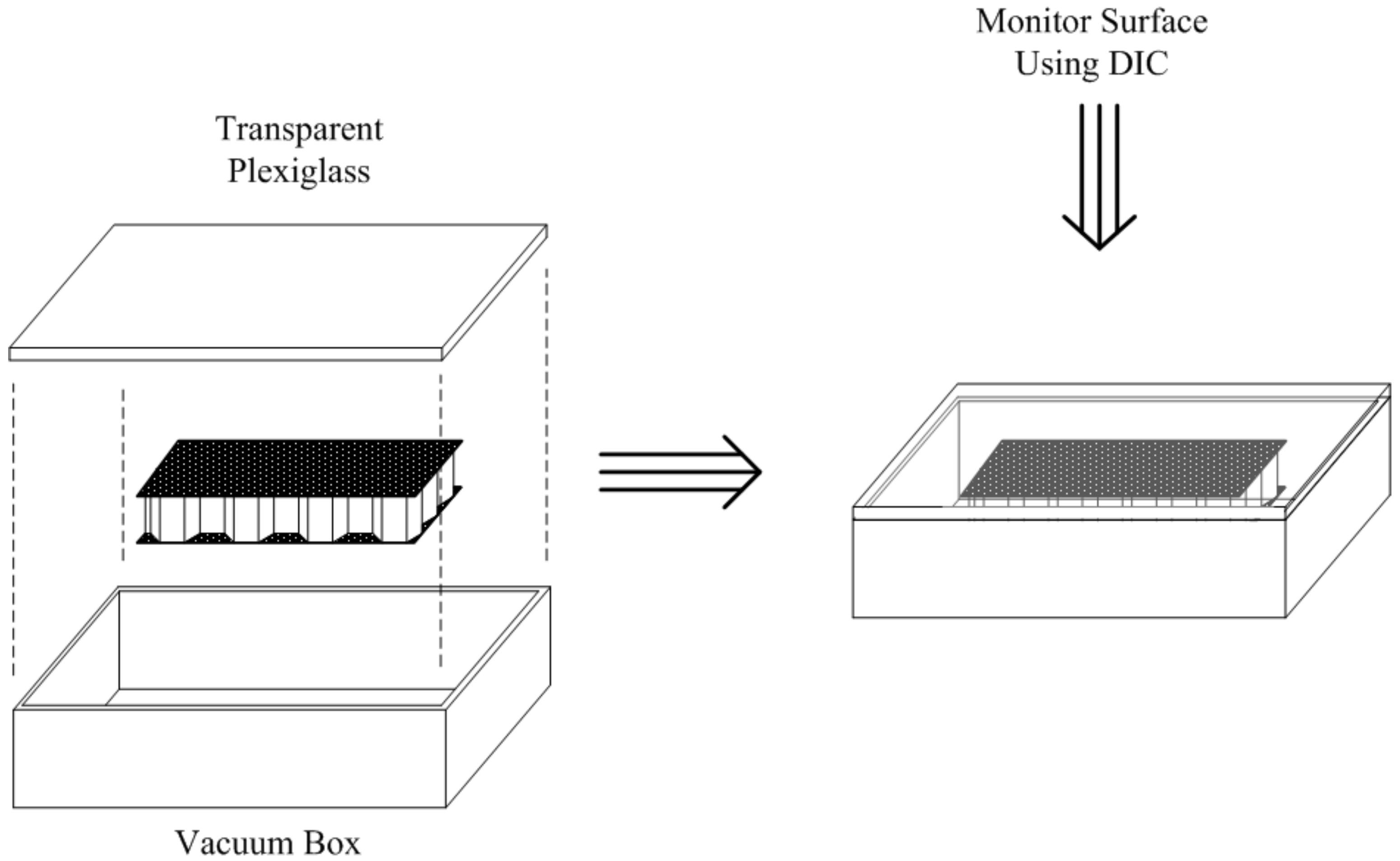

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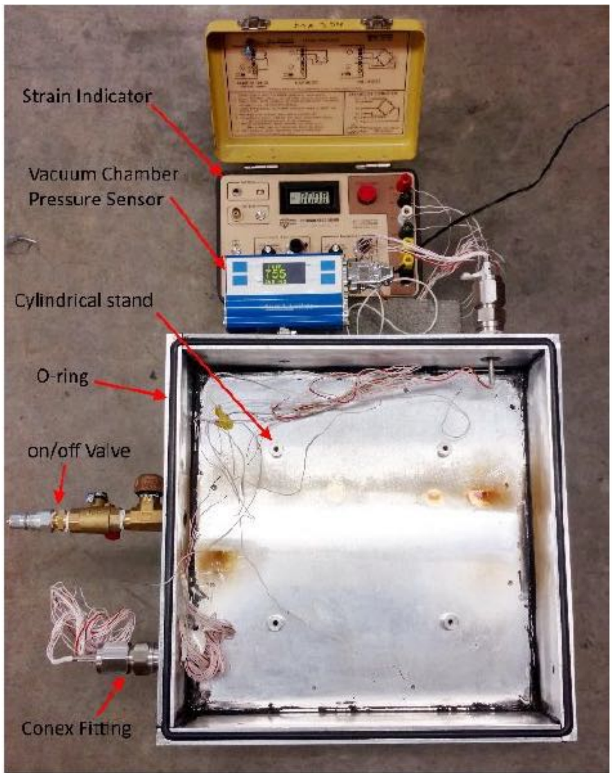

