Effects of Moisture Diffusion in Sandwich Composites

2016 Technical Review

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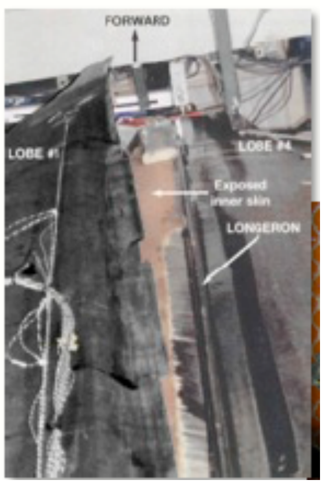
Shuyu 'Frank' Xia, and Mark Tuttle
Department of Mechanical Engineering
University of Washington

Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

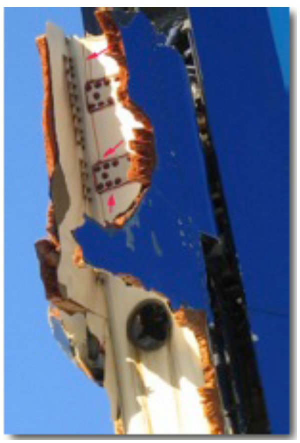
- In-service bond failures between composite facesheets and honeycomb cores have been reported in the space, marine, and aviation industries

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

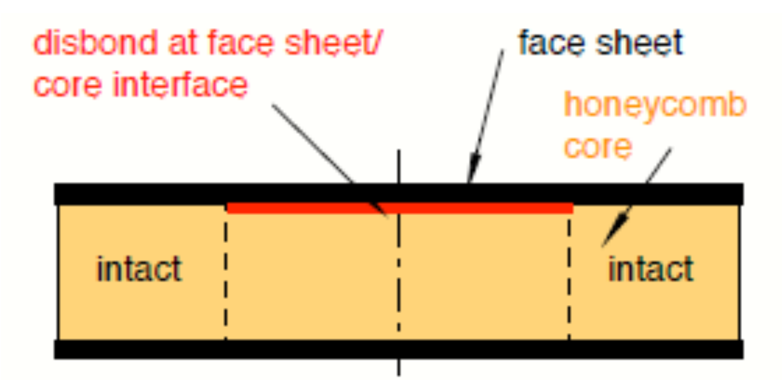
Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

- Core-to-skin disbond initiation and growth are not completely understood, but are thought to occur due to combination of factors:
  - Pressure differences between inside and outside of unvented honeycomb structures (Ground-Air-Ground or 'GAG' pressure cycles)

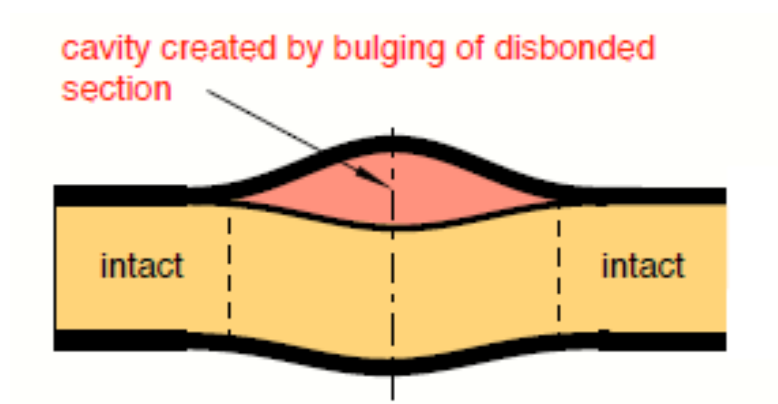
Configuration at ground level

P_o = 100 kPa = 14.7 psi



Configuration at 35,000 ft

P_o = 24 kPa = 3.5 psi



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    - Pressure differences between inside and outside of unvented honeycomb structures (Ground-Air-Ground or ‘GAG’ pressure cycles)
    - In-plane (design) loads
    - Water ingression into core, followed by freeze-thaw cycles
- Water ingression most commonly attributed to wicking of liquidous water through microcracks, along fiber/matrix interface, and/or through improper edge closeouts (all accentuated by GAG pressure cycles)
- Water ingression may also occur due to diffusion of water molecules through (undamaged) facesheets

Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

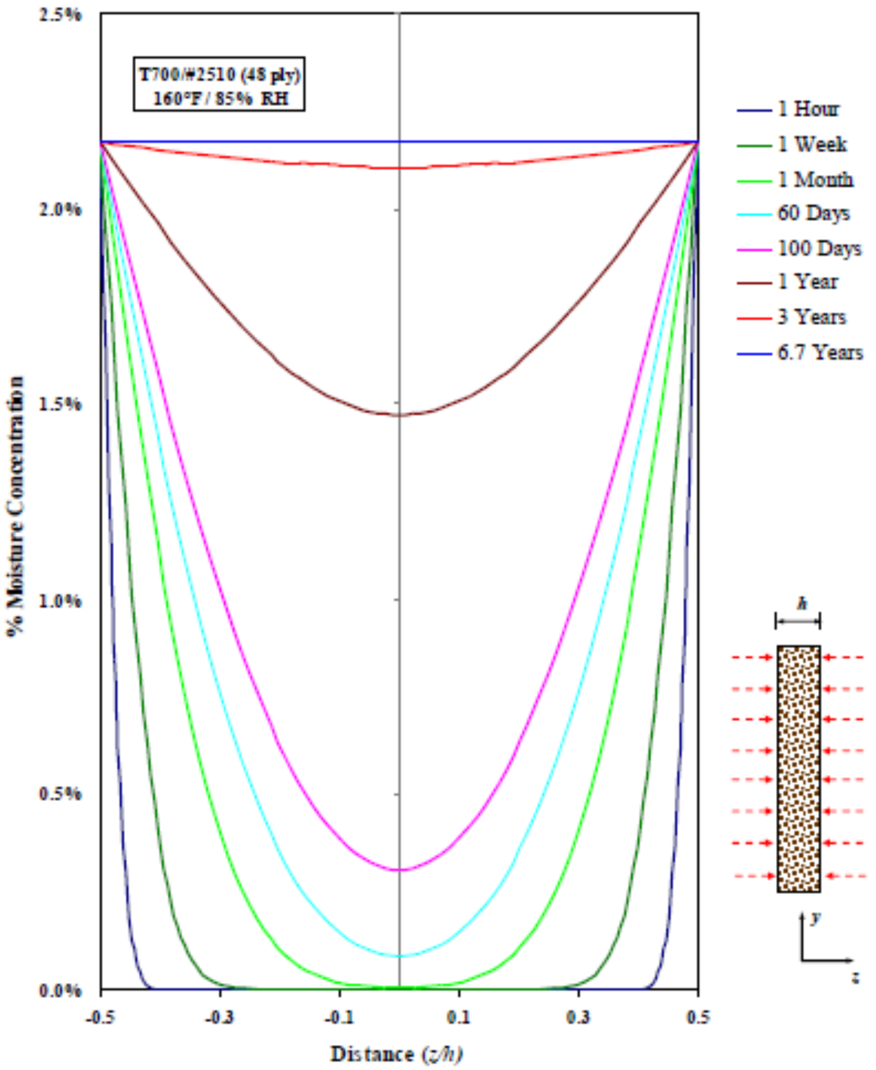
•Significant moisture transport via diffusion typically requires months or years, depending on:

- Temperature
- Thickness and material properties
- External humidity level

Effects of Moisture Diffusion in Sandwich Composites

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

Moisture diffusion in solid 48-ply Gr-Ep laminate; 160ºF, 85%RH (W. Seneviratne and J. Tomblin, JAMS 2012)



