Effects of Moisture Diffusion in Sandwich Composites

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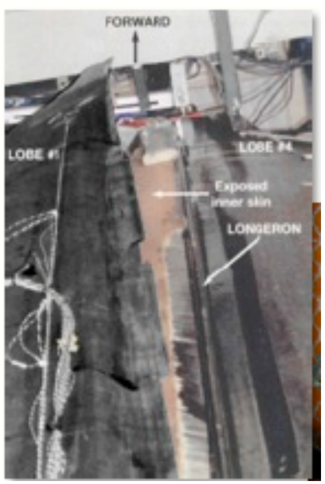
Motivation and Key Issues:

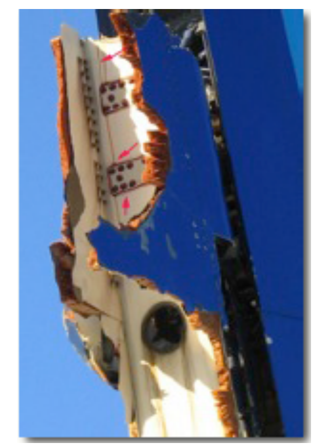
- In-service **bond failures** between composite facesheets and honeycomb cores have been reported

X-33 Liquid Hydrogen Tank Failure



Boeing 747 upper skin disbonds

Airbus A-310 Rudder Failure

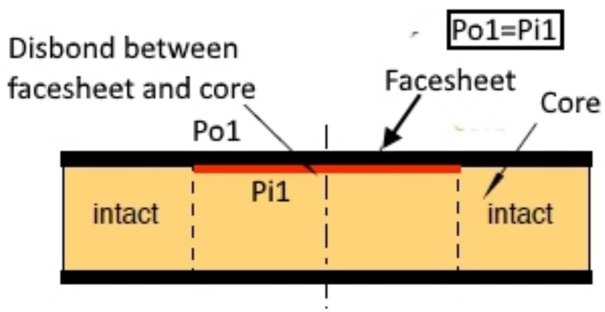


(Photos courtesy of Ronald Krueger, National Institute of Aerospace)

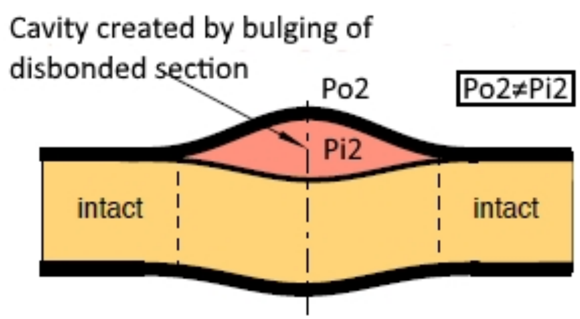
Mechanisms leading to the disbond between facesheet and core

- Impact
  - Due to bird strike, hailstorm
- Water ingression into the core followed by freeze thaw cycles
- Ground Air Ground Cycles (GAG)
  - Pressure differences between inside and outside of unvented honeycomb cores (Ground-Air-Ground or 'GAG' pressure cycles)

Initial configuration at ground elevation



Deformed configuration at cruising altitude



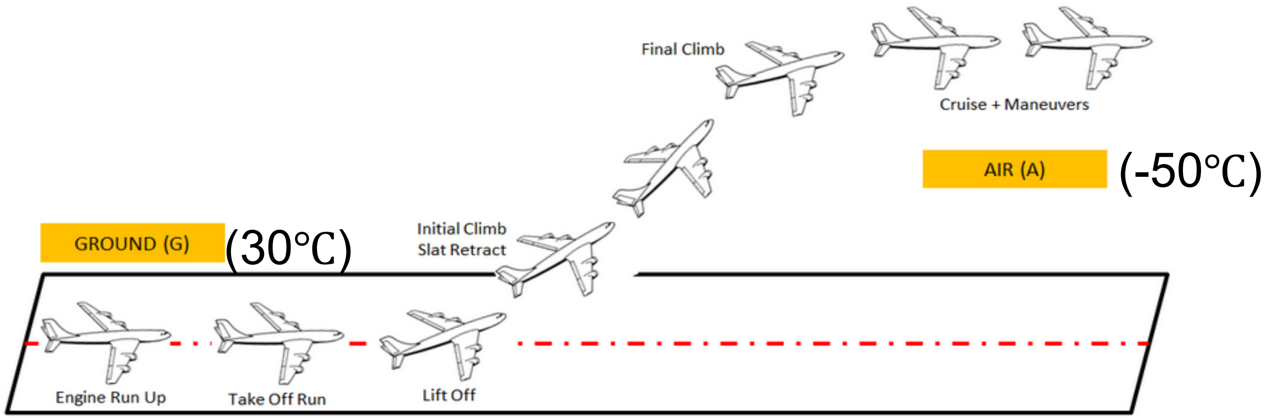
ME Tuttle et al., Proceedings of the American Society for Composites, 2018
ME Tuttle et al., AMTAS, 2018

Mechanisms leading to the disbond between facesheet and core

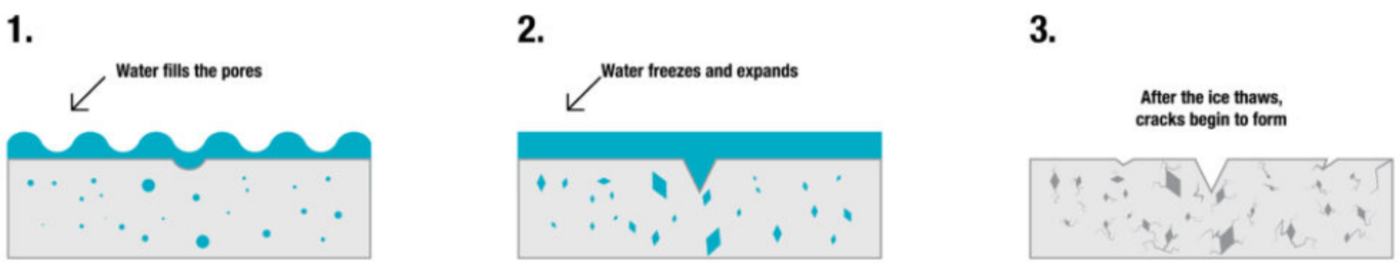
- Impact
- Water ingression into the core followed by freeze thaw cycles
- Ground Air Ground Cycles (GAG)
  - Pressure differences between inside and outside of unvented honeycomb cores (Ground-Air-Ground or ‘GAG’ pressure cycles

Objective of Study:

- Determine the effects of condense-freeze-thaw-evaporate of humid air trapped with the core coupled with thermal cycles encountered by transport aircraft at flight altitudes (-50ºC)



* *Sketch modified from http://www.stressebook.com/aircraft-ultimate-loads/*



Crack propagation due to condense-freeze-thaw cycles

Effects of Moisture Diffusion in Sandwich Composites

Key Issues to understand:

- Water ingression into core volume 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

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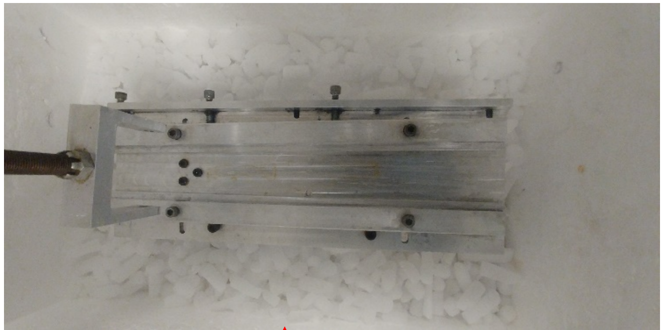
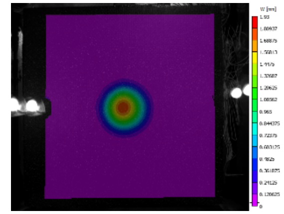
Summary of work with Prof Mark Tuttle:

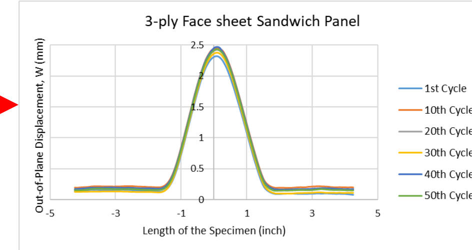


Construction of SCB Test Jig and obtained limited results

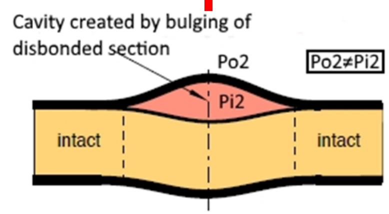
1st year



External pressure = 10.2 psi
Core pressure = 14.61 psi



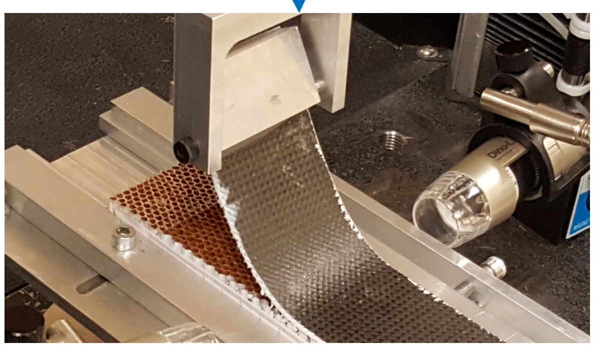
Out of plane displacements



Ground Air Ground Cycles (GAG) & SCB test- Environmental conditioned specimens tested at room temperature