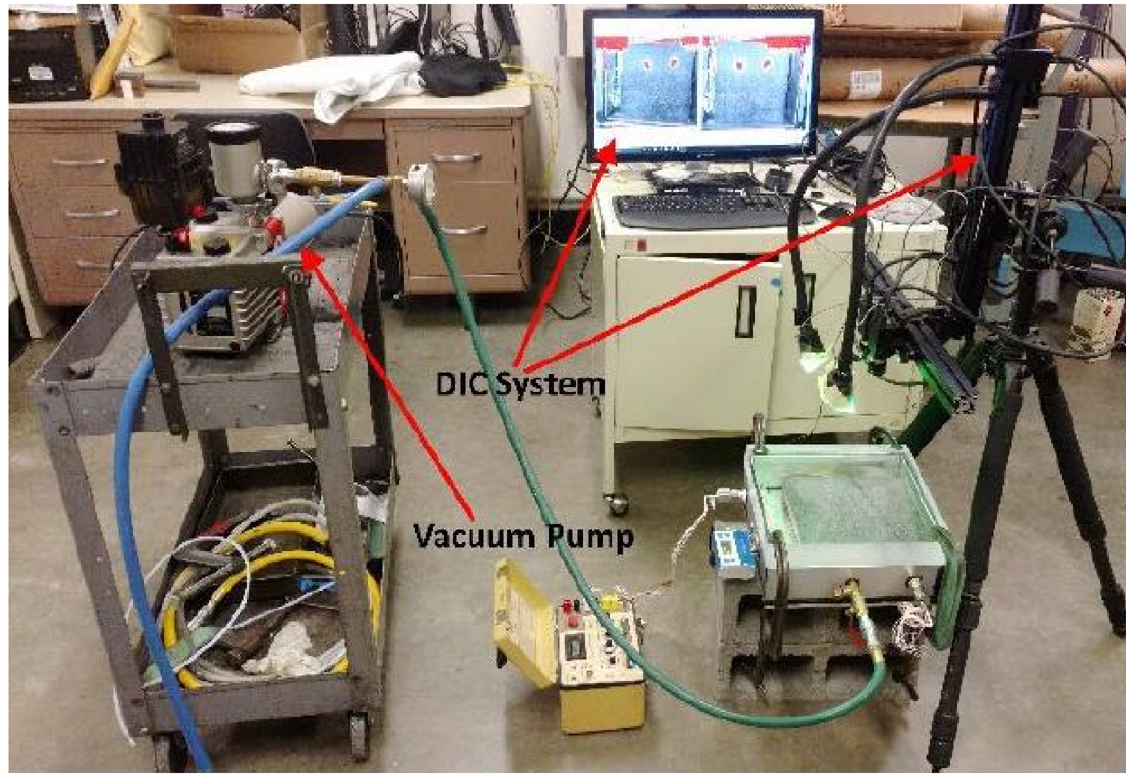

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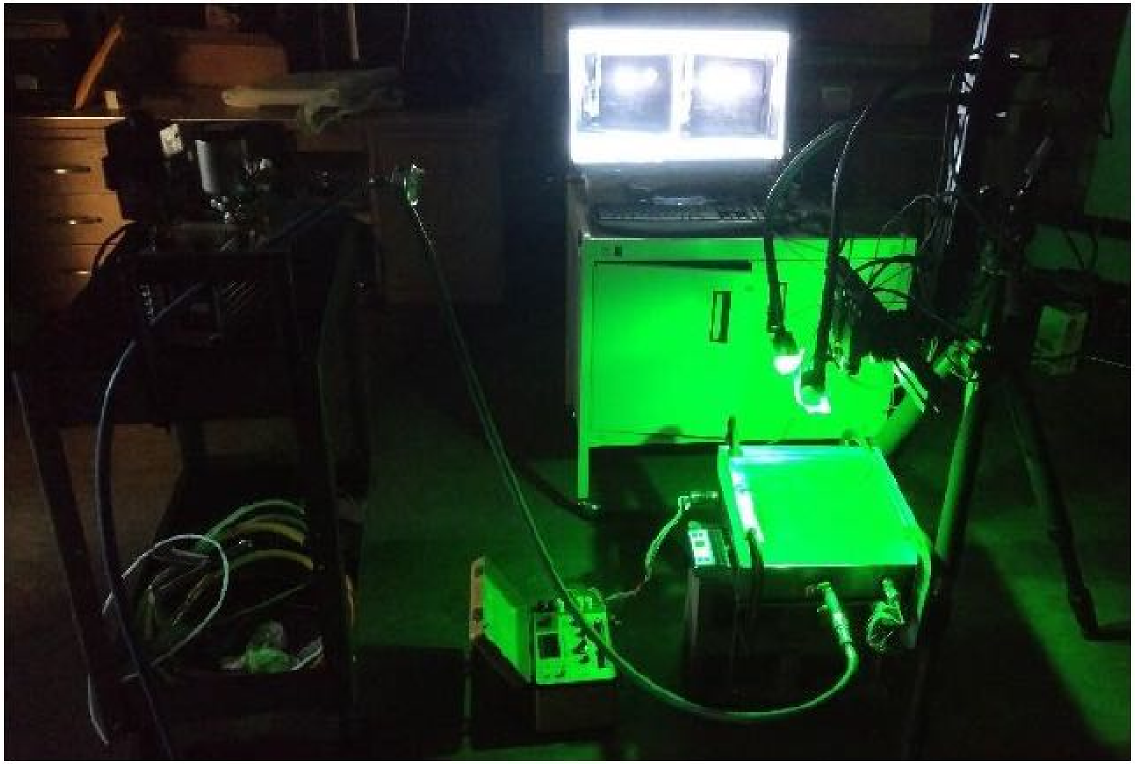

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Design and Fabrication of GAG Specimen and Test Setup

$[0/45/0]_T$ w/1.0 Nomex core

External pressure = 14.7 psi
Core pressure = 14.8 psi

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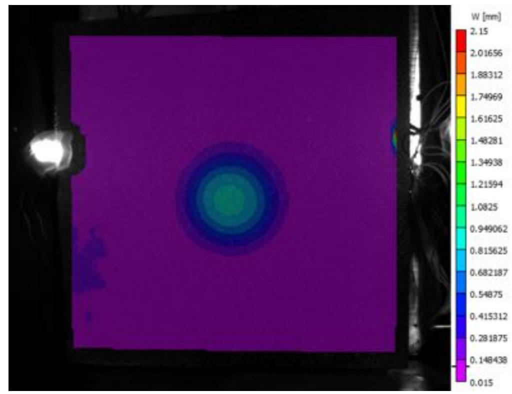