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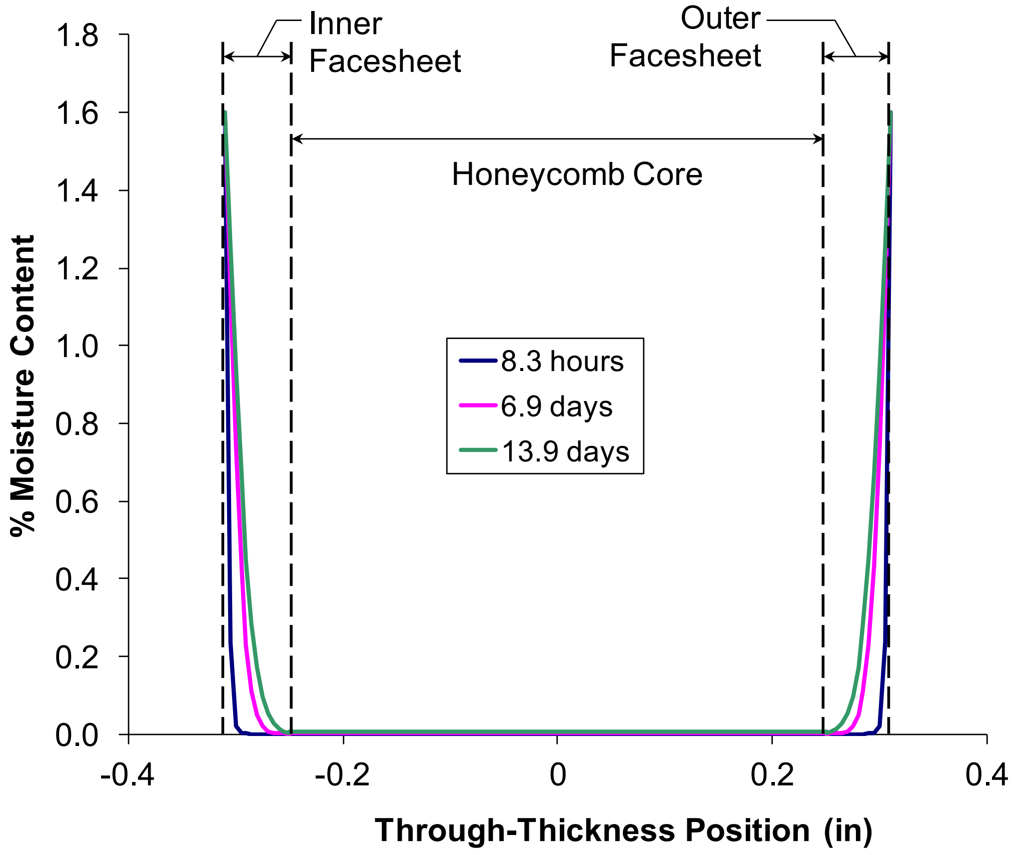
Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

Moisture diffusion in honeycomb sandwich panel:
-12-ply Gr-Ep facesheets
- 0.5 in Nomex core
- 90ºF, 80%RH
(Tuttle, AMTAS 2009)



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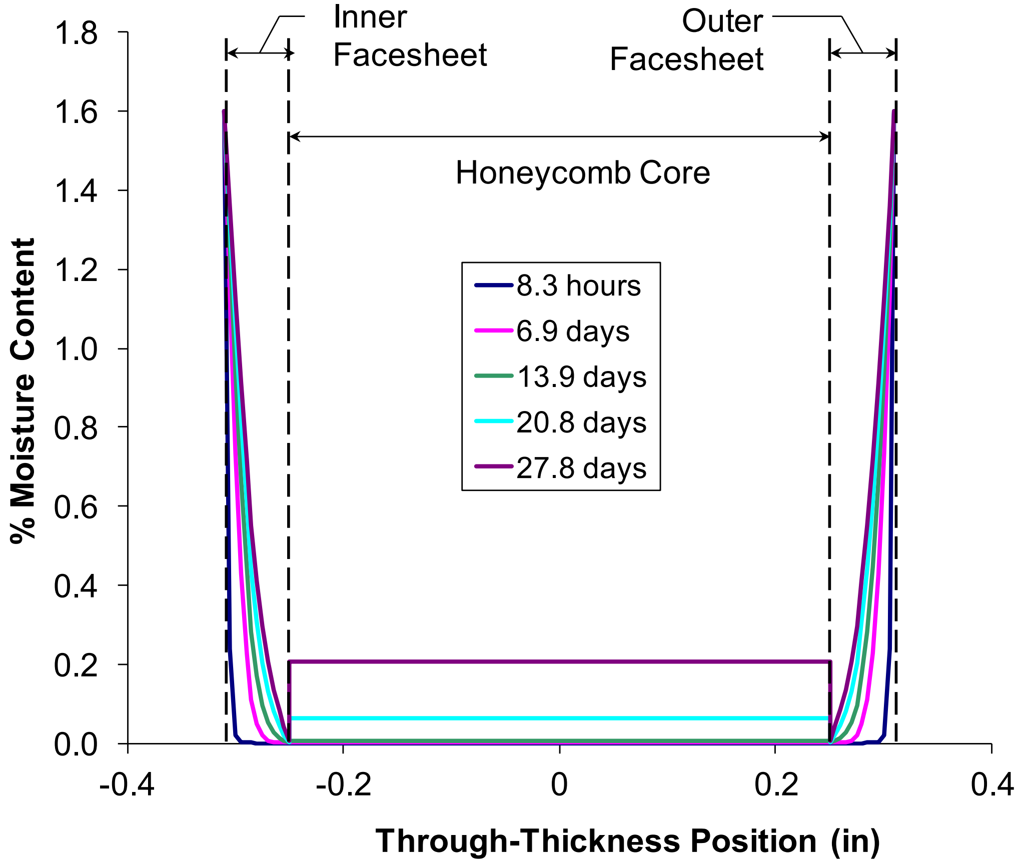