3rd year

2nd year



As-produced tested at room temperature
And humidity measurements

4th year

As-produced and environmental conditioned tested at **-50**°C

* As-produced-without any moisture and thermal cycles-Reference

Research overview

Effects of Moisture followed by thermal cycling on SCB fracture toughness

Manufacture the specimens

Exposure to Moisture

Thermal cycling

Environmental conditioned

SCB Fracture test at -50°C

Fracture toughness (Gc) results

Comparison of Gc with As-produced

Conclusion

* As-produced-without any exposure to humidity and thermal cycles-Reference

Effects of Moisture Diffusion in Sandwich Composites

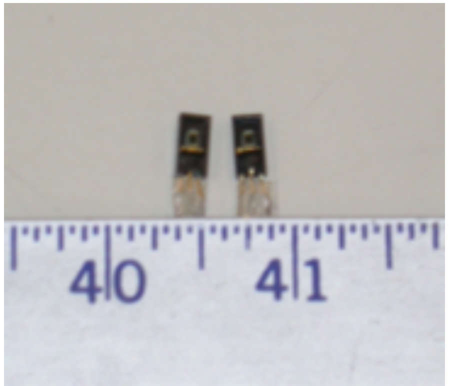
Test Matrix for SCB Sandwich specimens

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

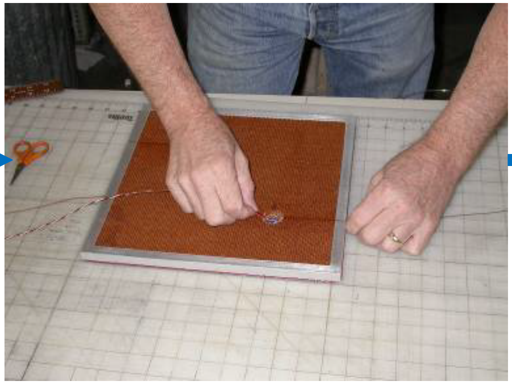
We tested 4 specimens for each combination

Humidity measurements :

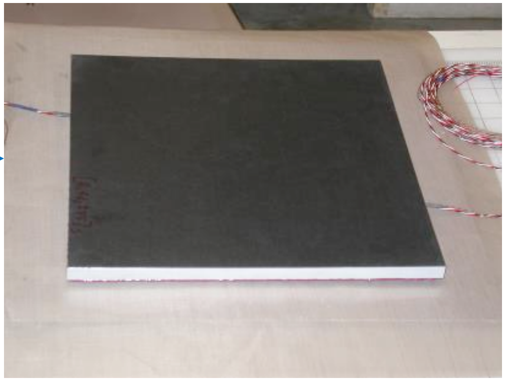
- Witness panels were used to measure changes in core humidity levels due to diffusion of water molecules through the facesheets
- Eight witness panels were produced using the various facesheet-core



Ohmic Instr Model HC-610 humidity sensors



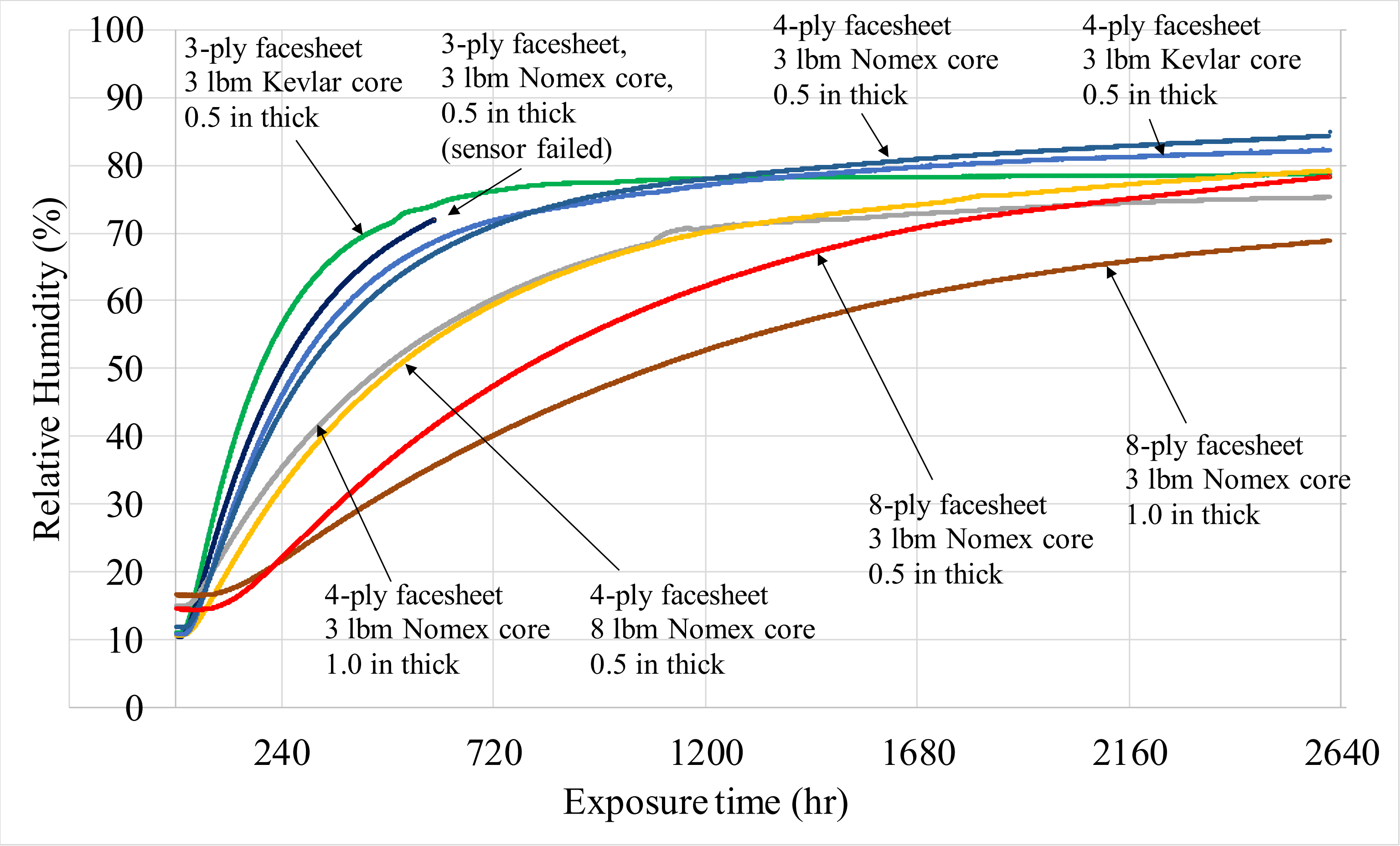
Humidity sensors embedded in the core



Witness panels exposed to humidity at 65°C and 90%RH

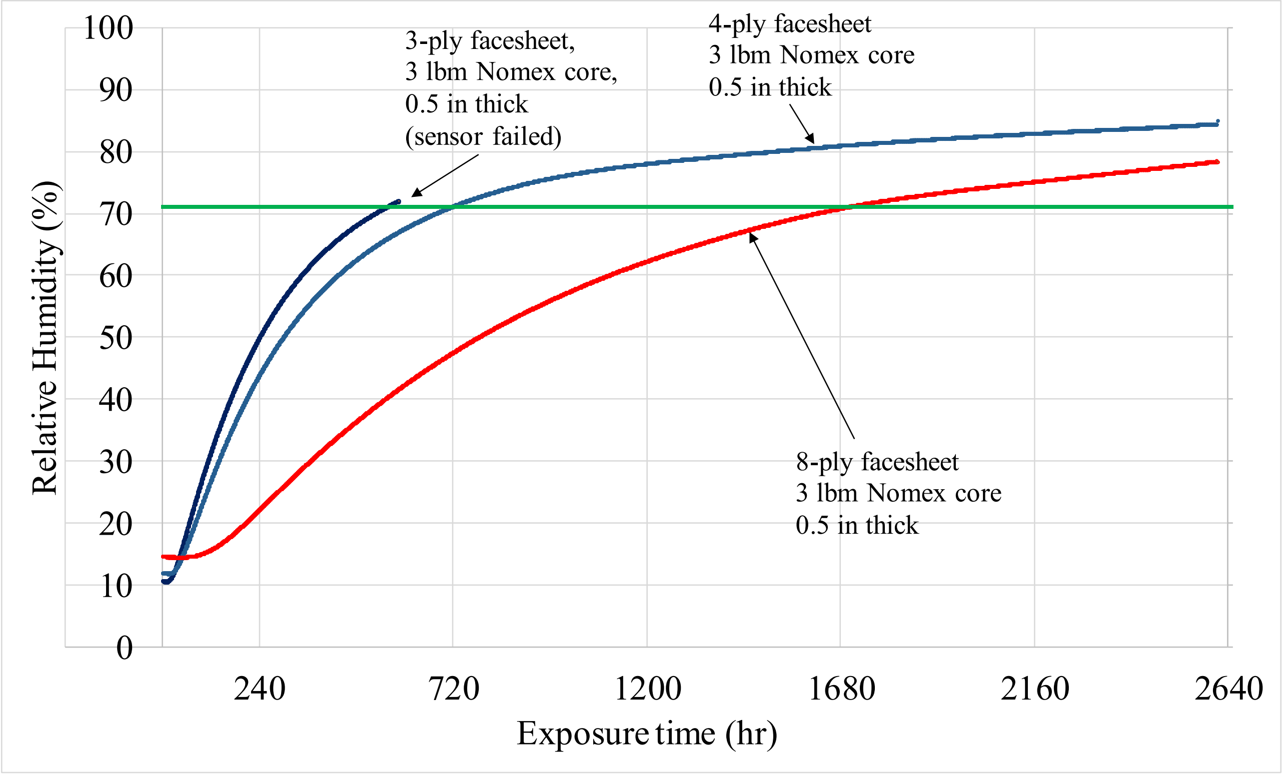
Humidity Measurements: *Exposure to elevated temperature and humidity*