External pressure = 12.4 psi
Core pressure = 14.3 psi

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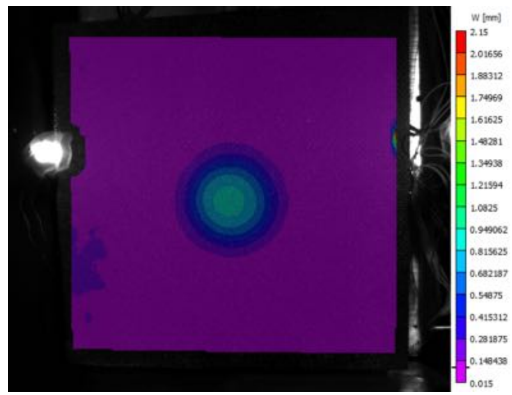
$[0/45/0]_T$ w/1.0 Nomex core

External pressure = 14.7 psi
Core pressure = 14.8 psi



External pressure = 12.4 psi
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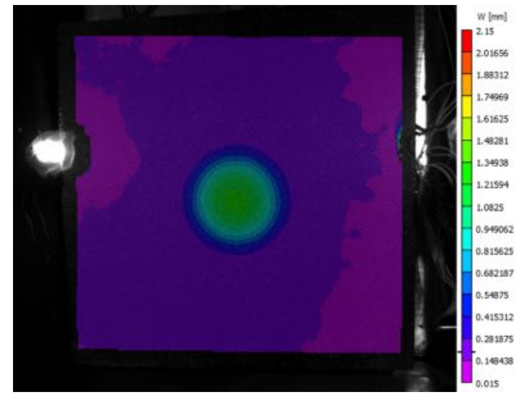

External pressure = 9.6 psi
Core pressure = 13.4 psi

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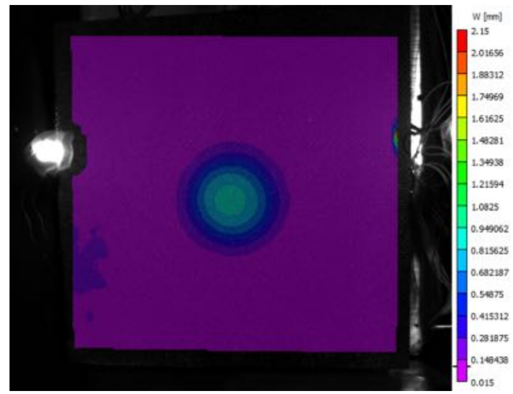
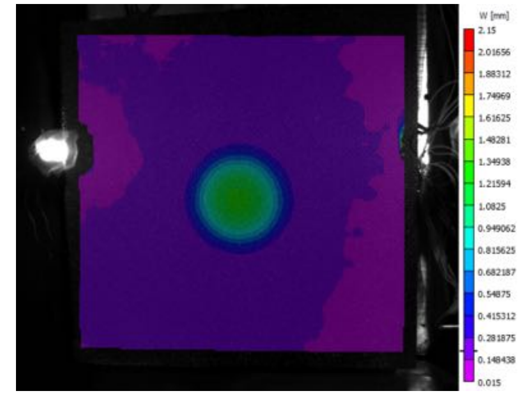
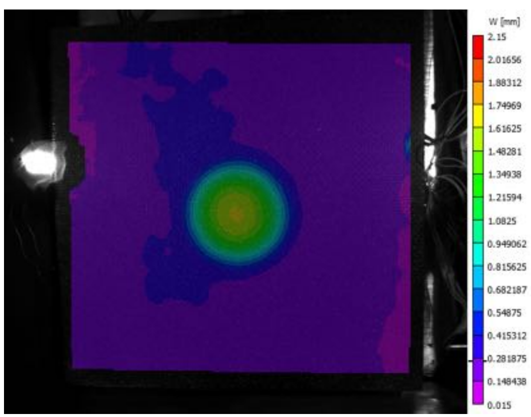
Core pressure = 14.8 psi



