# Effects of Moisture Diffusion in Sandwich Composite Structures

2018 Technical Review

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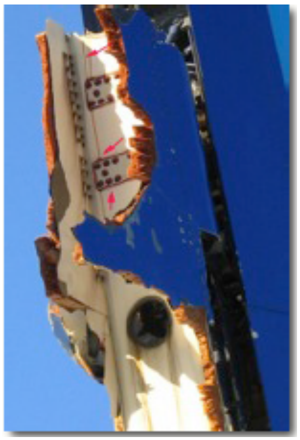
# Effects of Moisture Diffusion in Sandwich Composite Structures

Motivation and Key Issues:

In-service bond failures between composite facesheets and honeycomb cores have been reported (photos courtesy of Ronald Krueger, National Institute of Aerospace)

Boeing 747 upper skin disbonds


Airbus A-310 Rudder Failure



# Effects of Moisture Diffusion in Sandwich Composite Structures

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

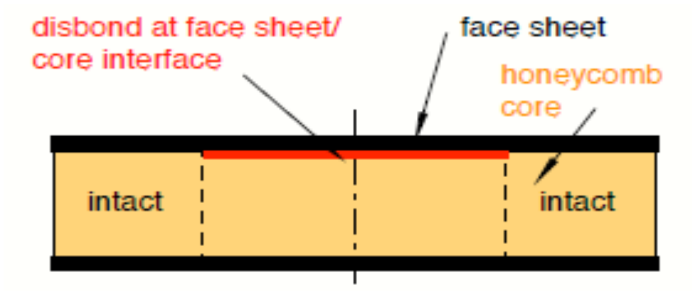
- Core-to-skin disbond initiation and growth are thought to occur due to combination of factors:
  - Water ingression into core volume, followed by freeze-thaw cycles….water ingression may occur due to:
    - Wicking of liquidous water through facesheet microcracks, along fiber/matrix interfaces, and/or 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)

# Effects of Moisture Diffusion in Sandwich Composite Structures

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

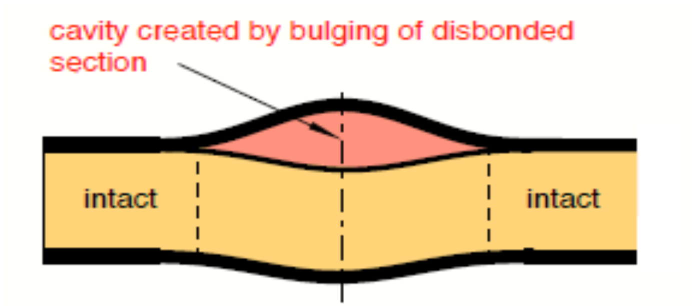
Configuration at ground level

$P_o$ = 100 kPa = 14.7 psi




Configuration at 35,000 ft

$P_o$ = 24 kPa = 3.5 psi

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To determine if long-term exposure to humid air (causing moisture build-up in the core volume due to diffusion) coupled with thermal cycles encountered by transport aircraft is detrimental to the mechanical properties of composite sandwich structures.

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<u>Technical Approach</u>:

- The critical strain energy release rate associated with sandwich facesheet/core debonding ($G_c$) was measured before & after environmental exposure, to evaluate whether environment humidity & freeze-thaw cycles have an effect.

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- Environmental conditioning consisted of:
    - Constant exposure to 65°C and 90%RH until humidity within the core volume reached ~70%RH (required ~0.7, 2, and 4 months for 3- 4- and 8-ply facesheets, respectively)
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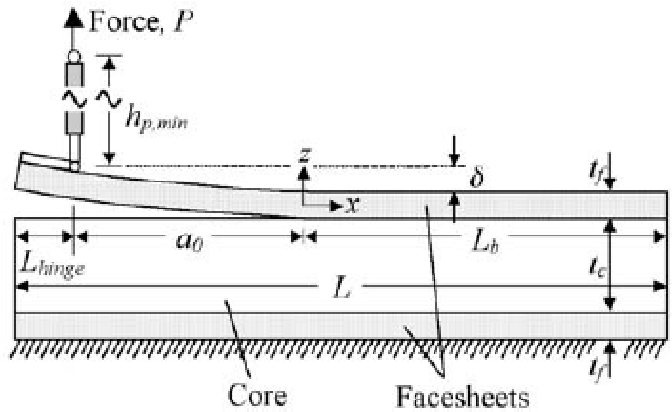
- (Added in 2017): Develop an experimental setup to simulate ground-air-ground (GAG) pressure cycles and study delamination growth in both as-produced and env conditioned panels

# The Single-Cantilever Beam (SCB) Test Geometry*




Summary of test procedure:

(a) Sawcut used to produce starter crack
(b) Crack propagated in the ribbon (L) direction of honeycomb core
(c) Crack tip location monitored using two optical microscopes
(d) Initial natural crack created by causing the crosshead to move upward at a rate of 0.5 mm/min, until a ~5 mm crack had formed; the specimen was then unloaded
(e) The crosshead was then moved upward at a rate of 30 mm/min until the crack has grown by ~10 mm; the specimen was then unloaded at 30 mm/min ("Load Cycle 1")
(f) Step (f) was repeated once ("Load Cycle 2")
(g) The critical strain energy release rate $G_c$ was determined using the "area method", based on load-displacement curves measured during Load Cycles 1 and 2

* Sketch extracted from: Ratcliffe, J.G., and Reeder, J.R., "Sizing a Single Cantilever Beam Specimen for Characterizing Facesheet-Core Debonding in Sandwich Structure", *Jrnl Composite Materials*, Vol 45 (25), pp 2669-2684, (2011).

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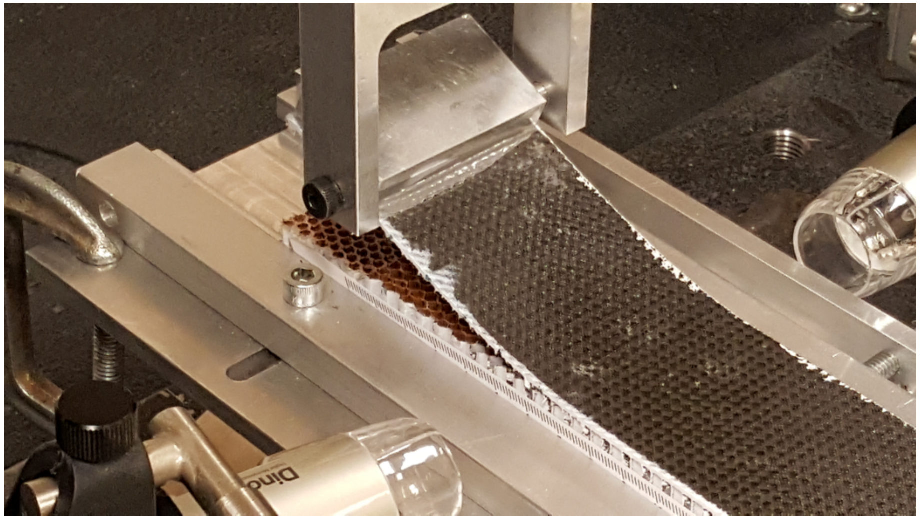