- Moisture growth rate for sandwich composites for 70% RH.
- Exposed to 65°C and 90%RH



Humidity Measurements

Core Humidity Measured Over 2640 Hrs (110 days ~ 3.6 mos)

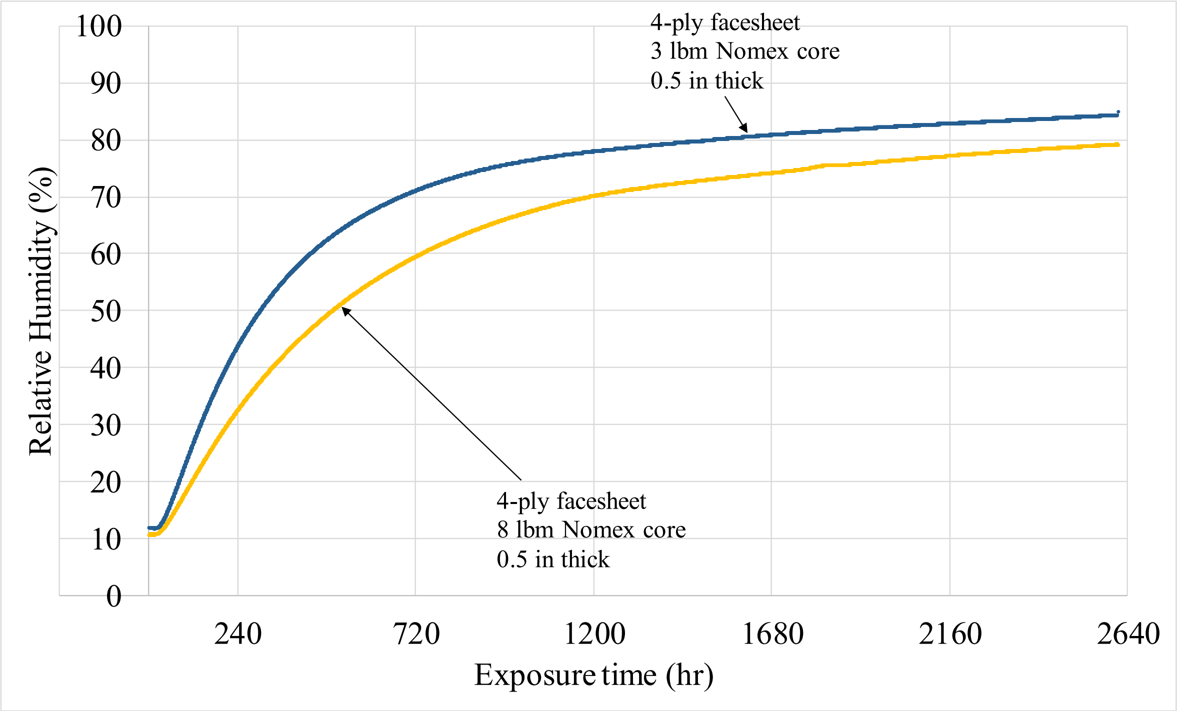


<u>Observations:</u>

• Rate of moisture diffusion is <u>*decreased*</u> by

- Increase in <u>*facesheet thickness*</u>: e.g., compare panels with 0.5 in thick, 3 lbm Nomex core but 3-, 4- and 8-ply facesheets

Core Humidity Measured Over 2640 Hrs (110 days ~ 3.6 mos)

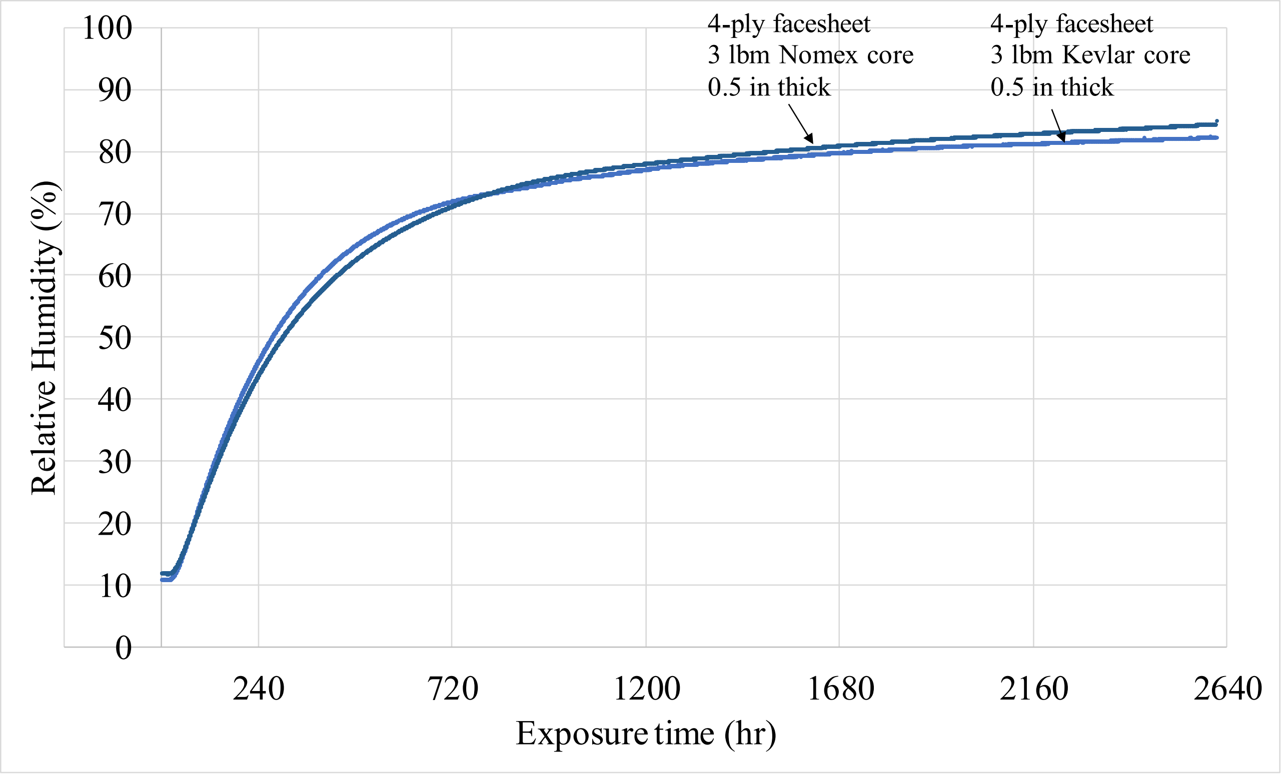


<u>Observations:</u>

• Rate of moisture diffusion is <u>*decreased*</u> by

- Increase in <u>*core density*</u>: compare panels with 4-ply facesheets and 0.5 in thick cores but 3 lbm vs 8 lbm Nomex cores

Core Humidity Measured Over 2640 Hrs (110 days ~ 3.6 mos)



<u>Observations:</u>

• Humidity buildup for Nomex and Kevlar cores with same density seem to be roughly equivalent

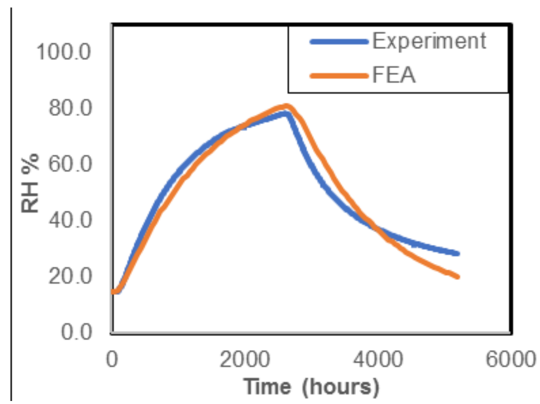
Discussion on humidity measurements

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

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

These results are well predicted by both Finite Element and Finite difference analysis.