External pressure = 12.4 psi
Core pressure = 14.3 psi



External pressure = 9.6 psi
Core pressure = 13.4 psi



External pressure = 6.7 psi
Core pressure = 12.2 psi

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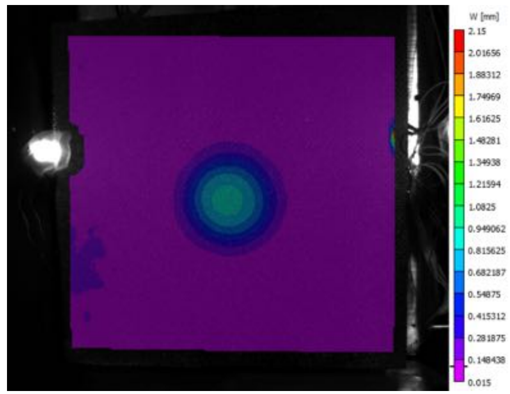
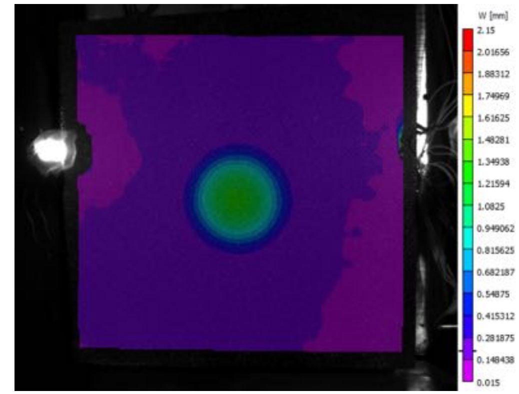
Design and Fabrication of GAG Specimen and Test Setup

$[0/45/0]_T$ w/1.0 Nomex core

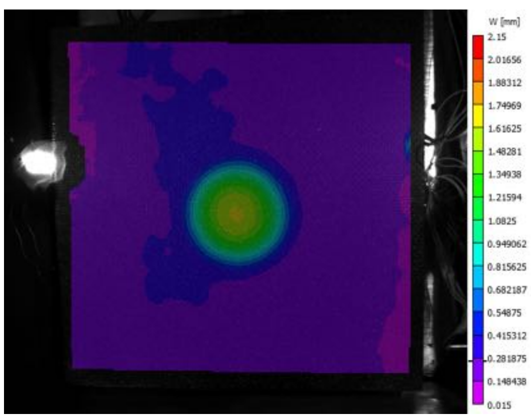
External pressure = 14.7 psi
Core pressure = 14.8 psi



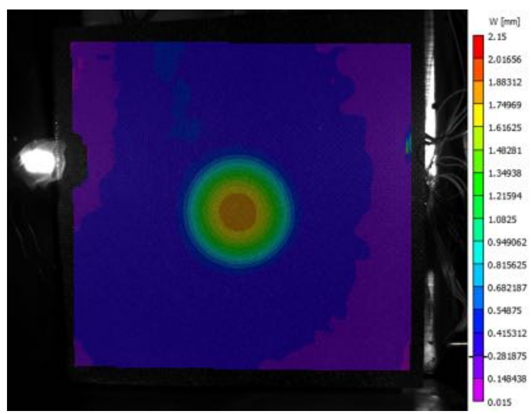
External pressure = 12.4 psi
Core pressure = 14.3 psi