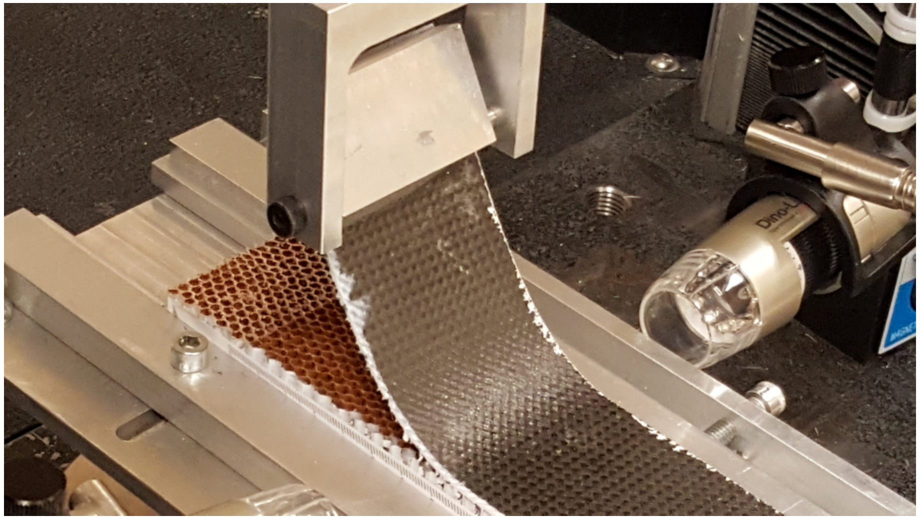


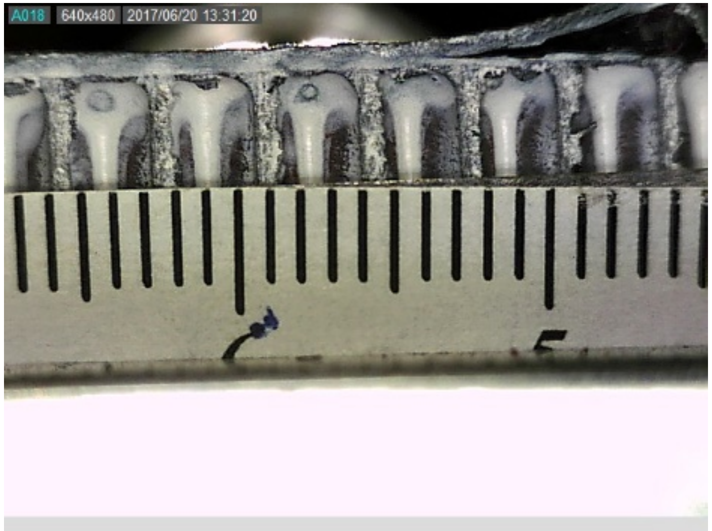


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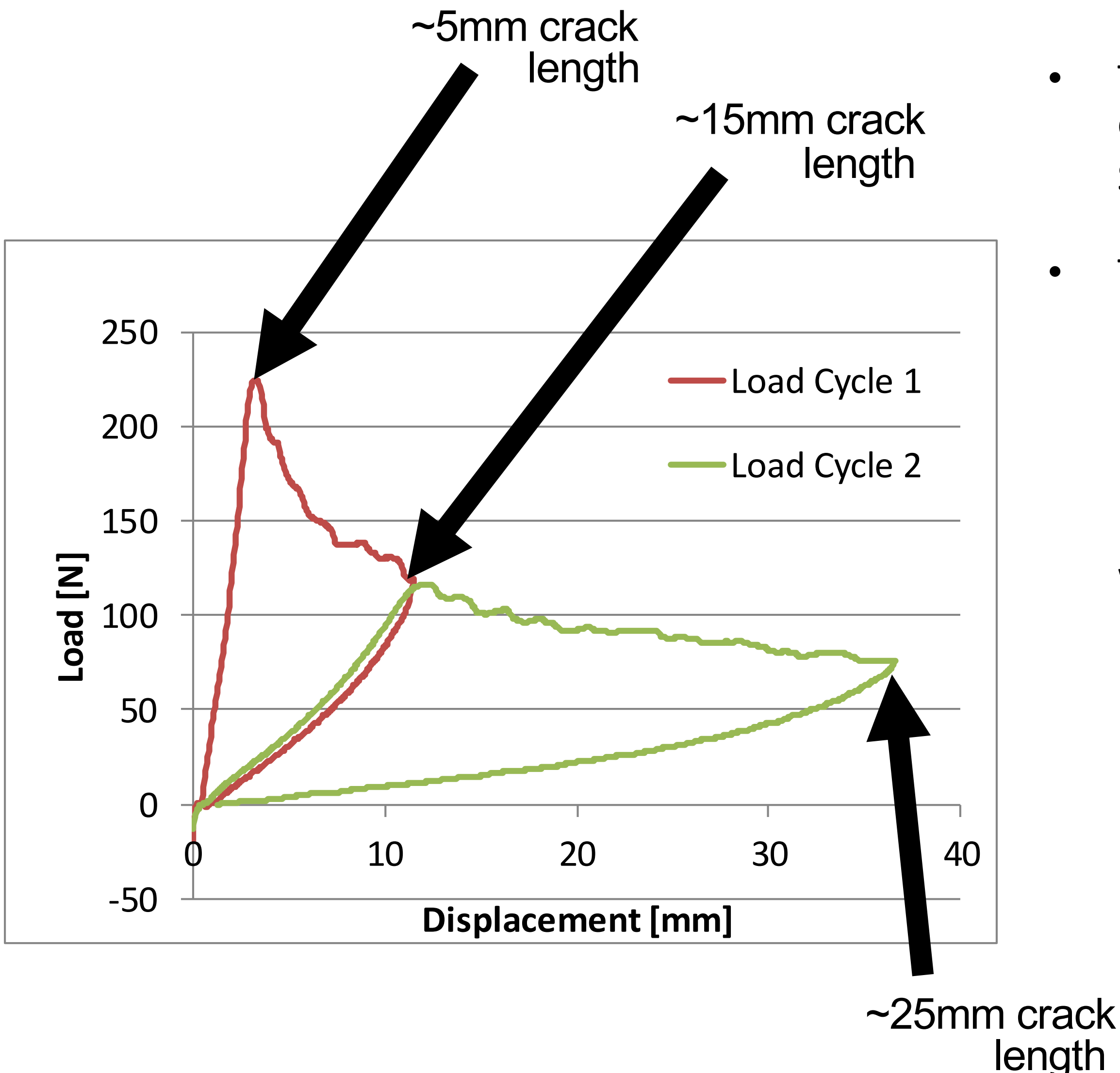
# Typical Single-Cantilever Beam (SCB) Test Data




- Typical load-displacement curves measured during a SCB test
- The critical strain energy release rate was calculated using the so-called area method:

$$G_c = \frac{\Delta U}{B \Delta a}$$

where:

$\Delta U$ = area defined by the load-displacement envelope

$B$ = specimen width

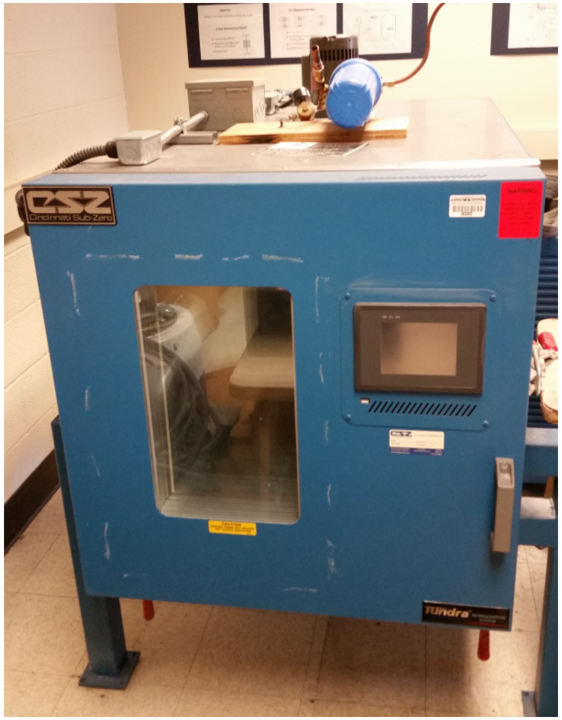
$\Delta a$ = crack extension

# The Single-Cantilever Beam (SCB) Test Specimens

| Component | Description | Product Designation |
|---|---|---|
| Facesheet panels | Carbon/Epoxy plane weave prepreg: | Cytec (Solvay) T300/970 3k PW |
| | Three-ply: $[0/45/0]_T$ | |
| | Four ply: $[0/90]_s$ | |
| | Eight ply: $[0/45/90/45]_s$ | |
| Core Materials | Nomex 48 kg/m$^3$ honeycomb core, 12.7 mm thick (3 lb/ft$^3$; 0.5 in) | Hexcel HRH-10-1/8-3 |
| | Nomex 48 kg/m$^3$ honeycomb core, 25.4 mm thick (3 lb/ft$^3$; 1.0 in) | Hexcel HRH-10-1/8-3 |
| | Nomex 128 kg/m$^3$ honeycomb core, 12.7 mm thick (8 lb/ft$^3$; 0.5 in) | Hexcel HRH-10-1/8-8 |
| | Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick (3 lb/ft$^3$, 0.5 in) | Hexcel HRH-36-1/8-3 |
| Adhesive | Thin film adhesive | 3M Scotch-Weld AF 163-2k |

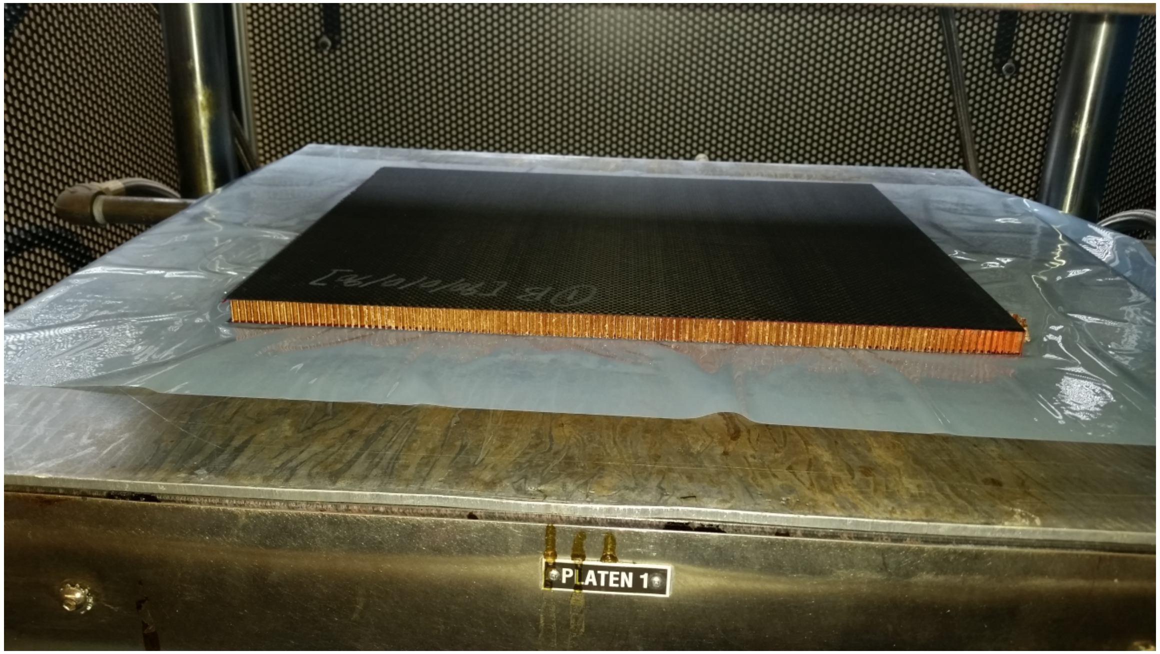
# Producing Sandwich Test Panels

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



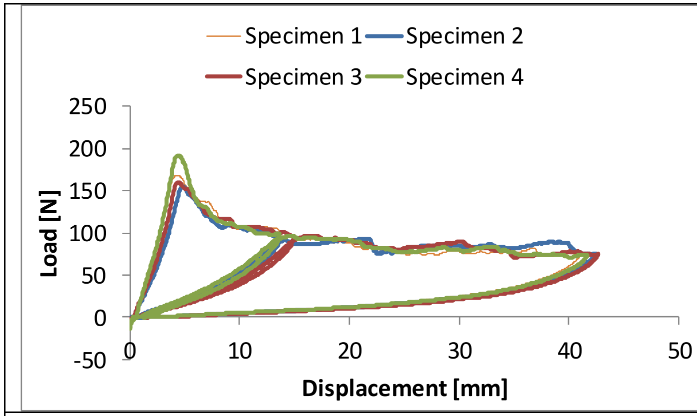

# Producing Sandwich Test Panels

Parent panels were then produced by bonding the facesheets to honeycomb cores using thin film adhesive and a hot press
SCB specimens were machined from the “parent” panels

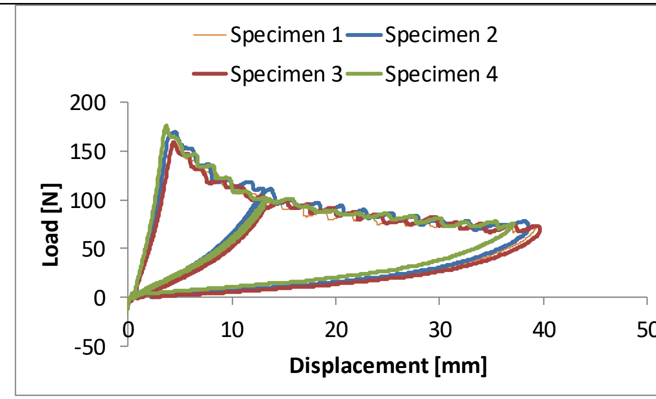


# Raw Data Collected for As-Produced $[0/90/0]_T$ Specimens

*(Superimposed data from four individual tests for each type)*

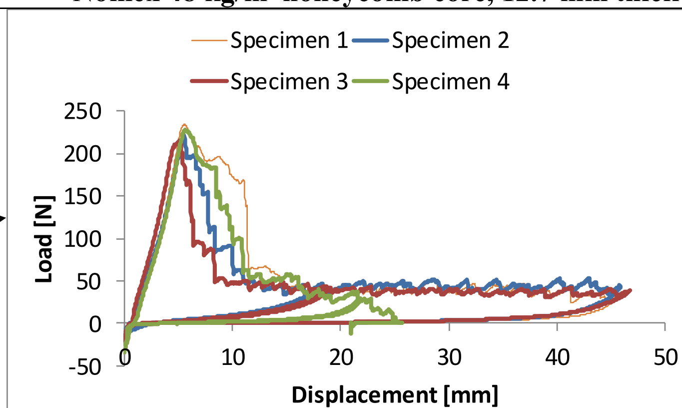



**(a) Measurements for as-produced specimens with Nomex 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

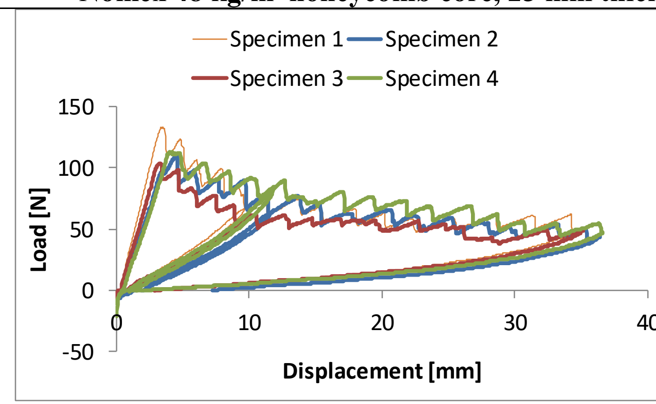



**(b) Measurements for as-produced specimens with Nomex 48 kg/m$^3$ honeycomb core, 25 mm thick**

- Facesheet delamination & tearing during load loop 2




**(c) Measurements for as-produced specimens with Nomex 128 kg/m$^3$ honeycomb core, 12.7 mm thick**




**(d) Measurements for as-produced specimens with Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

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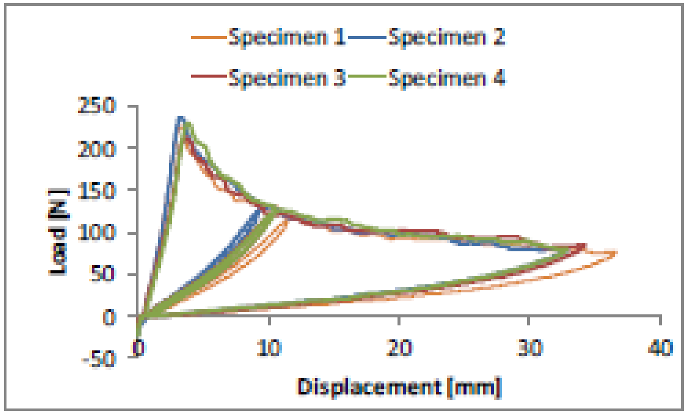