0.5 in thick 3lbm Nomex core



ME Tuttle et al., International Conference on Composite Materials, 2009
ME Tuttle et al., ASC Conf, Seattle, 2018

Manufacturing Sandwich Test Panels

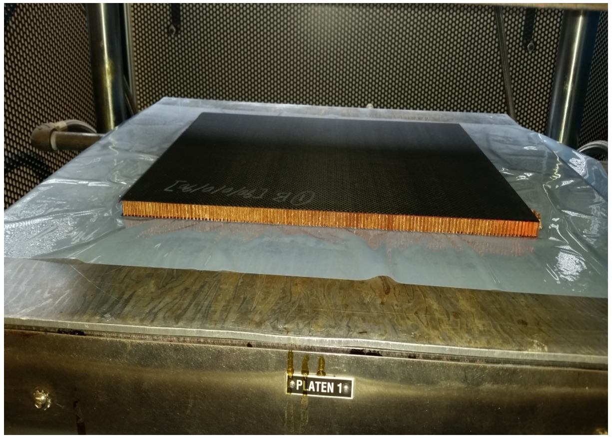
- Facesheets and core materials were machined to size
- These materials stored for 1month at 50°C (122°F) at 8% RH in a humidity chamber, to ensure components were as “dry” as possible

Core materials Facesheets

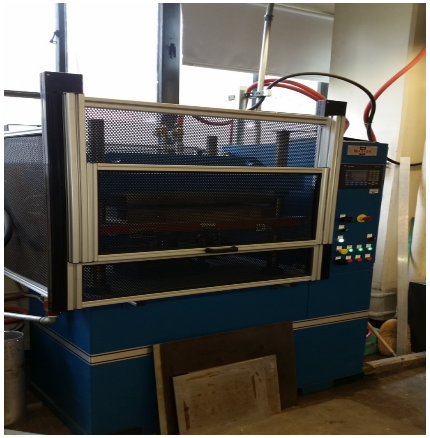
Humidity chamber, UW

Manufacturing Sandwich Test Panels

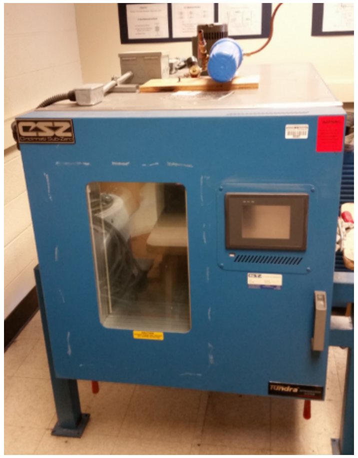
- Parent panels were then produced by bonding the facesheets to honeycomb cores using thin film adhesive.
- These parent panels are cured in a hot press
- SCB test specimens were machined from the “parent” panels
- These parent panels are exposed to humidity measurements until it reaches 70%RH, measurements taken from previous witness panels.



Bonding of facesheet and core



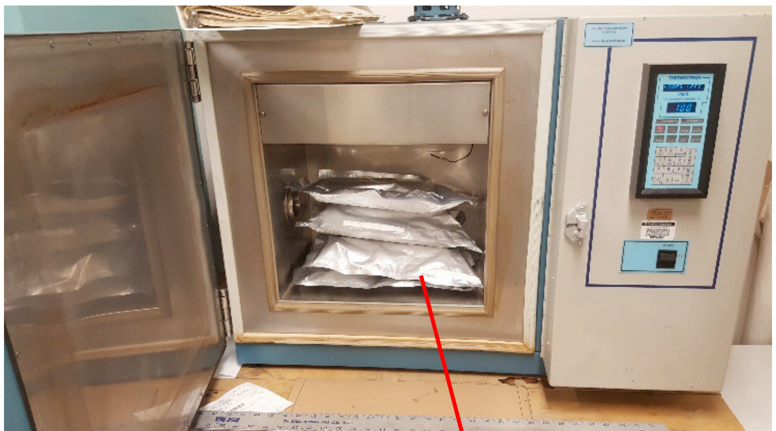
Curing of parent panels using Hot-press, UW



Specimens exposed to humidity measurements

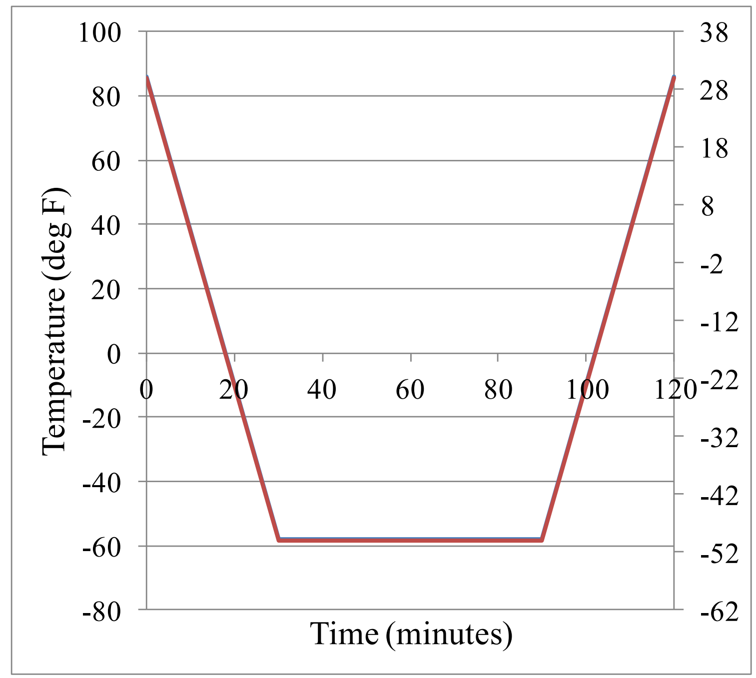
Thermal cycling

- Once the specimens reached 70% RH, the corresponding specimens were sealed in metal-coated bags (to maintain internal core humidity), placed within a temperature chamber, and subjected to 255 one-hour (10.5days) temperature cycles from +30°C to -50°C.



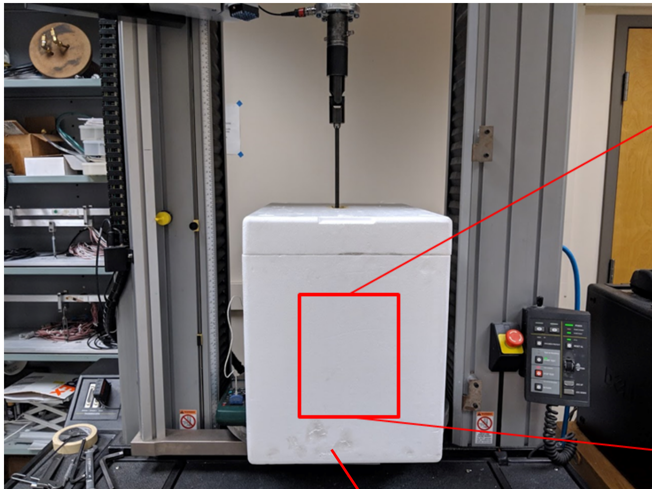
Thermotron Model S.12 Temperature Chamber, UW

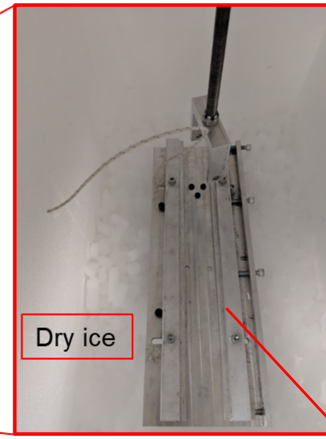
Metal coated bags



Thermal cycling , +30°C to -50°C over 255 1hr loops

SCB test fixture for sandwich composites





Styrofoam box setup used to maintain the environment at ~ -50ºC

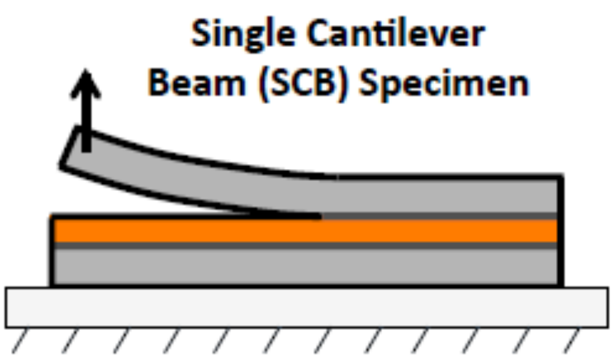
UW SCB test fixture immersed in a bed of dry ice

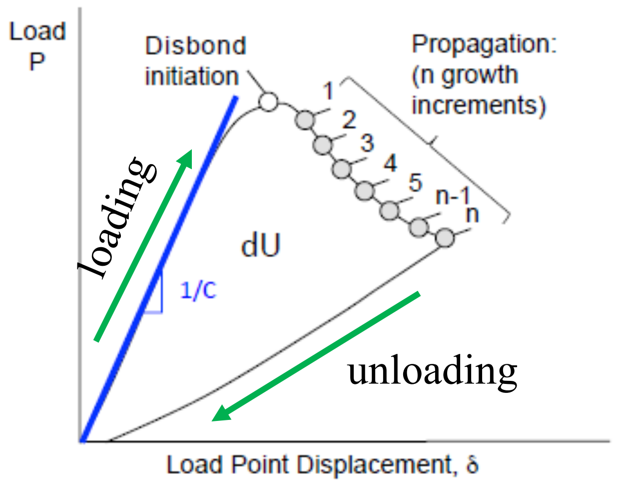
Dry ice

The specimen is maintained at -50℃

Single-Cantilever Beam (SCB) test procedure

- Initial saw cut the specimen ~10mm to initiate the crack
- Load specimen (Displacement control) and unload after required amount of disbonding.
- Record load/displacement response and crack propagation. Continue the same procedure for 'N' loops.
- Document changes in disbond growth for every loop
- Compute interfacial fracture toughness, Gc (initiation and propagation values)