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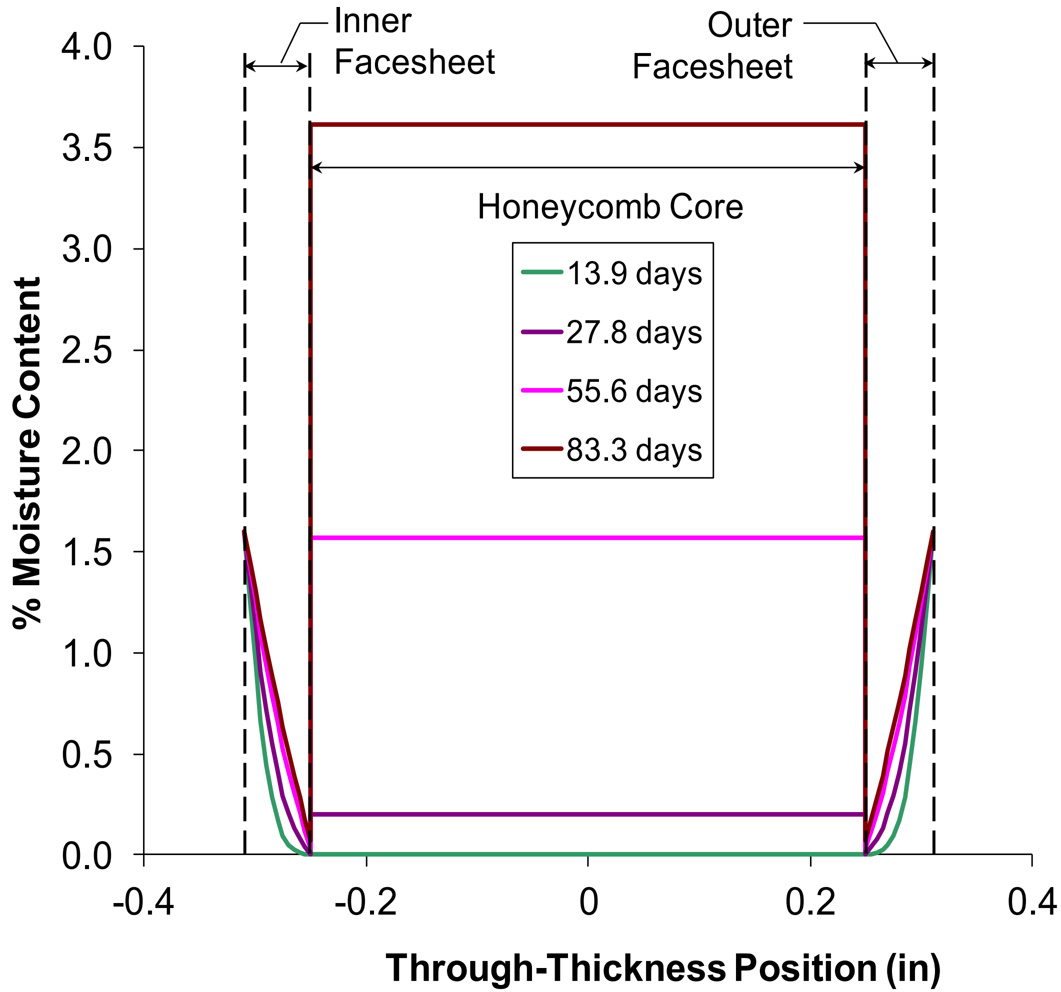