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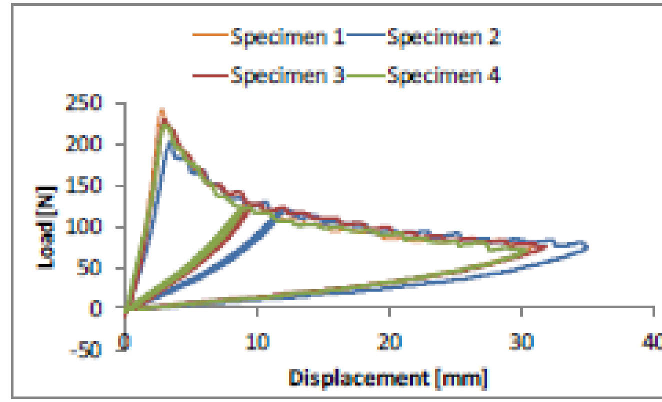
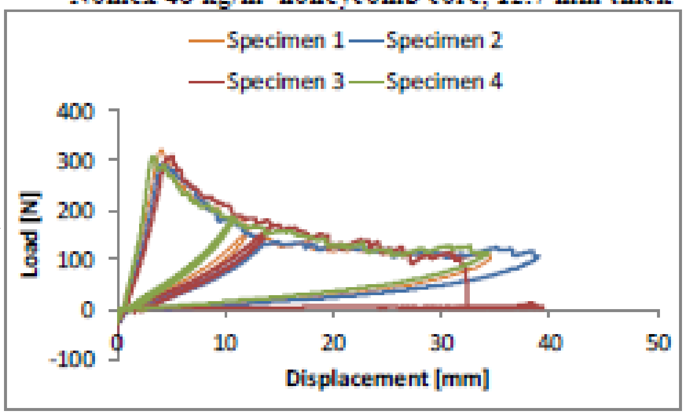



(b) Measurements for as-produced specimens with Nomex 48 kg/m$^3$ honeycomb core, 25 mm thick

- Facesheet bending failure during load loop 2, specimen 3

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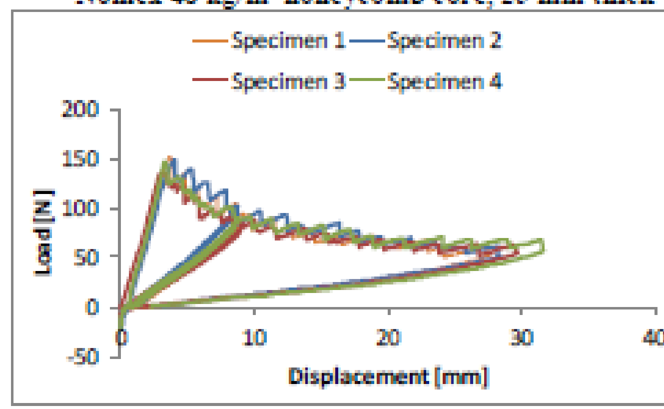


(d) Measurements for as-produced specimens with Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick

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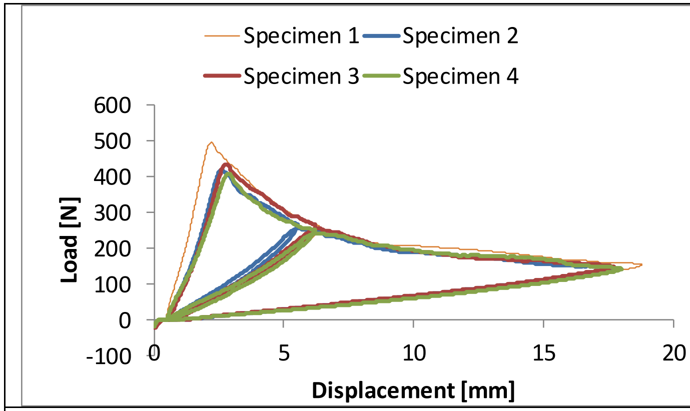
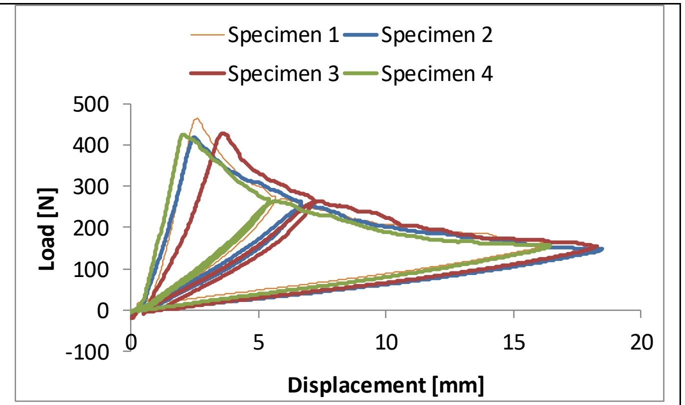
*(Superimposed data from four individual tests for each type)*




**(a) Measurements for 8-ply as-produced specs with Nomex 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

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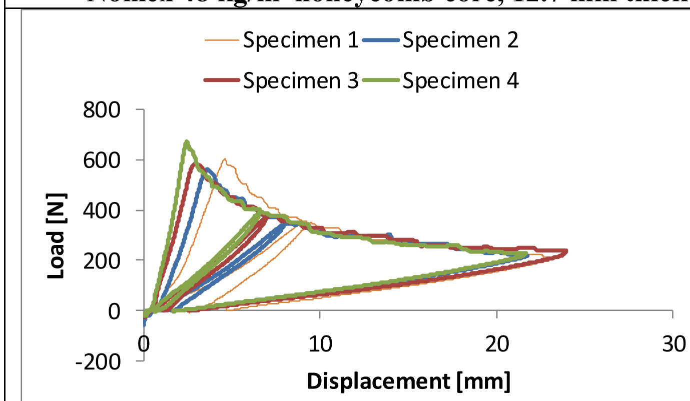


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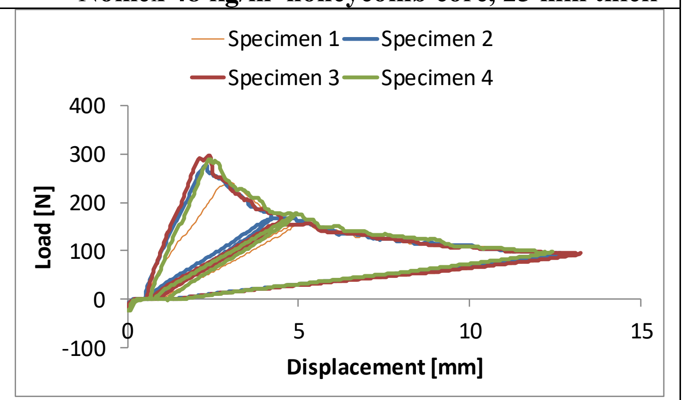
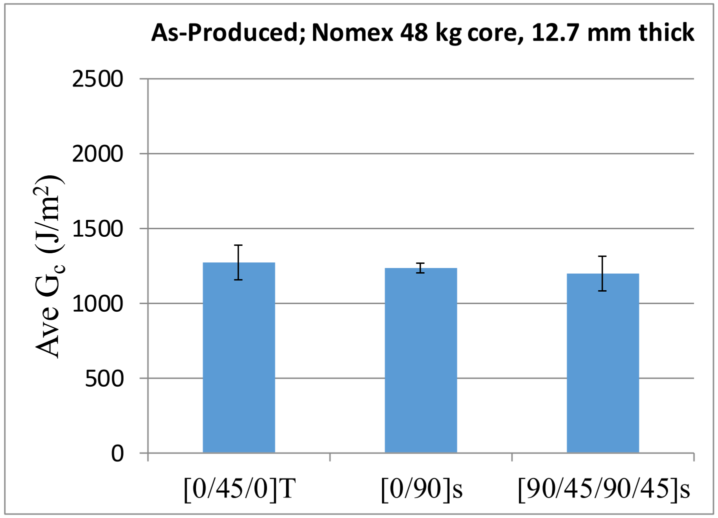
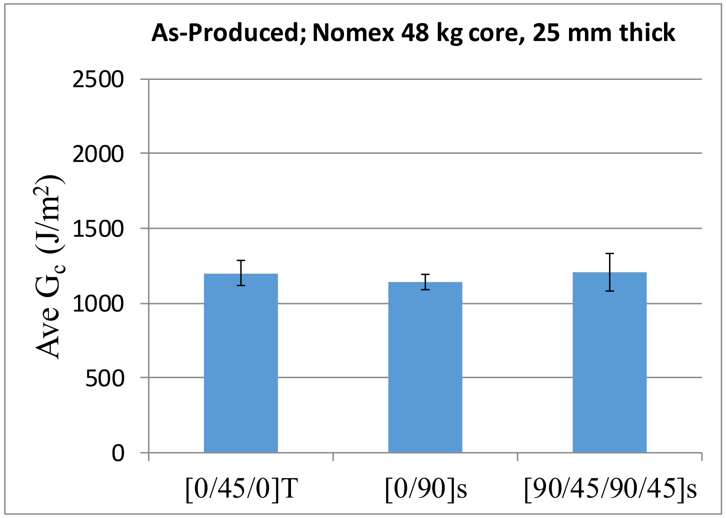