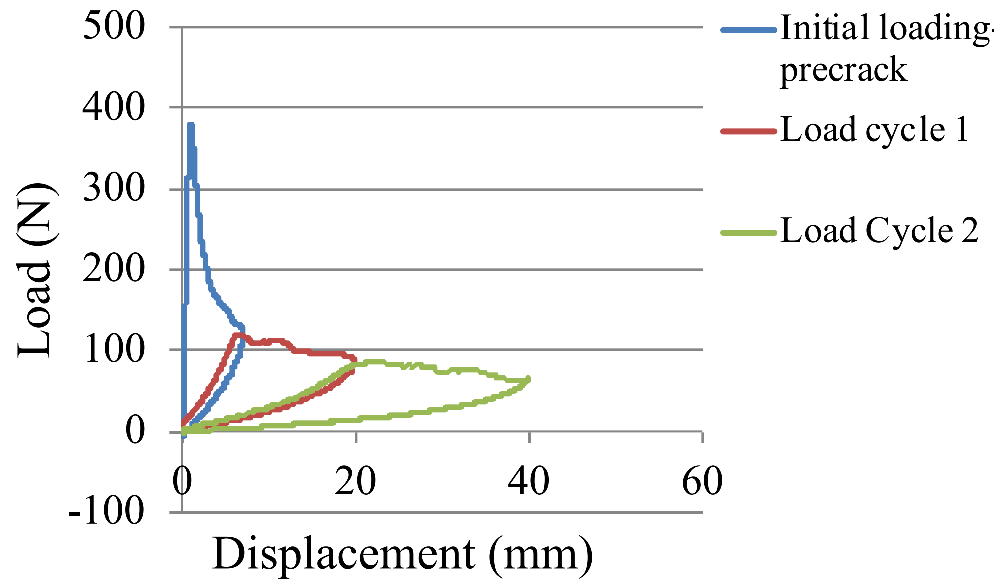


Single-Cantilever Beam (SCB) test procedure

• The critical strain energy release rate was calculated using the area method

ΔU = area defined by the load-displacement envelope
B = specimen width
Δa = crack extension

• 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



• The critical strain energy release rate was calculated using the area method

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

ΔU = area defined by the load-displacement envelope
B = specimen width
Δa = crack extension

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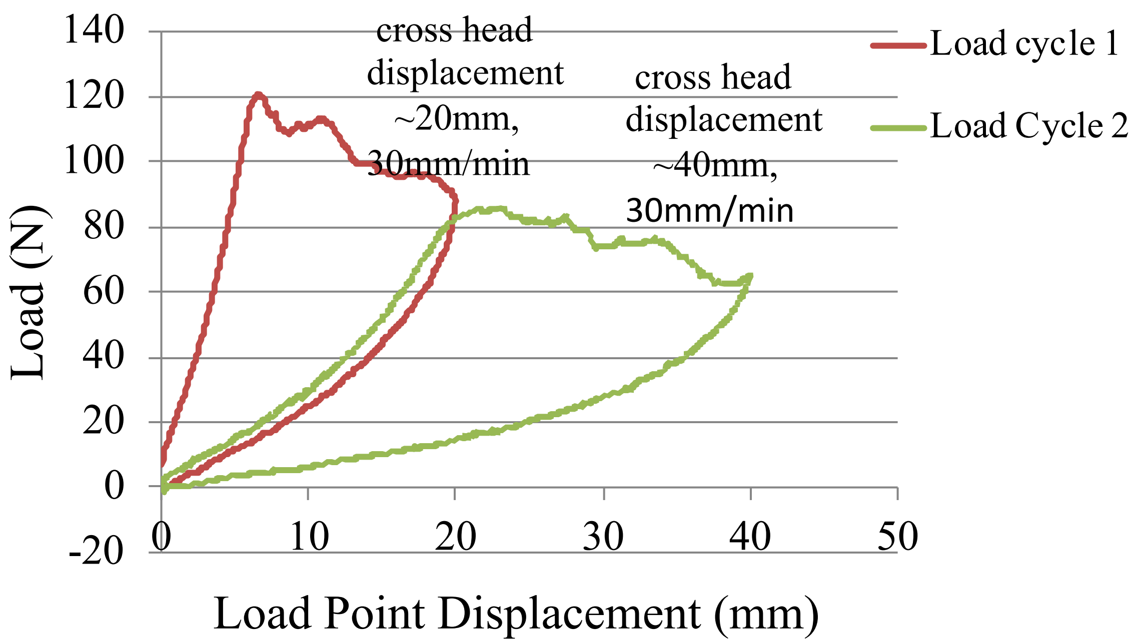
Single-Cantilever Beam (SCB) test procedure

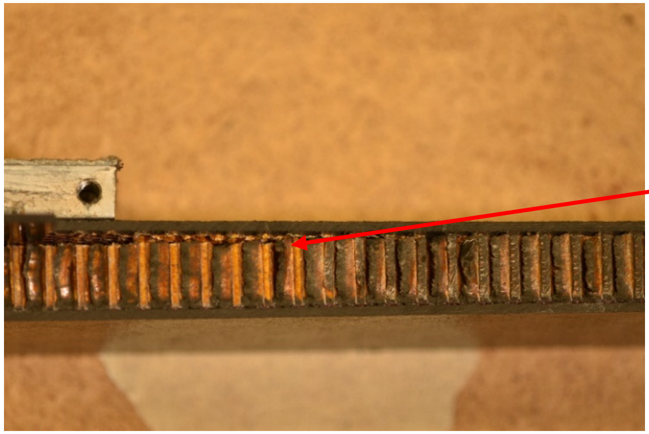


We considered only load cycle 1 for measuring fracture toughness values as

- Few 3 ply honeycomb specimens failed in facesheet during loop 2
- Due to high nonlinear behavior for some specimens in loop 2.