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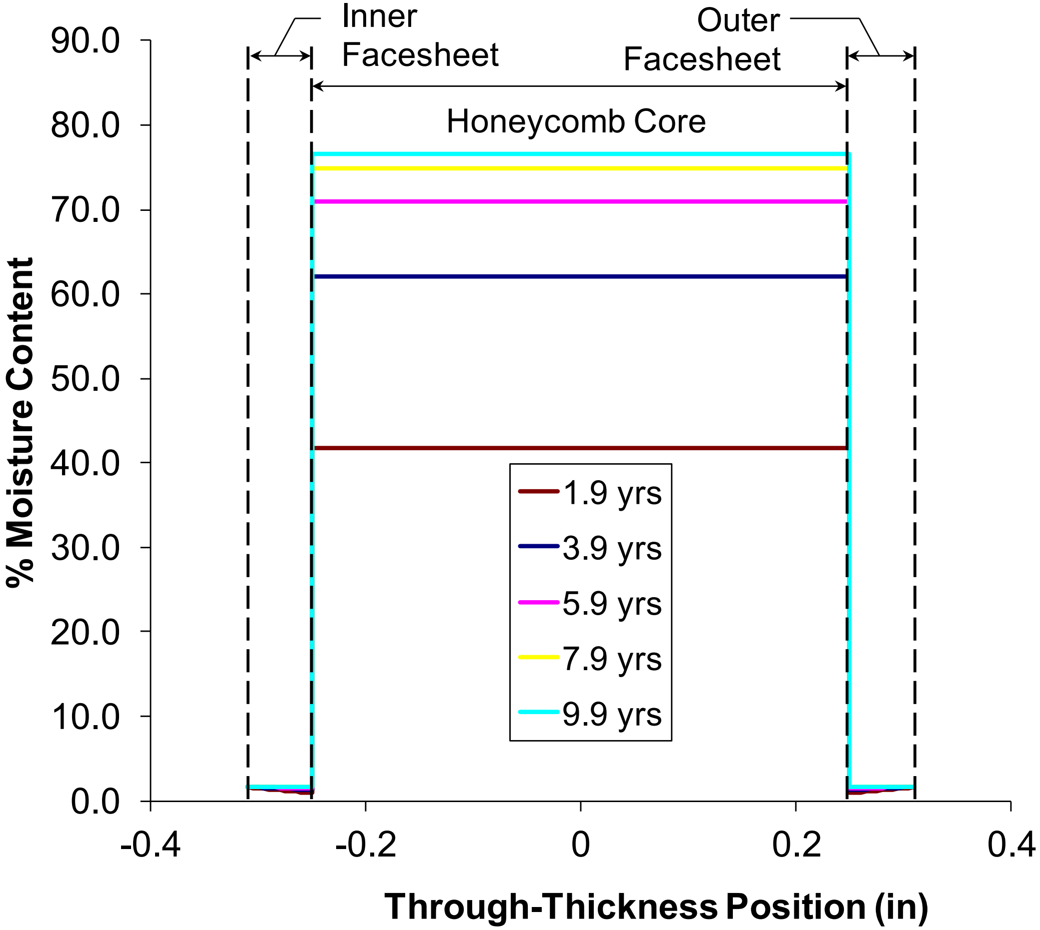


Moisture diffusion in honeycomb sandwich panel:

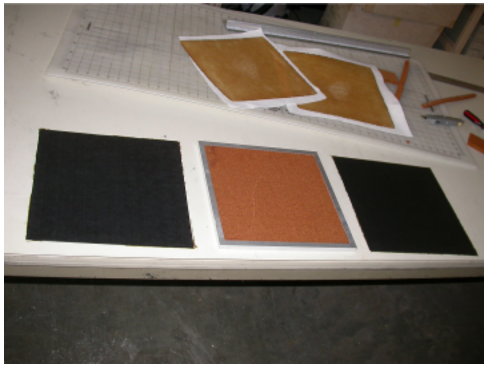
-12-ply Gr-Ep facesheets
- 0.5 in Nomex core
- 90ºF, 80%RH
- Core moisture content eventually equals external humidity

(Tuttle, AMTAS 2009)

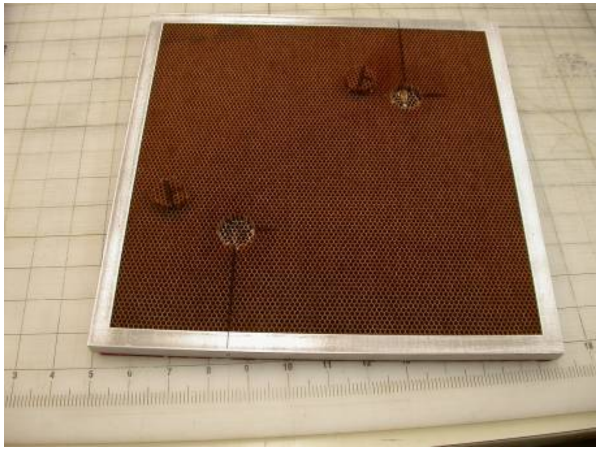
Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)