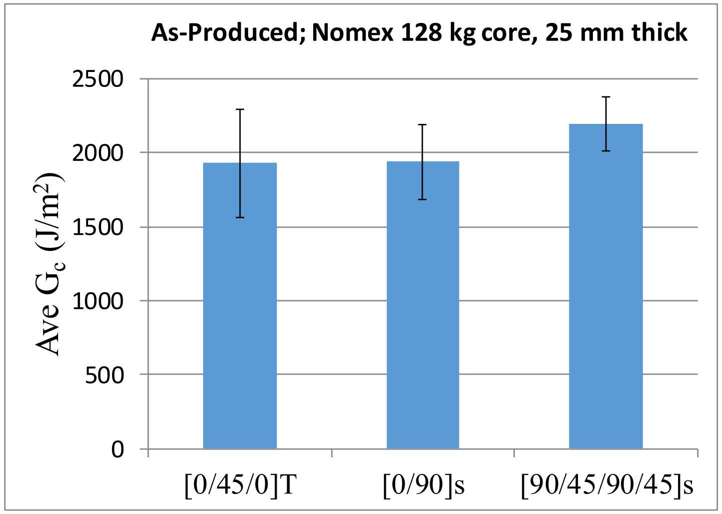

**(d) Measurements for 8-ply as-produced specs with Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

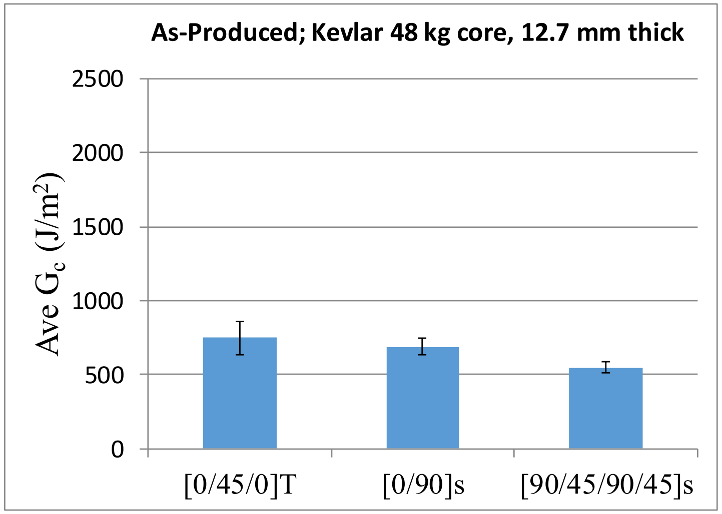
# $G_c$ Measured for As-Produced Specimens

*Average and std deviation, based on 4 replicate tests*



# Discussion

*As-produced specimens*

Measured trends:

If facesheet failure is avoided, then $G_c$ is nearly independent of core and facesheet thickness:

- For 48 kg/m$^3$ Nomex core: average $G_c$ (24 specimens) = 1208 ± 43.7 J/m$^2$
- For 128 kg/m$^3$ Nomex core: average $G_c$ (12 specimens) = 2021 ± 150 J/m$^2$

$G_c$ increases with an increase in core density:

- Average $G_c$ measured for 128 kg/m$^3$ Nomex core was 67% higher than that measured for 48 kg/m$^3$ Nomex core

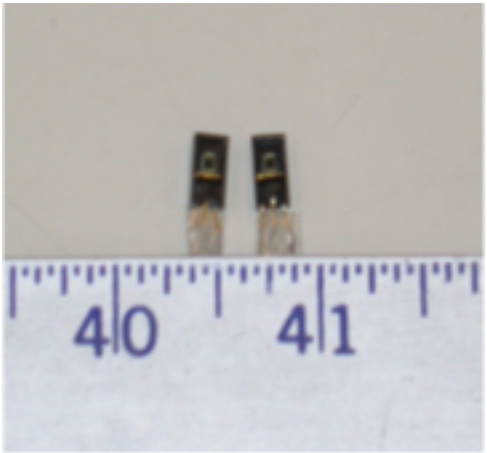
$G_c$ is significantly lower for Kevlar vs Nomex core:

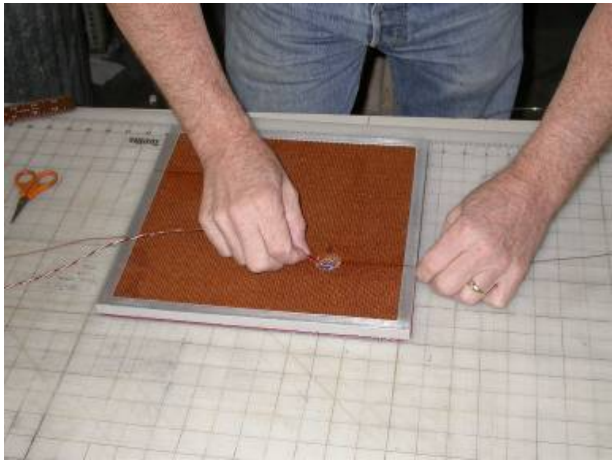
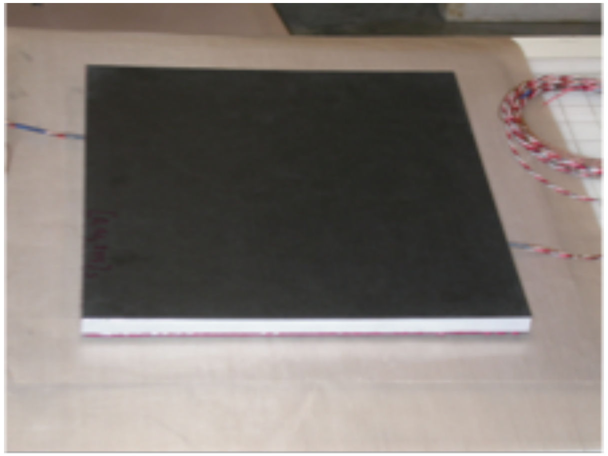
For 48 kg/m$^3$ cores the average $G_c$ measured for Nomex and Kevlar cores was 1208 J/m$^2$ and 661 J/m$^2$, respectively, a decrease of 45%

# Environmental Conditioning

*Producing “Witness” Test Panels*

- Witness panels were used to measure changes in core humidity levels due to diffusion of water molecules through the facesheets
- Ohmic Instr Model HC-610 humidity sensors (now marketed as Honeywell Model HIH-4010-003 sensors), were embedded within the core volume
- Outer aluminum frames were used in insure diffusion was 1-D
- Eight witness panels were produced using the various facesheet-core combinations considered



# Environmental Conditioning

*Exposure to elevated temperature and humidity*

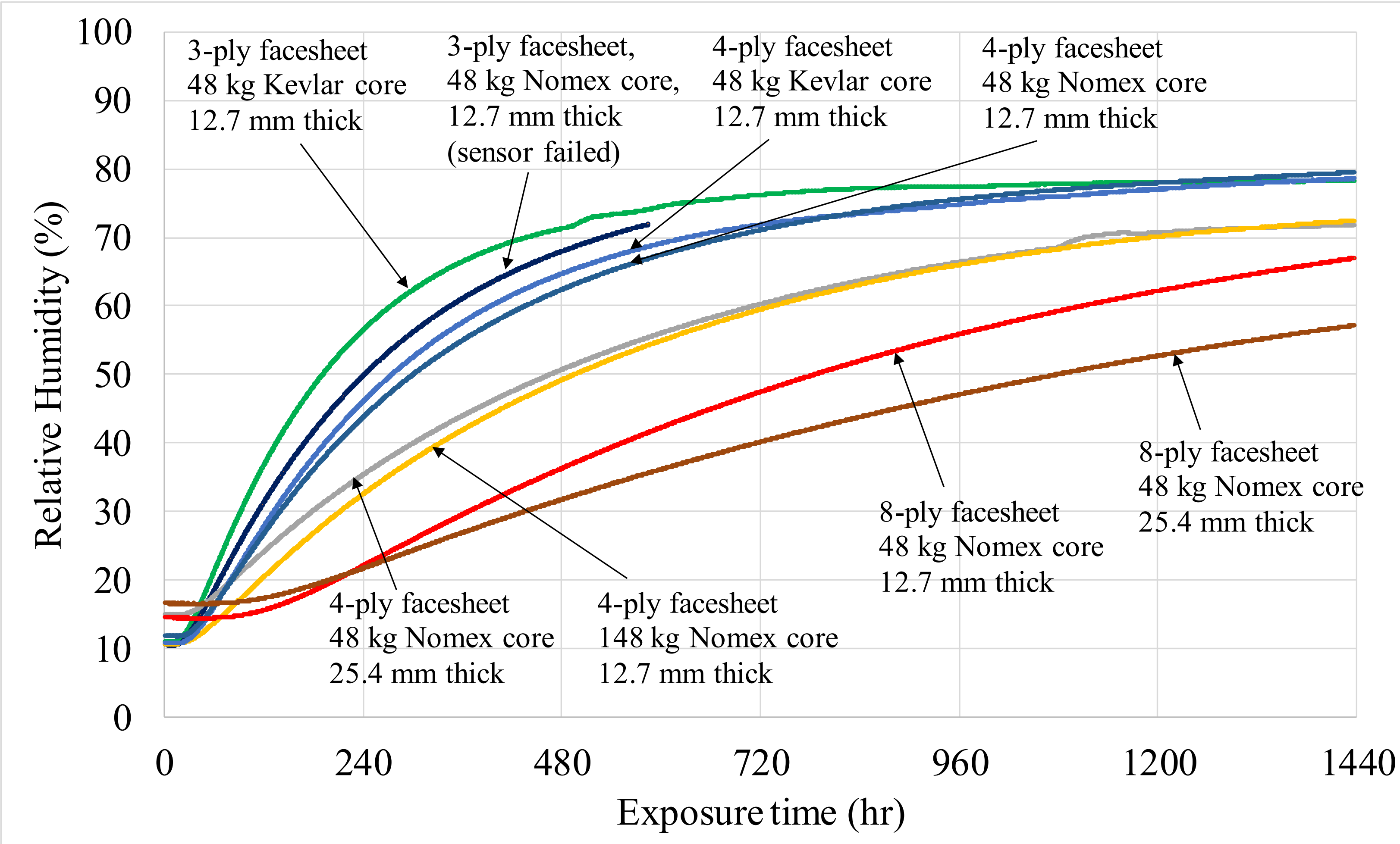
- A total of 48 SCB specimens, 8 witness panels*, and a separate “free standing” HC-610 humidity sensor were placed in a humidity chamber and exposed to 65°C (149 °F) and 90%RH until core humidity levels were about 70%RH

- Humidity levels within the cores of the witness panels and the corresponding SCB specimens was assumed to be identical

** the humidity sensor in one witness panel failed after about 550 hrs*

# Environmental Conditioning

*Measurements during first 1440 hrs of exposure to 65°C and 90% RH*



# Discussion

*Exposure to elevated humidity*

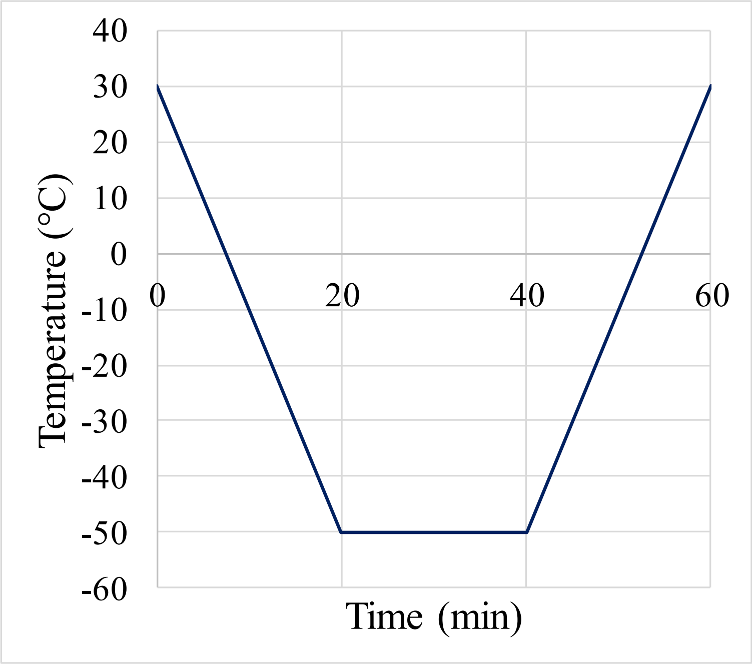
Measured results show that *rate* of core humidity level buildup is decreased with:

- an increase in facesheet thickness, and/or
- an increase in core thickness, and/or
- an increase in core density

# Environmental Conditioning

*Exposure to thermal cycles*

After witness panel core humidity reached ~70%RH the corresponding SCB specimens were sealed in metal-coated bags (to maintain internal core humidity), placed within a temperature chamber, and subjected to 150 one-hour temperature cycles from +30°C to -50°C…thermal cycling required 6.25 days.