To maintain consistency, we considered only loop 1 for all the specimens

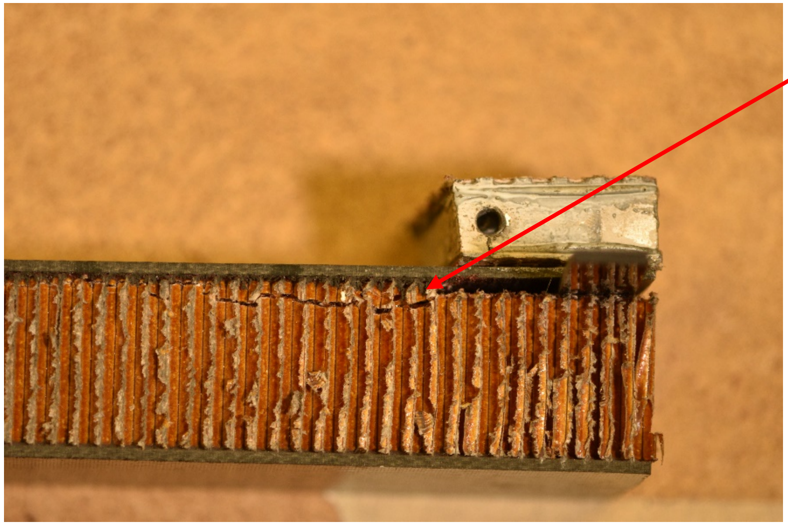
Failure site in SCB test specimens



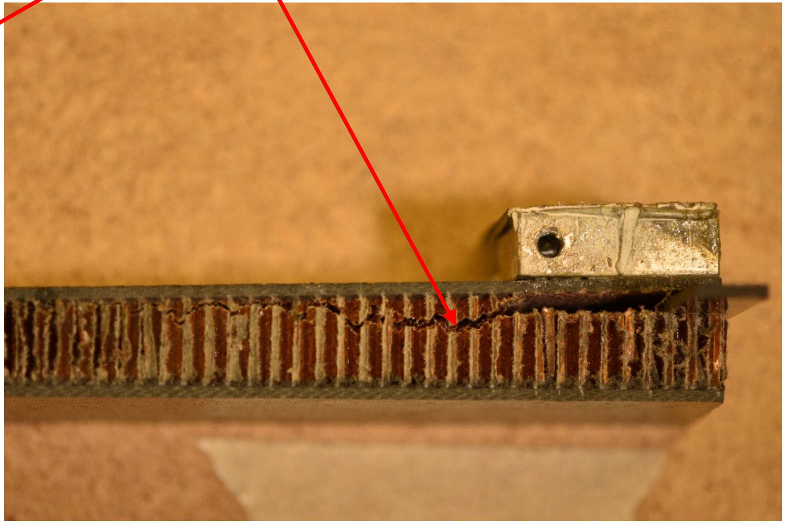
Nomex 8lb/ ft^3 core, 0.5in thick, 8ply

In most cases failure occurred just below the adhesive filet

For several specimens with 8-ply facesheets failure occurred in the core



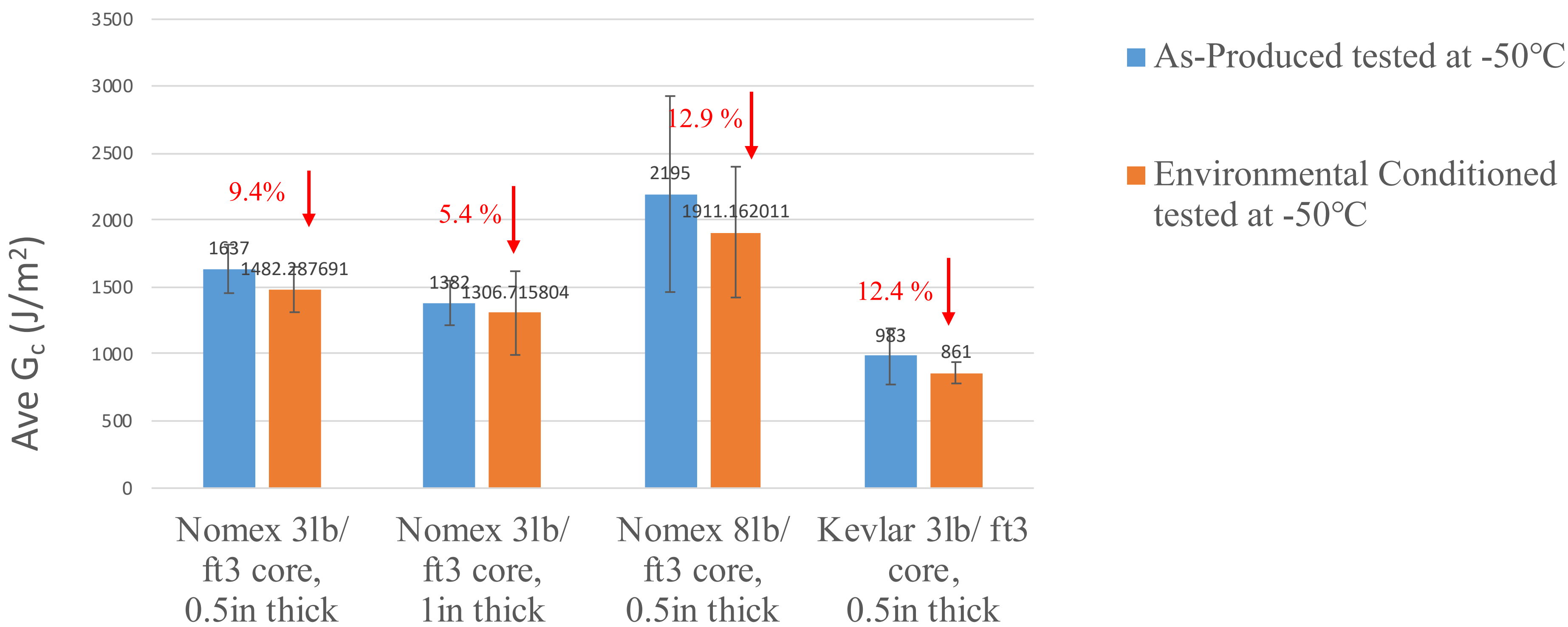
Nomex 3lb/ ft^3 core, 1in thick, 8ply



Kevlar 3lb/ ft^3 core, 0.5in thick, 8ply

Comparison of SCB Fracture toughness

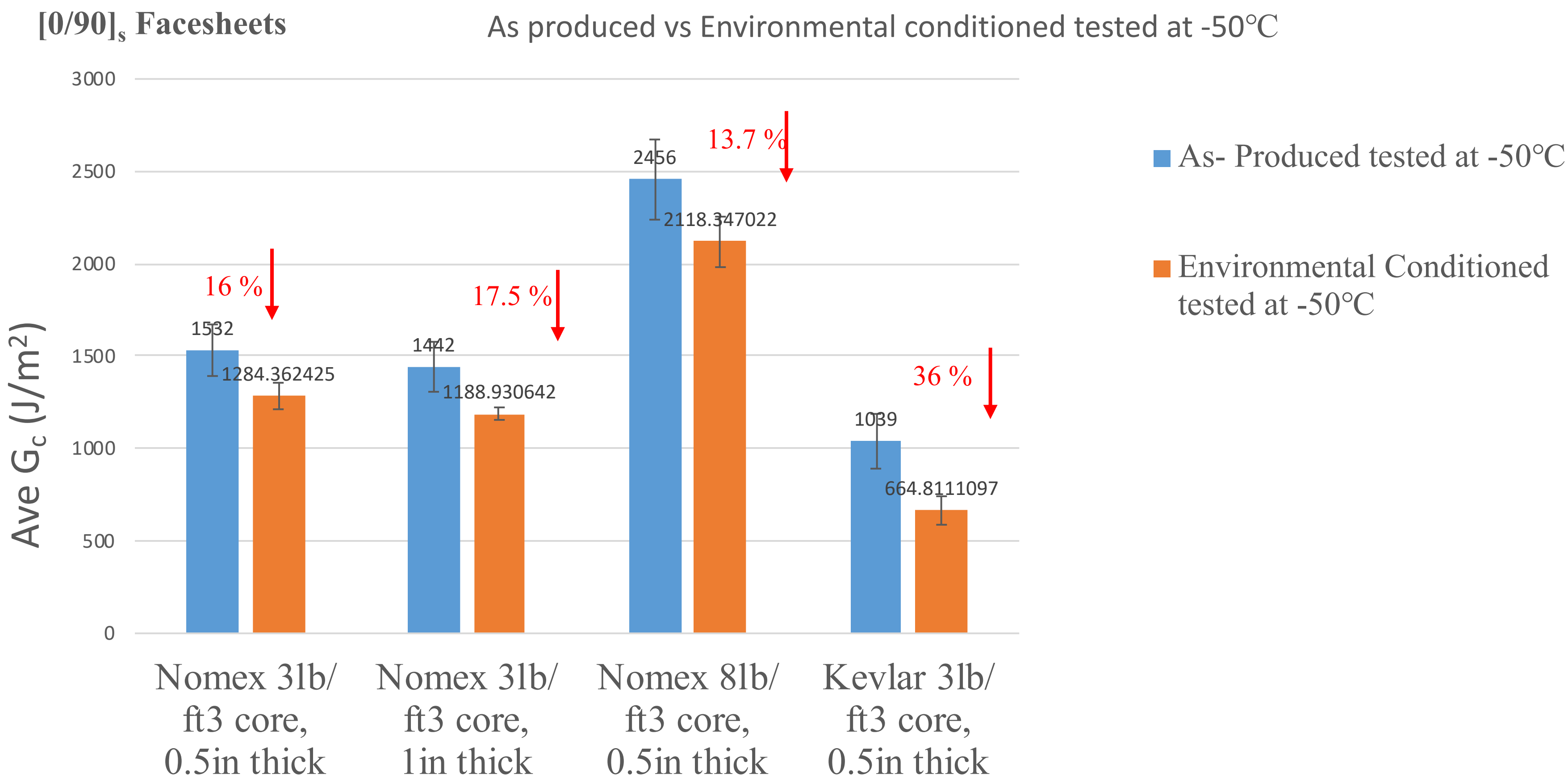
$[0/45/0]_T$ Facesheets — As produced vs Environmental conditioned tested at -50°C



For the 3 ply facesheets,

- There is a decrease in G_c for Environmental conditioned specimens compared to as produced, tested at -50°C for 3ply facesheet
- The effect of moisture followed by thermal cycles, have effect on G_c for 3 ply facesheet with different grades of core material tested at at -50°C

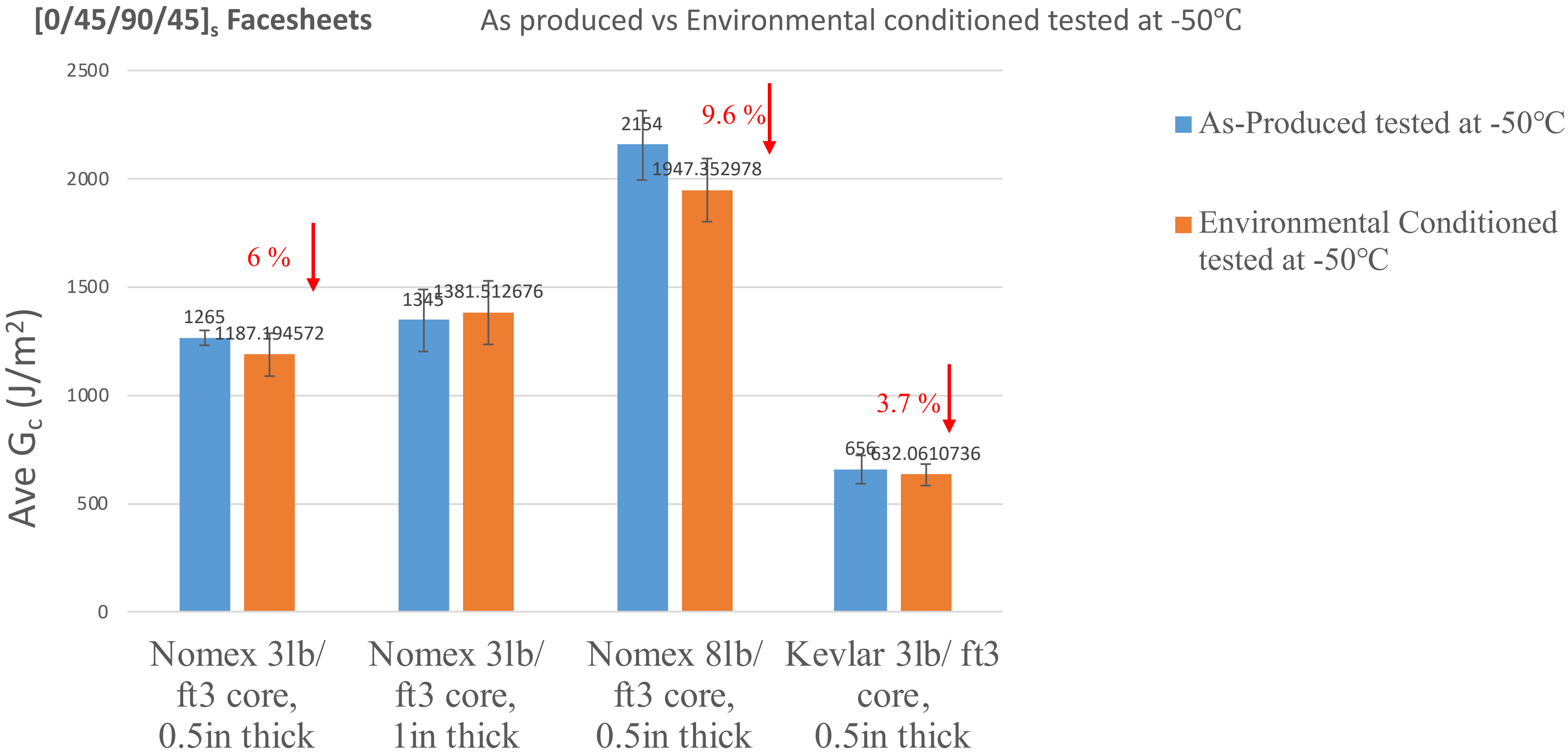
Comparison of SCB Fracture toughness of as-produced with environmental conditioned specimens, tested at -50℃ for 4 ply facesheet