External pressure = 9.6 psi
Core pressure = 13.4 psi



External pressure = 6.7 psi
Core pressure = 12.2 psi



External pressure = 2.9 psi
Core pressure = 9.7 psi

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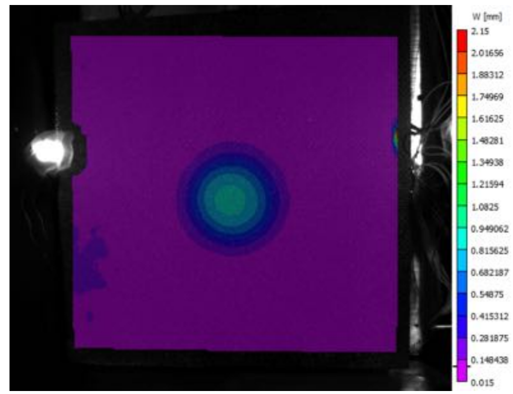
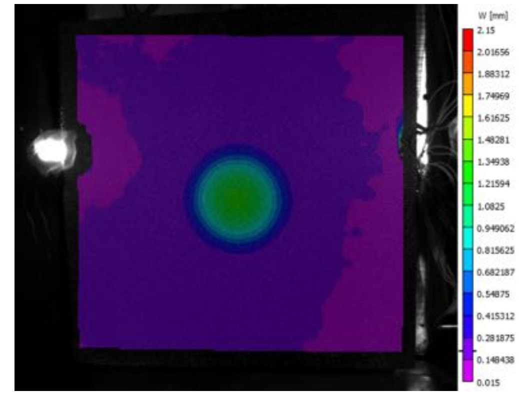
Design and Fabrication of GAG Specimen and Test Setup

$[0/45/0]_T$ w/1.0 Nomex core

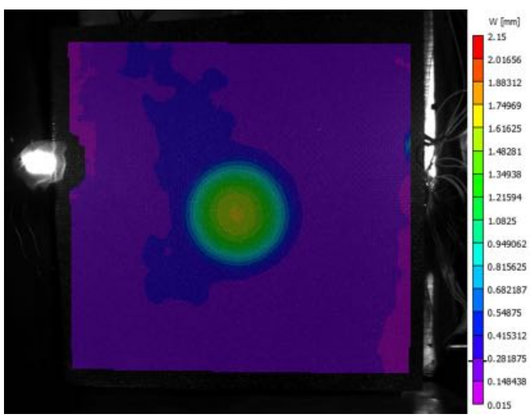
External pressure = 14.7 psi
Core pressure = 14.8 psi



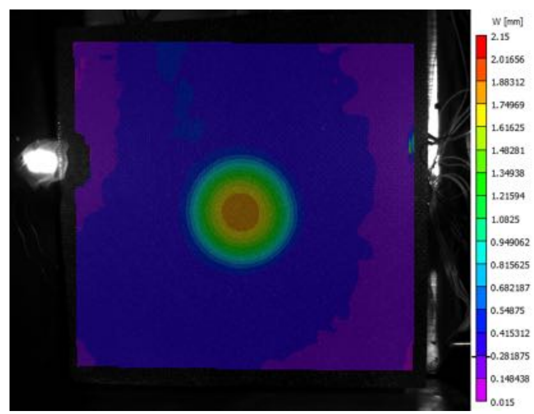
External pressure = 12.4 psi
Core pressure = 14.3 psi



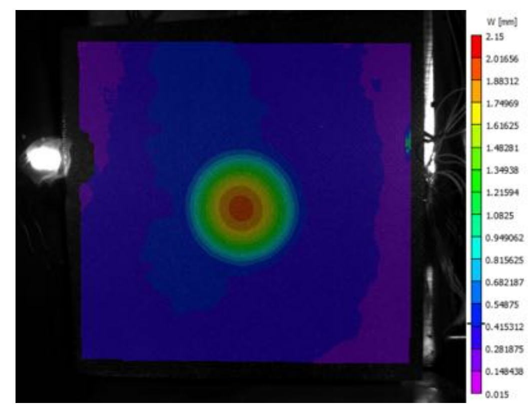
External pressure = 9.6 psi
Core pressure = 13.4 psi



External pressure = 6.7 psi
Core pressure = 12.2 psi



External pressure = 2.9 psi
Core pressure = 9.7 psi



External pressure = 0.96 psi
Core pressure = 8.2 psi

Effects of Moisture Diffusion in Sandwich Composites

Summary

- This study has two overall objectives:
  - Determine if the condense-freeze-thaw-evaporate cycle of core humidity impacts the interfacial fracture toughness, G_c, of sandwich structures
  - Develop experimental techniques to study/evaluate the GAG phenomenon, and the impact of condense-freeze-thaw-evaporate cycle

- Substantial progress has been made:
  - 48 SCB tests of as-produced specimens completed
  - Testing of 48 environmentally-conditioned specimens will be completed by ~ 1 January
  - GAG tests ongoing

Thank You!

Questions, Comments, Suggestions?