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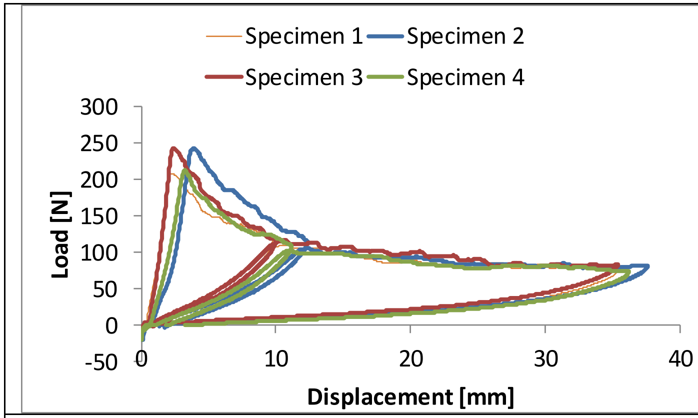
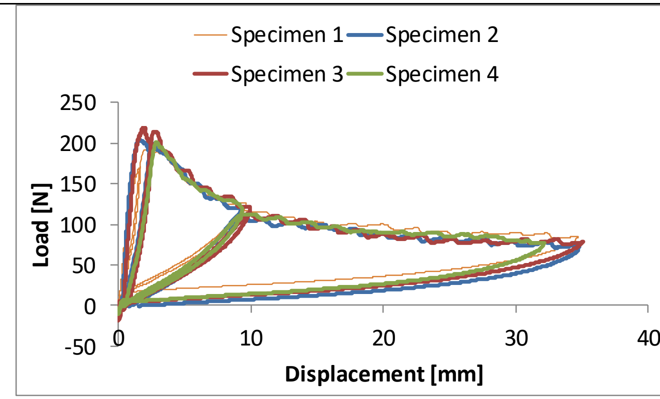
# Raw Data for Conditioned [0/90/0]$_T$ Specimens

*(Superimposed data from four individual tests for each type)*

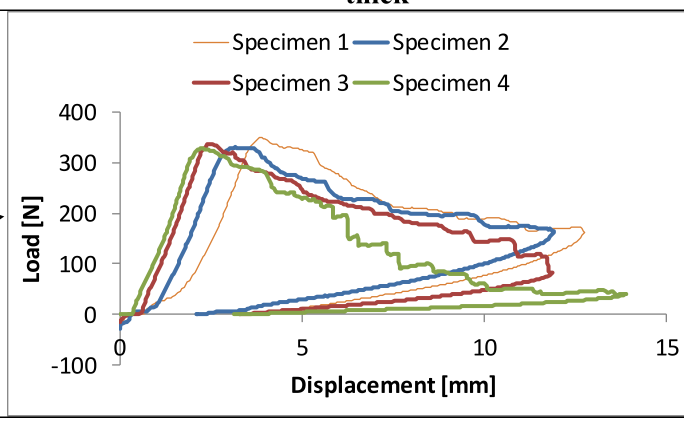



**(a) Measurements for env-conditioned specimens with Nomex 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

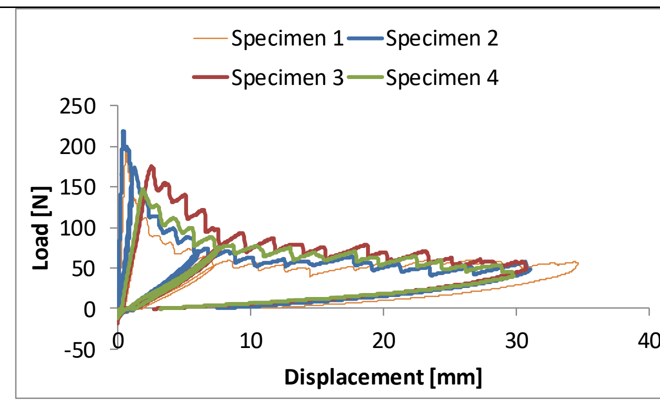



**(b) Measurements for env-conditioned specs with Nomex 48 kg/m$^3$ honeycomb core, 25 mm thick**

- Facesheet delamination & tearing during load loop 2




**(c) Measurements for env-conditioned specimens with Nomex 128 kg/m$^3$ honeycomb core, 12.7 mm thick**

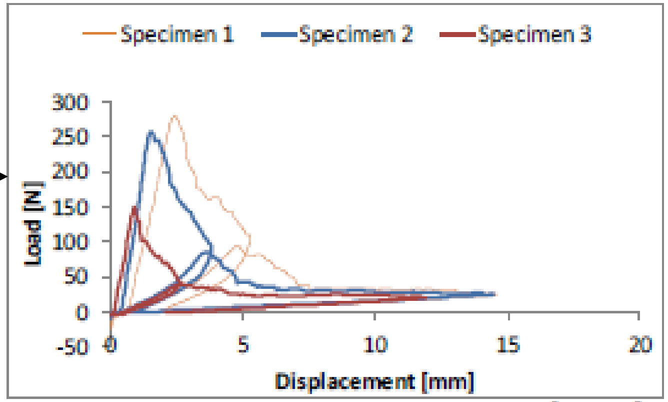



**(d) Measurements for env-conditioned specs with Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

# Raw Data for Conditioned [0/90]$_s$ Specimens

*(Superimposed data from 3 or 4 individual tests for each type)*

Operator error during test of specimen 4

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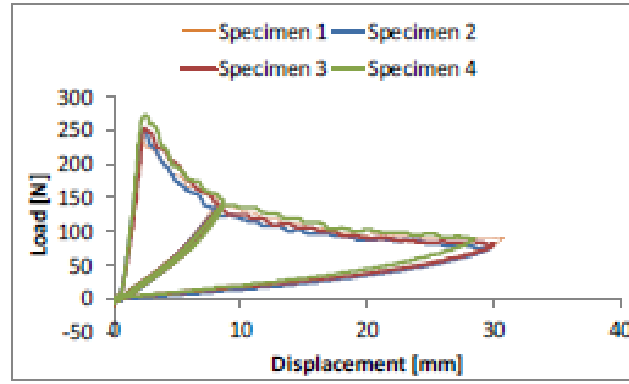
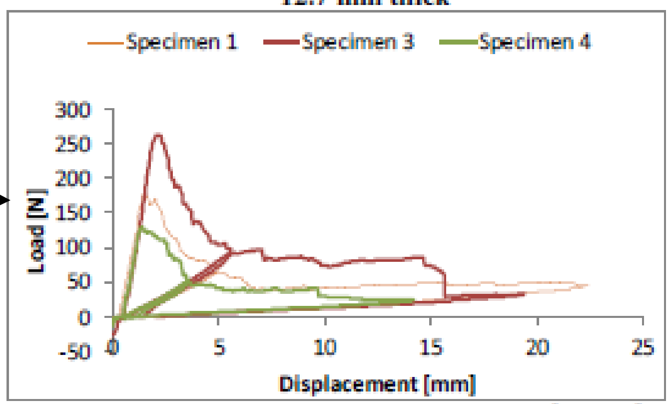
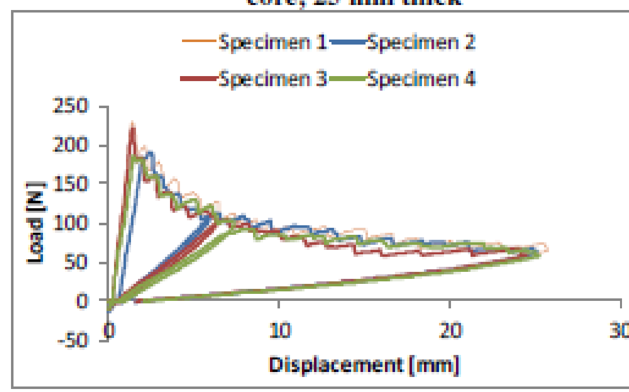



(b) Measurements for environmentally-conditioned specimens with Nomex 48 kg/m³ honeycomb core, 25 mm thick

- Equipment malfunction during test of specimen 2
- Facesheet failure during load loop 2, specimen 3




(c) Measurements for environmentally-conditioned specimens with Nomex 128 kg/m³ honeycomb core, 12.7 mm thick




(d) Measurements for environmentally-conditioned specimens with Kevlar 48 kg/m³ honeycomb core, 12.7 mm thick

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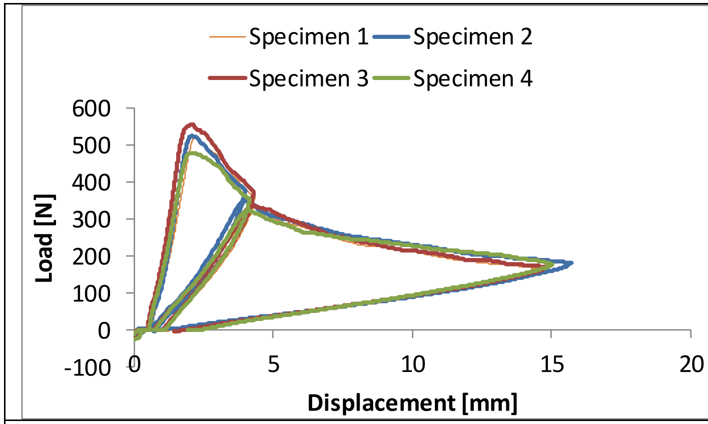
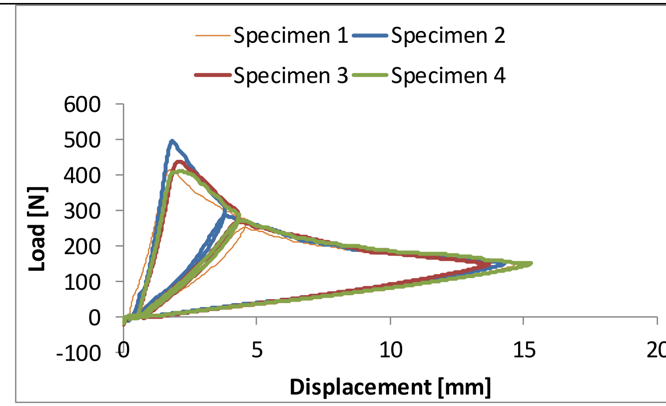
# Raw Data for Conditioned [0/45/90/45]s Specimens

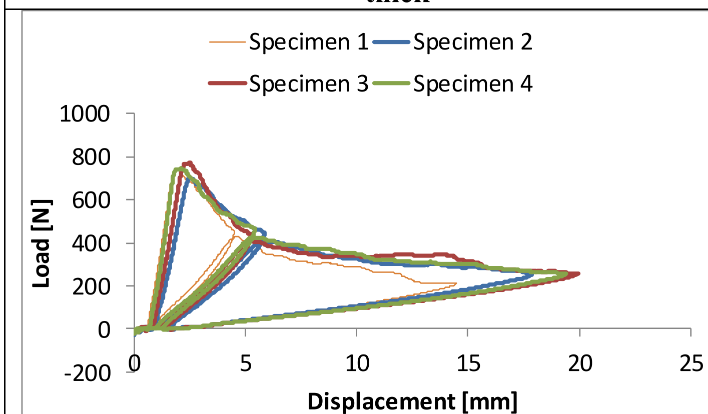
*(Superimposed data from four individual tests for each type)*