For the 4 ply facesheets,

- There is a significant decrease in G_c for Environmental conditioned specimens compared to as produced, tested at -50℃ for 4ply facesheet
- The effect of moisture followed by thermal cycles, have significant effect on G_c for 4 ply facesheet with different grades of core material tested at at -50℃

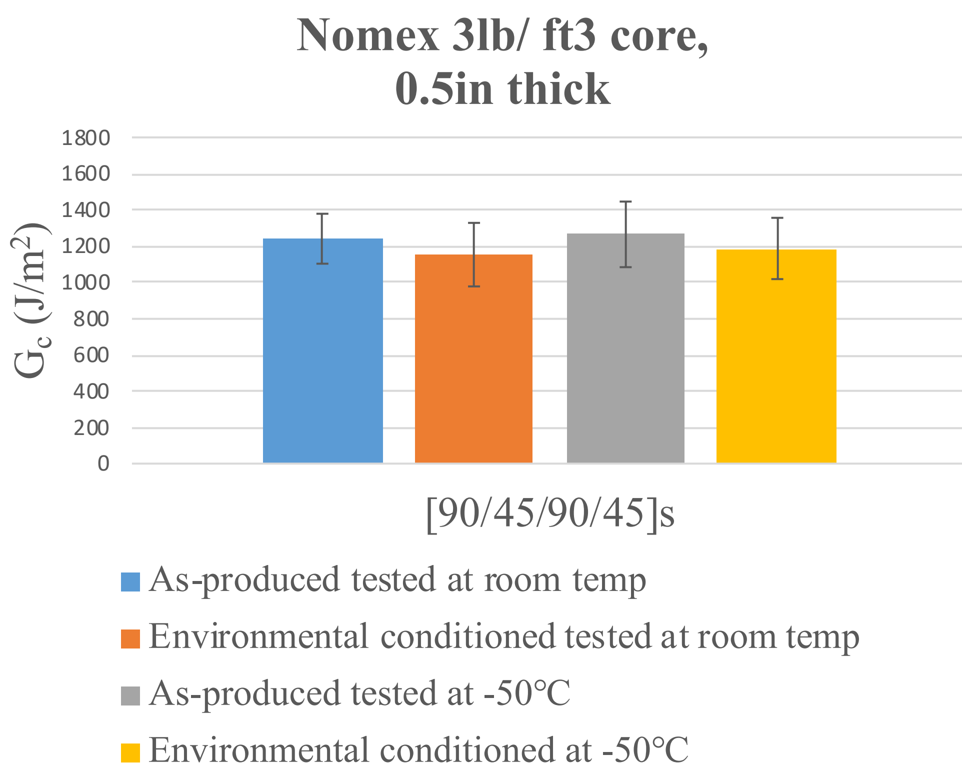
Comparison of SCB Fracture toughness of as-produced with environmental conditioned specimens, tested at -50℃ for 8 ply facesheets



For the 8 ply facesheets,

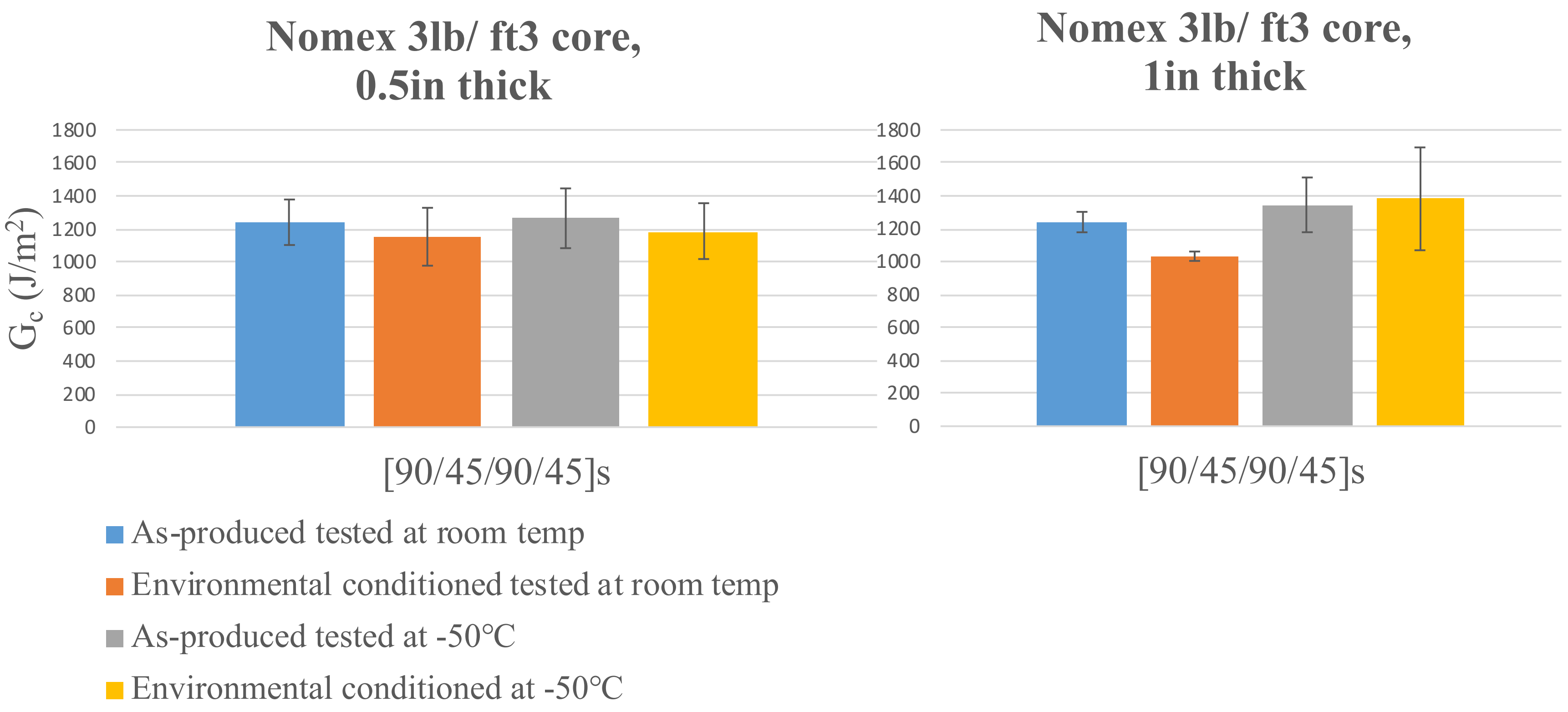
- There is a not much difference in G_c for Environmental conditioned specimens compared to as produced, tested at -50°C for 8ply facesheet
- The effect of moisture followed by thermal cycles, have very less on G_c for 8 ply facesheets with different grades of core material tested at at -50℃