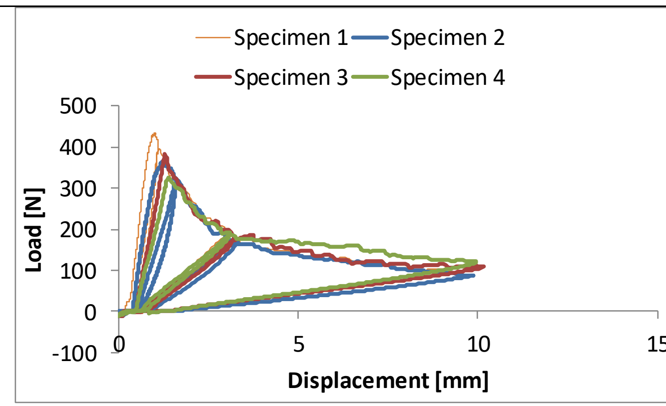

**(a) Measurements for env-conditioned specimens with Nomex 48 kg/m$^3$ honeycomb core, 12.7 mm thick**




**(b) Measurements for env-conditioned specs with Nomex 48 kg/m$^3$ honeycomb core, 25 mm thick**

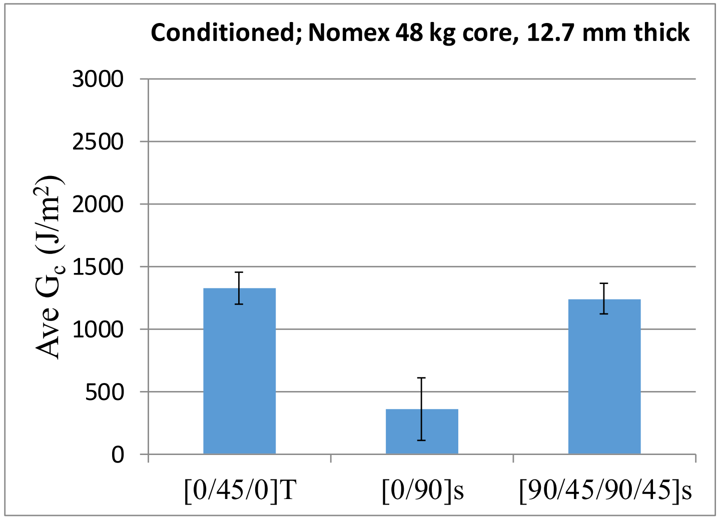


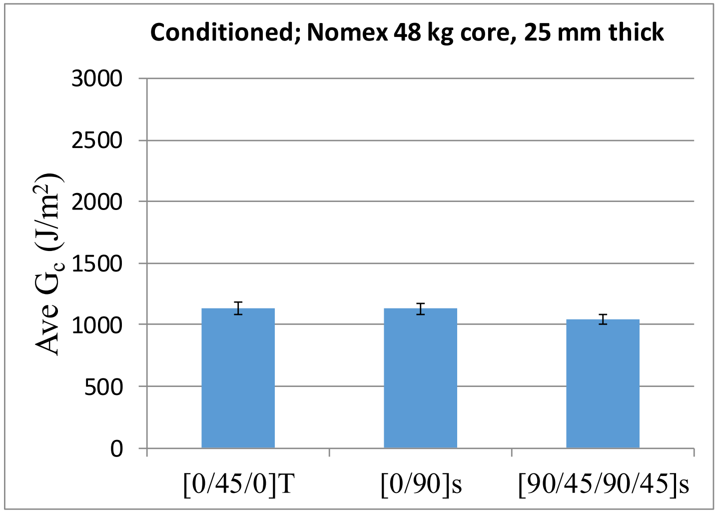

**(c) Measurements for env-conditioned specimens with Nomex 128 kg/m$^3$ honeycomb core, 12.7 mm thick**

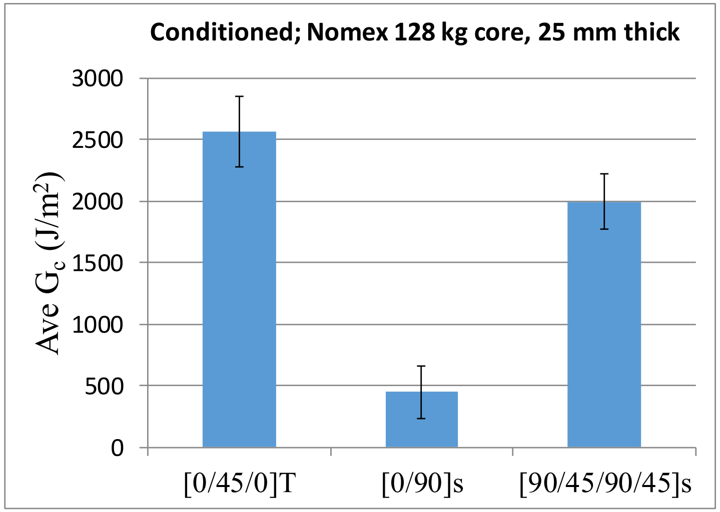


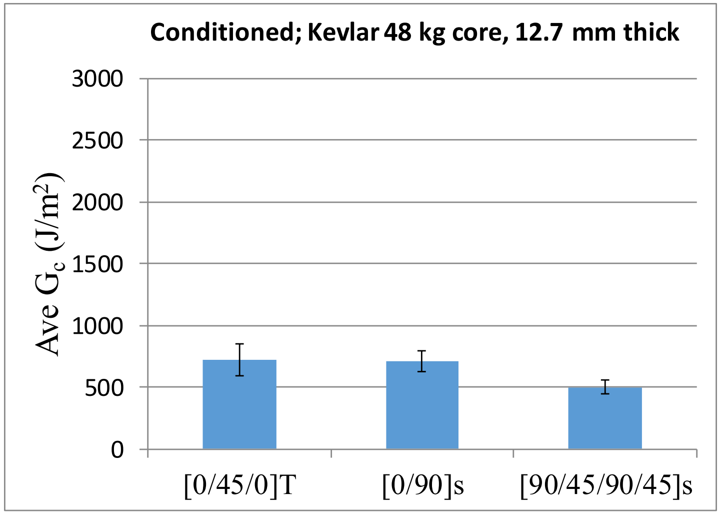

**(d) Measurements for env-conditioned specs with Kevlar 48 kg/m$^3$ honeycomb core, 12.7 mm thick**

# $G_c$ Measured for Conditioned Specimens



# Discussion

*Environmentally-conditioned specimens*

- Confounding trends…for some facesheet/core combinations environmental conditioning led to erratic and inconsistent behaviors, but for others conditioning had little or no effect

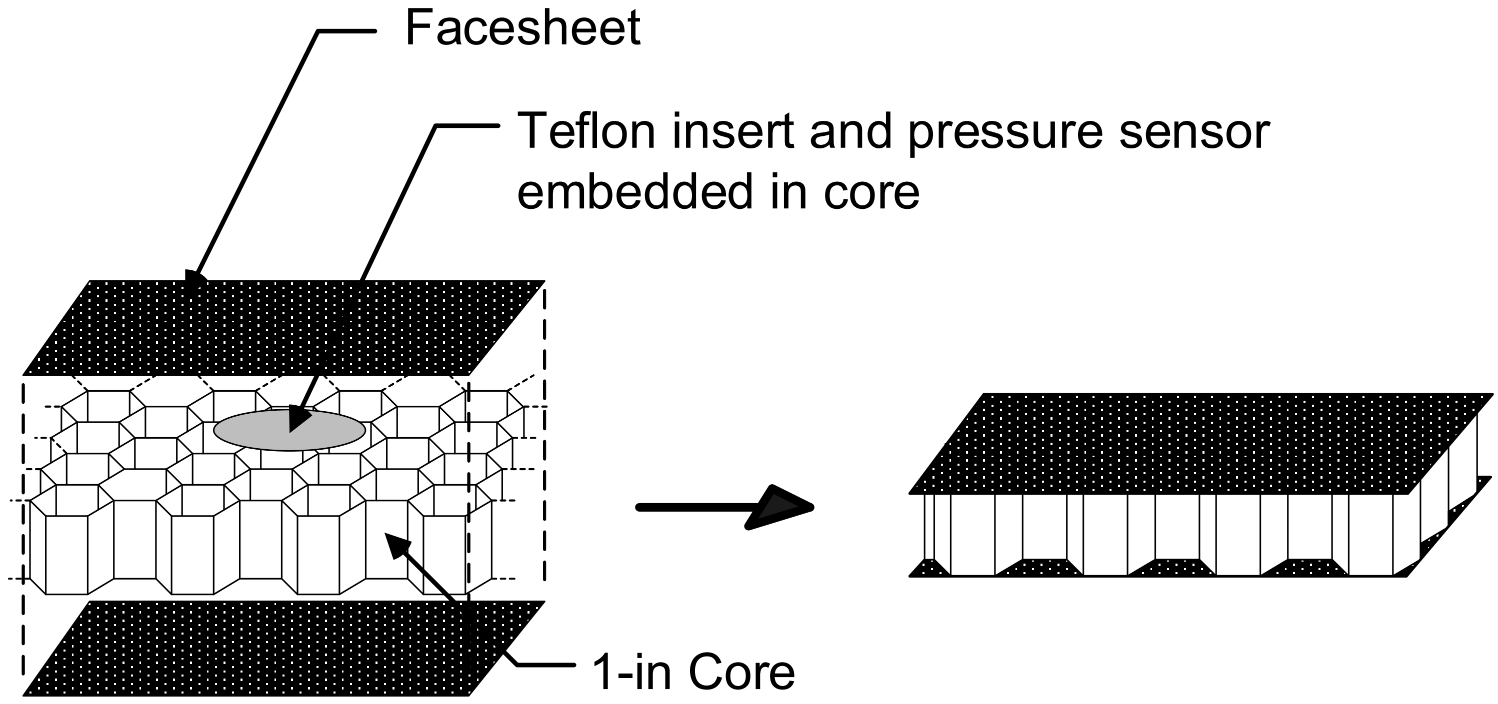
- Going forward, will conduct SCB tests at -50°C, using both as-produced and environmentally-conditioned specimens

- Prior to SCB tests will perform NDI of as-produced and conditioned specimens using CT Scan

# Ground-Air-Ground (GAG) Specimen and Test Setup

*Preliminary Results*

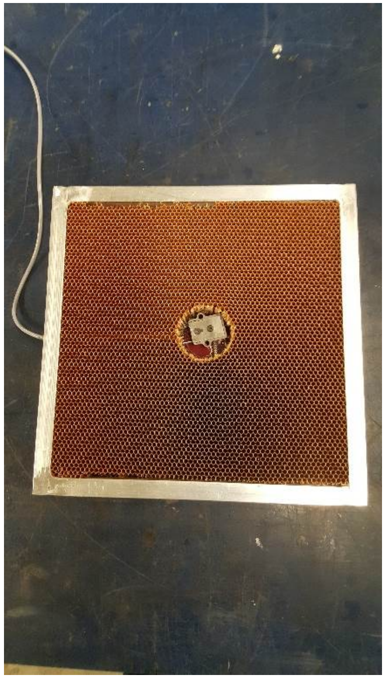
GAG Specimen:

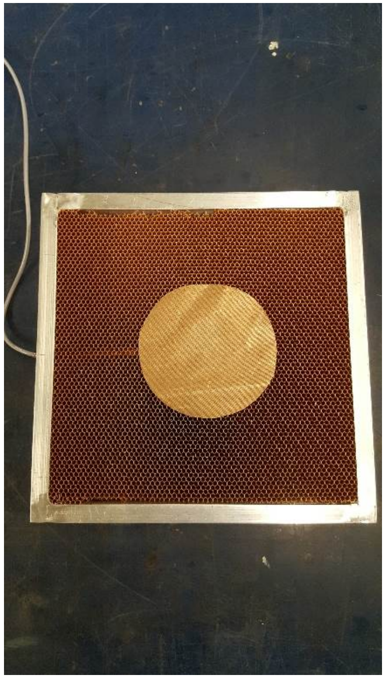


# Ground-Air-Ground (GAG) Specimen and Test Setup

*Preliminary Results*

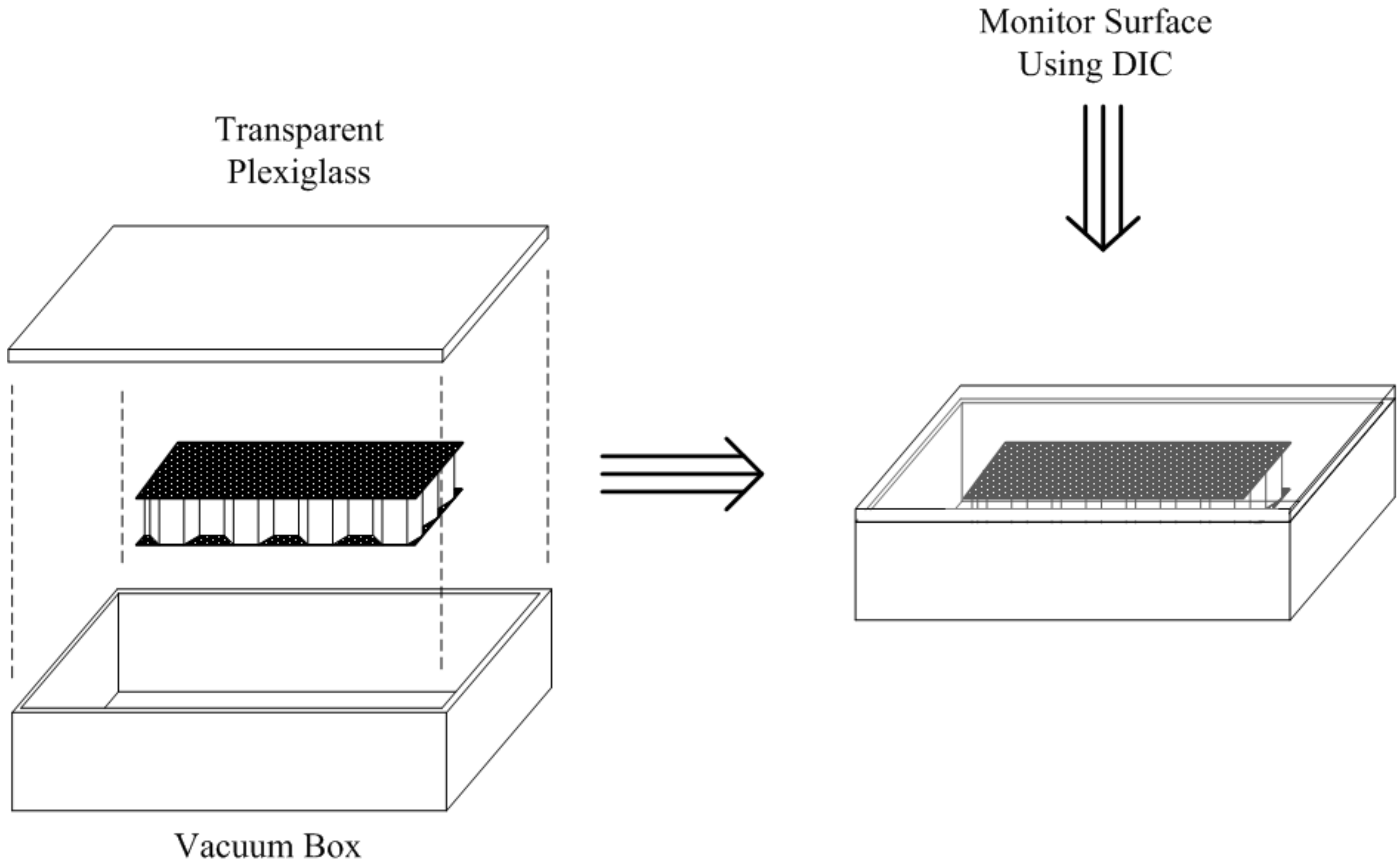
## GAG Specimen:





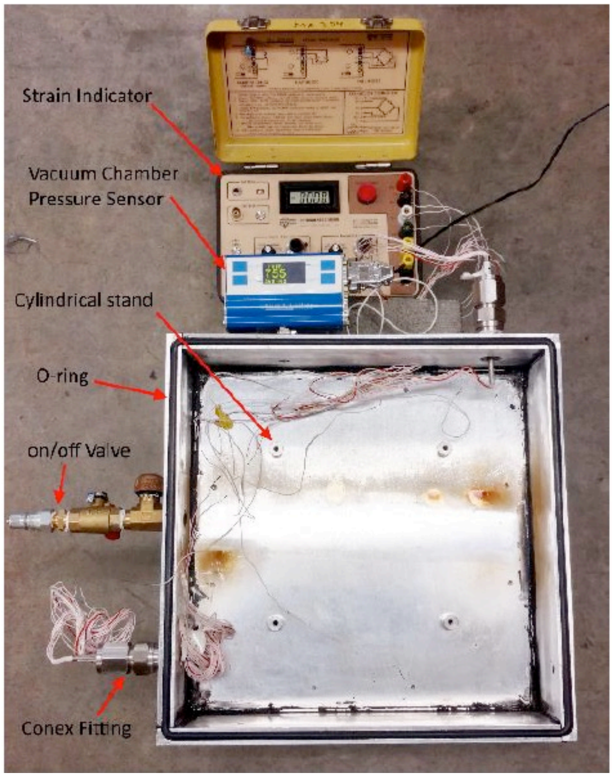
# Ground-Air-Ground (GAG) Specimen and Test Setup

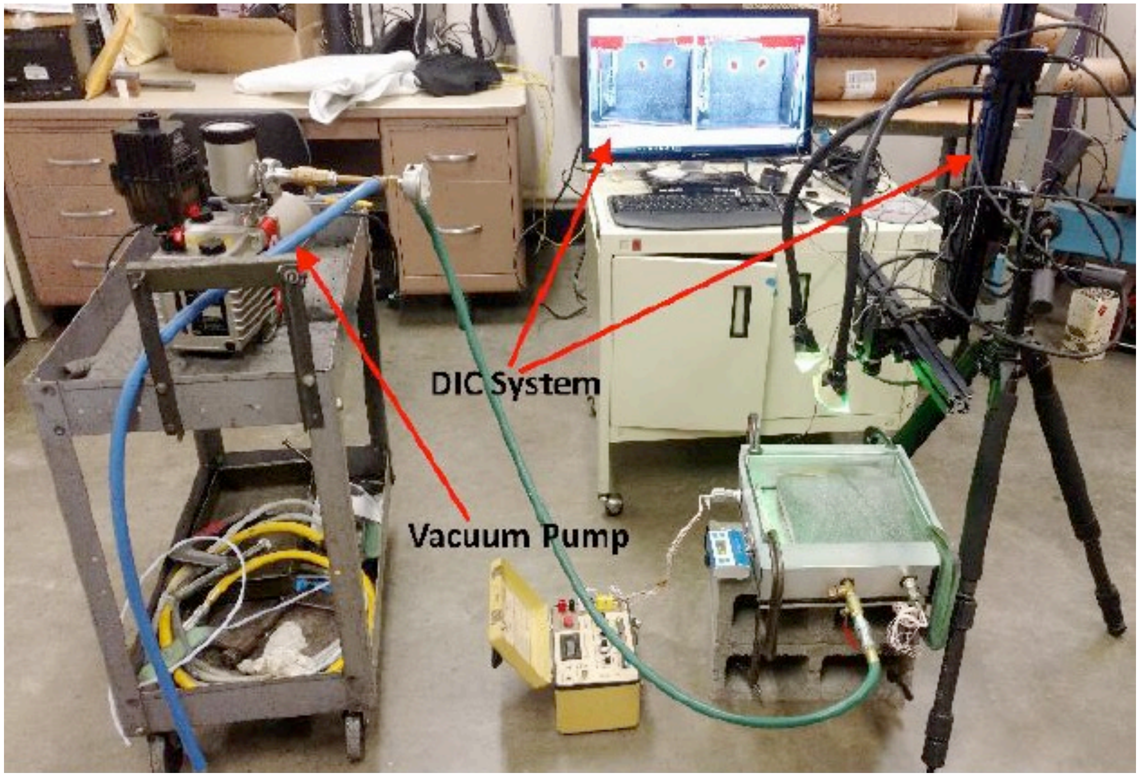
*Preliminary Results*



# Ground-Air-Ground (GAG) Specimen and Test Setup

*Preliminary Results*

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# Preliminary Ground-Air-Ground Test