SCB Test-Fracture Toughness G_{IC}- Temperature effects



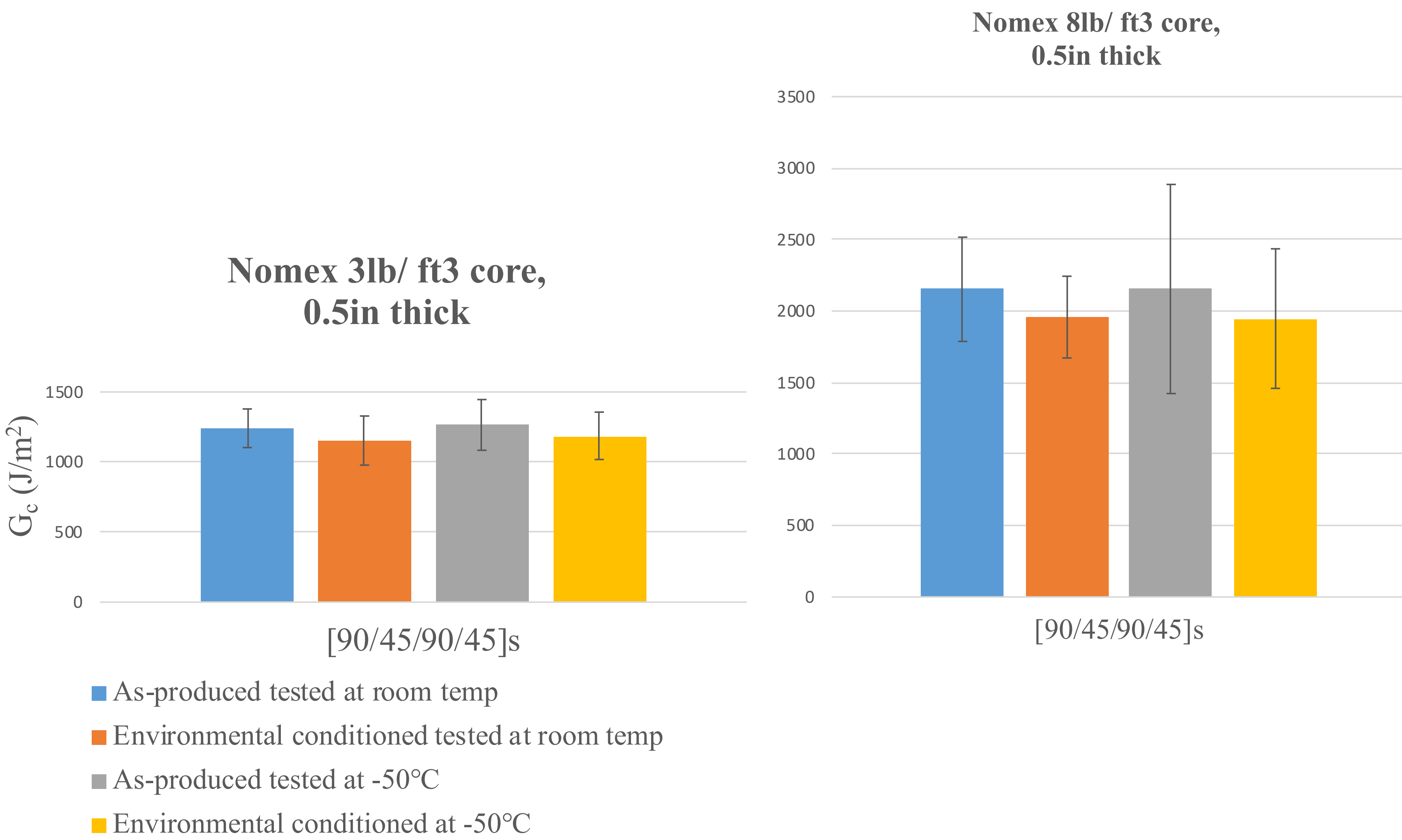
- Fracture toughness is higher for as-produced specimens tested at -50°C compared to as-produced tested at room temperature.

SCB Test-Fracture Toughness G_{IC}- Core Thickness effects



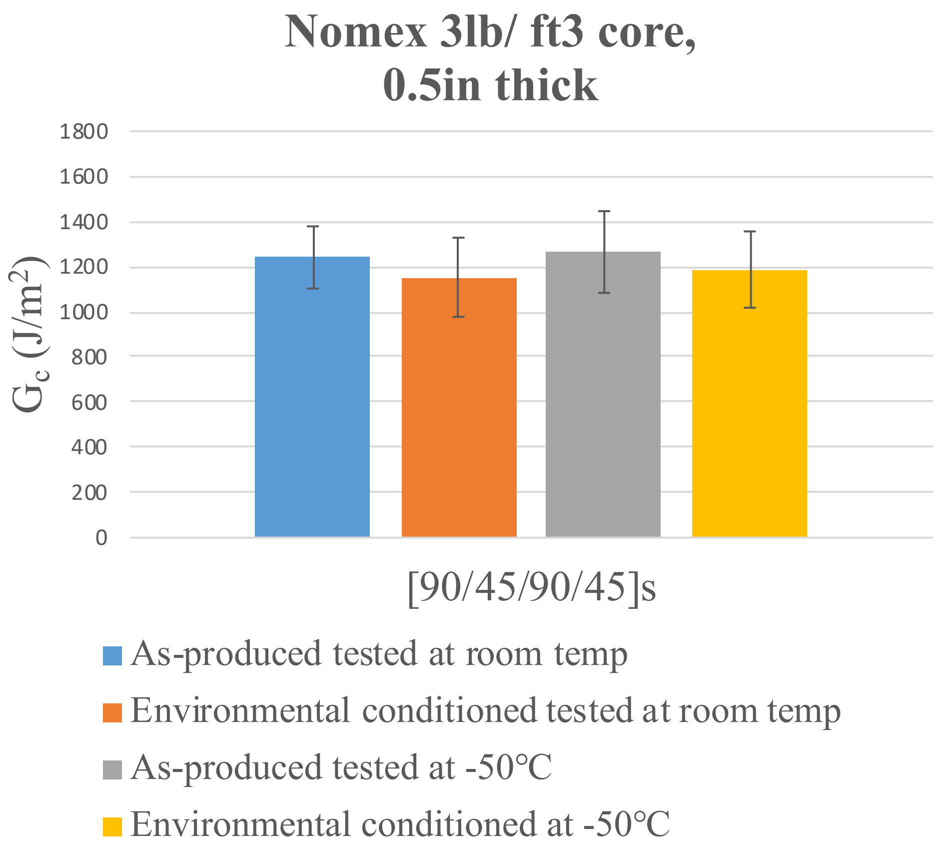
- **G_c is nearly independent of core thickness** in same density core material as in Nomex 3lb/ ft3, **0.5 vs 1inch** core, tested at both room temp and at -50℃

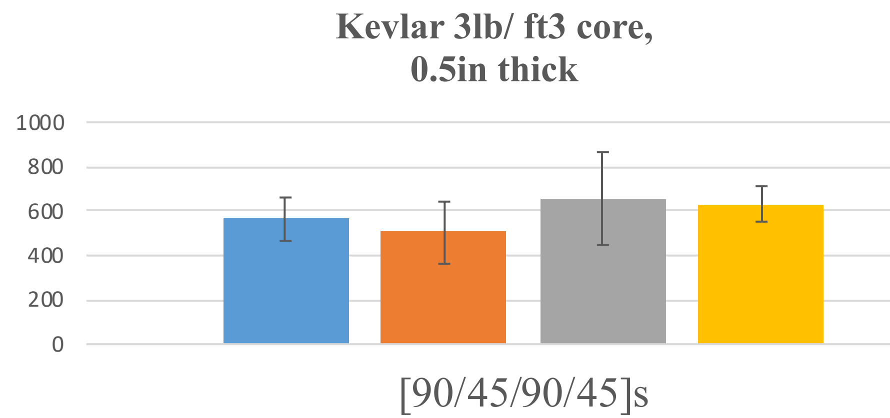
SCB Test-Fracture Toughness G_{IC}- Core Density effects



- **G_c increases significantly with increase in core density** in same thickness Nomex grade as in Nomex 0.5 in, **3lb/ ft3 vs 8lb/ ft3**, tested at both room temp and at -50℃

SCB Test-Fracture Toughness G_{IC}- Different Core materials





- **G_c is significantly lower in Kevlar grade compared with Nomex grade** with same thickness and density as in Nomex 3lb/ ft3 0.5 in vs Kevlar 3lb/ ft3 0.5 in, tested at both room temp and at -50°C

Summary and Conclusions

- The measured humidity level buildup in the core is in good agreement with Finite Difference and Finite Element predictions

- The effect of moisture followed by thermal cycles is studied at both room temperature and -50°C successfully:
  - Measured fracture toughness values have decreased between 5-35% in environmental conditioned specimens compared with as-produced specimens tested at -50°C in both 3 and 4 ply facesheets, however
  - There was an insignificant change in measured fracture toughness for environmentally conditioned specimens compared with as-produced tested at -50°C in 8 ply facesheets.

- Fracture toughness is higher for as-produced specimens tested at -50°C compared to as-produced tested at room temperature.
- G_c is nearly independent of core thickness for same density core
- G_c increases with an increase in core density
- G_c is significantly lower for Kevlar vs Nomex core

Effects of Moisture Diffusion in Sandwich Composites

- **Principal Investigator**
  - Mark E Tuttle
- **Students**
  - Current: Shiva Goutham Pattapu
  - Graduated: Hrishikesh (“Rishi”) Pathak, Anirudh Ashok, Andrew King, Ritika Singh, Karen Harban, Balakumaran (“Bala”) Gopalarethinam 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**

Thank You!

Questions, Comments, Suggestions?

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Advanced Materials in Transport Aircraft Structures
A part of the FAA Joint Advanced Materials & Structures Center of Excellence

Backup slides

Comparison of SCB Fracture toughness in different honeycomb core materials tested at both room temp and at -50°C