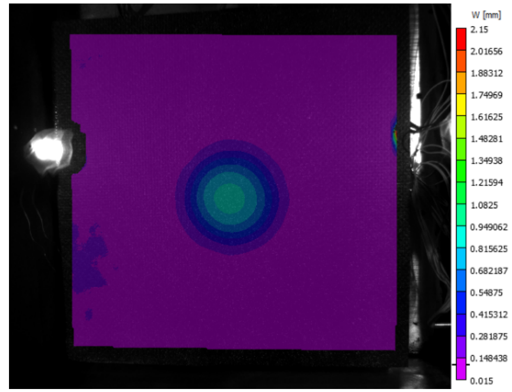
*[0/45/0]$_T$ w/1.0 Nomex core*


External pressure = 14.7 psi
Core pressure = 14.8 psi

# Preliminary Ground-Air-Ground Test

*[0/45/0]T w/1.0 Nomex core*


External pressure = 14.7 psi
Core pressure = 14.8 psi

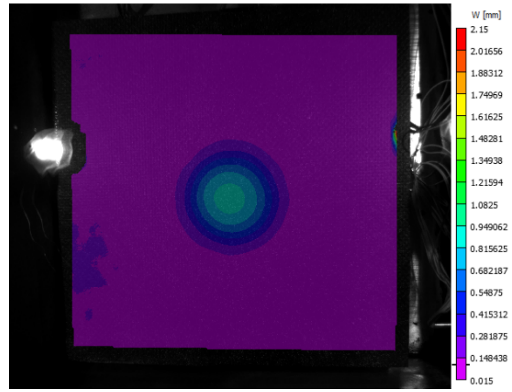



External pressure = 12.4 psi
Core pressure = 14.3 psi

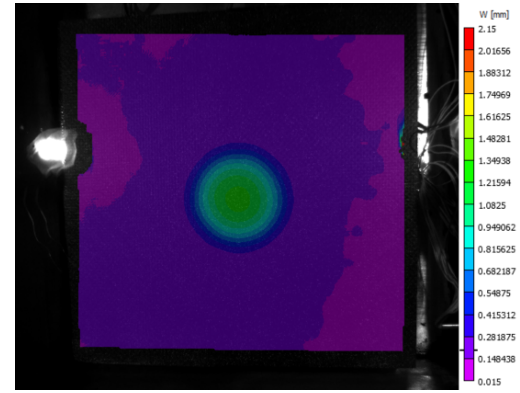
# Preliminary Ground-Air-Ground Test

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


External pressure = 14.7 psi
Core pressure = 14.8 psi



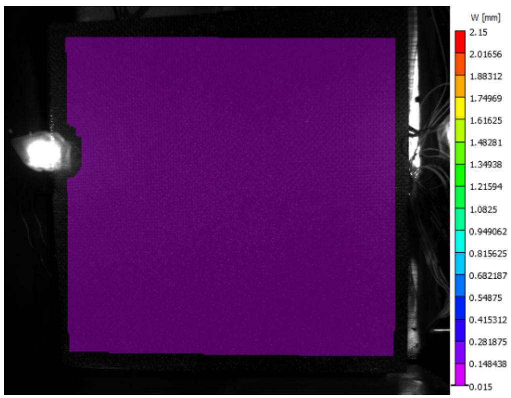

External pressure = 12.4 psi
Core pressure = 14.3 psi



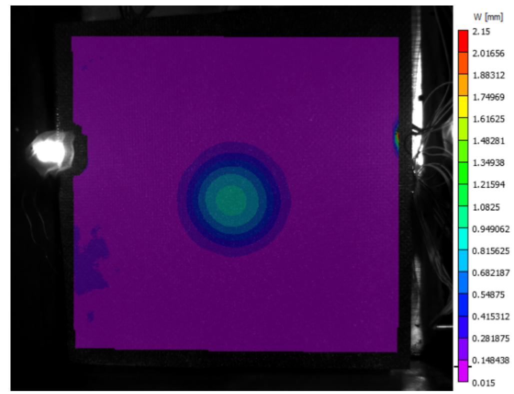

External pressure = 9.6 psi
Core pressure = 13.4 psi

# Preliminary Ground-Air-Ground Test

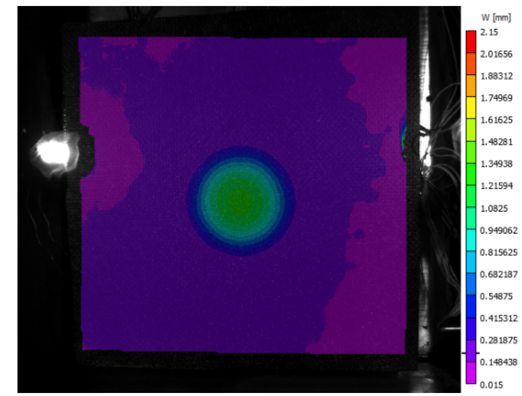
*[0/45/0]$_T$ w/1.0 Nomex core*



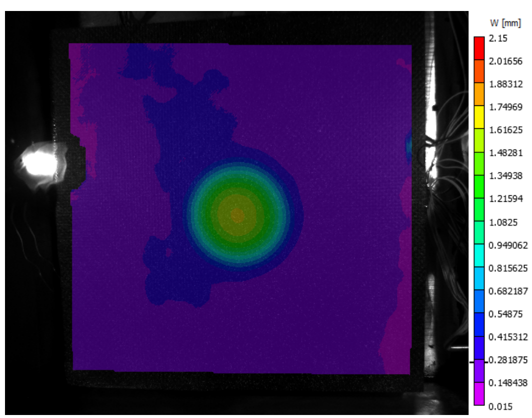

External pressure = 14.7 psi
Core pressure = 14.8 psi




External pressure = 12.4 psi
Core pressure = 14.3 psi



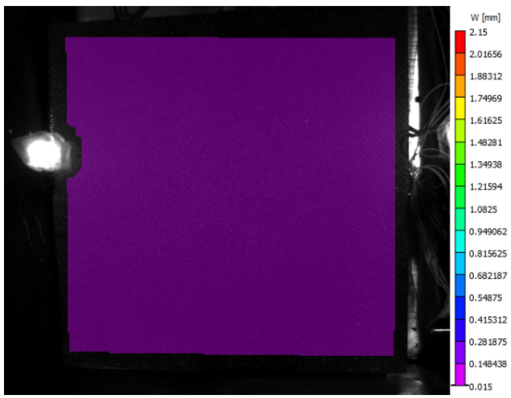

External pressure = 9.6 psi
Core pressure = 13.4 psi



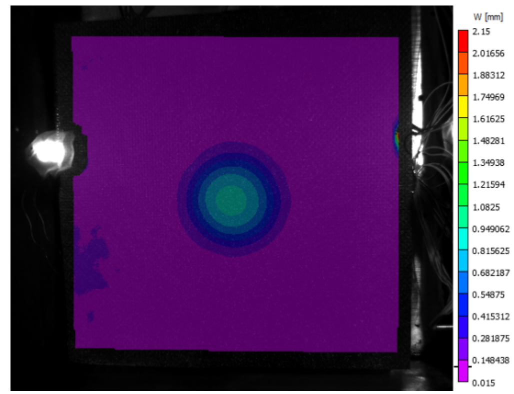

External pressure = 6.7 psi
Core pressure = 12.2 psi

# Preliminary Ground-Air-Ground Test

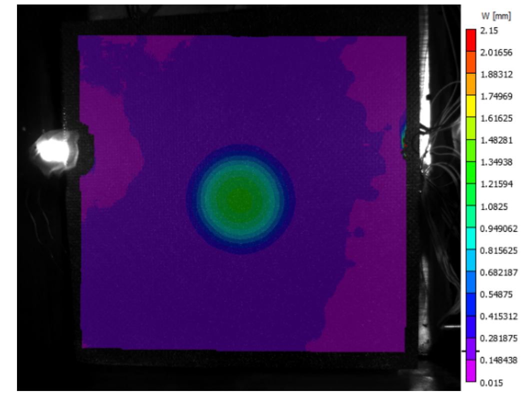
*[0/45/0]T w/1.0 Nomex core*



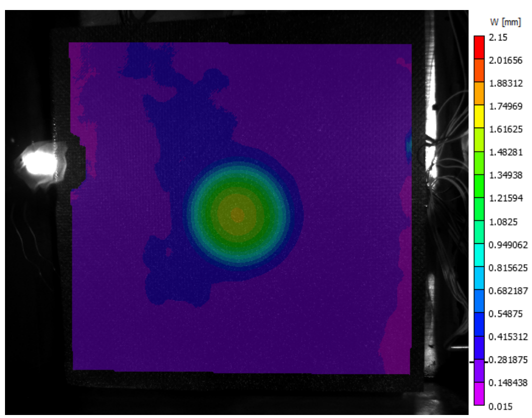

External pressure = 14.7 psi
Core pressure = 14.8 psi



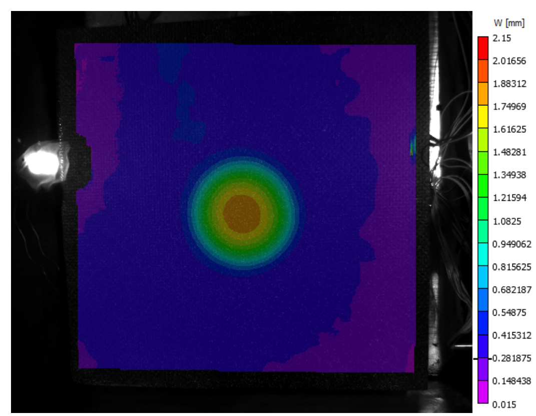

External pressure = 12.4 psi
Core pressure = 14.3 psi




External pressure = 9.6 psi
Core pressure = 13.4 psi




External pressure = 6.7 psi
Core pressure = 12.2 psi

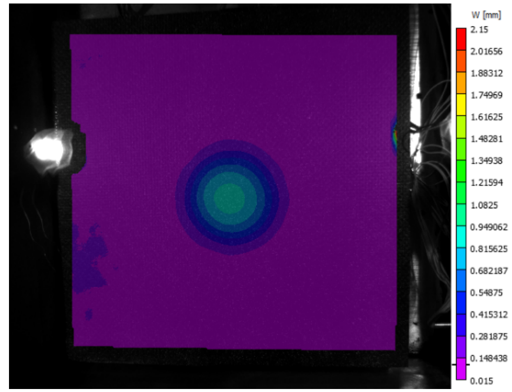



External pressure = 2.9 psi
Core pressure = 9.7 psi

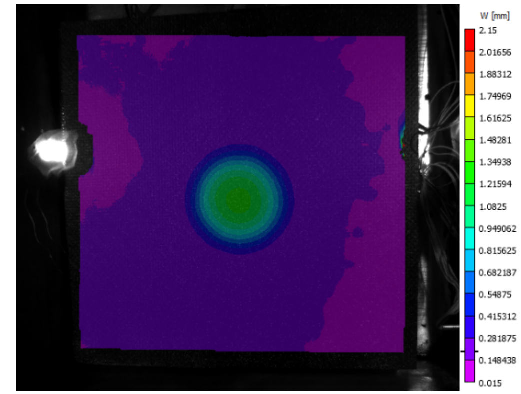
# Preliminary Ground-Air-Ground Test

*[0/45/0]T w/1.0 Nomex core*

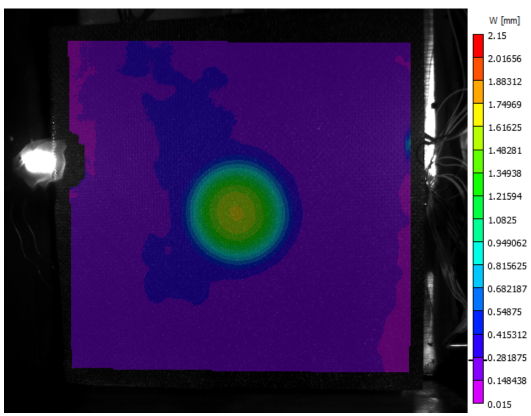

External pressure = 14.7 psi
Core pressure = 14.8 psi



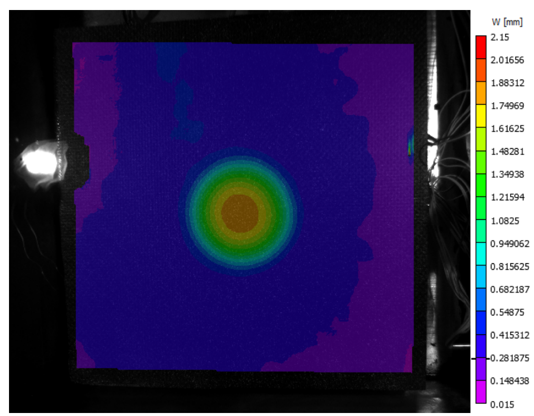

External pressure = 12.4 psi
Core pressure = 14.3 psi



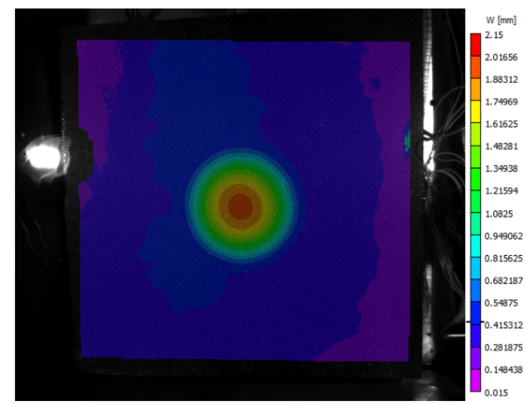

External pressure = 9.6 psi
Core pressure = 13.4 psi




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

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# Discussion

• Going forward, will conduct static and fatigue GAG tests at -50°C, using both as-produced and environmentally-conditioned panels

# Effects of Moisture Diffusion in Sandwich Composite Structures

## Benefit to Aviation:

- Will help to clarify mechanism(s) leading to initiation and growth of skin-core disbond in sandwich structures
- Will contribute to efforts to establish standard test protocols and data reduction practices for SCB testing of sandwich specimens

# Effects of Moisture Diffusion in Sandwich Composite Structures

Thank You!

Questions, Comments, Suggestions?

# End of Presentation.

# Thank you.

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