- Type 410 Nomex honeycomb core
- $[0/45/90/-45]_s$ Gr/Ep facesheets
- Core sized to fit within aluminum frame to insure 1-D, through-thickness diffusion



- First facesheet bonded to one side of panel using thin-film adhesive
- Pocket for embedded humidity sensors and thermocouples milled in core

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Motivation and Key Issues:

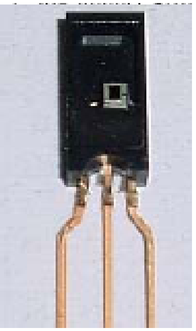
Experimental verification (Tuttle, AMTAS 2009)

Sandwich panel internally instrumented with:

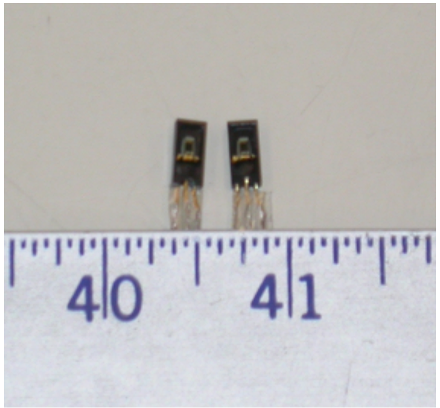
- 2 type K thermocouples
- 2 Ohmic Instruments Model HC-610 capacitive humidity sensors:
  - 5-95 %RH
  - -40 to 185°F operating range

HC-610 Thermoset polymer capacitive humidity sensor. Hybrid electronics. Linear output. Range 5 to 95 %RH 2%. Temp. – 40 to 185 °F. Supply voltage 4.0 - 5.8 VDC

PDF Data　PDF Man/Instructions



www.ohmicinstruments.com/



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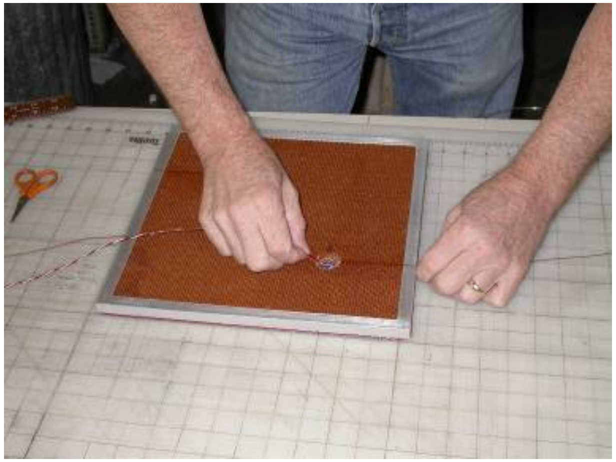
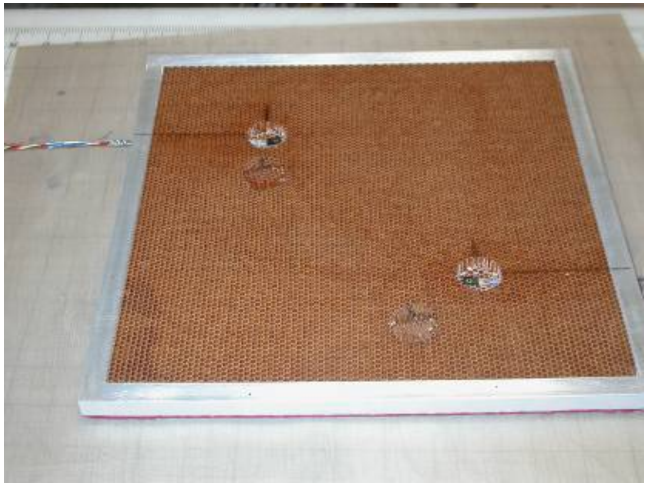


- Leadwires inserted through honeycomb and aluminum frame

- Installation of embedded sensors



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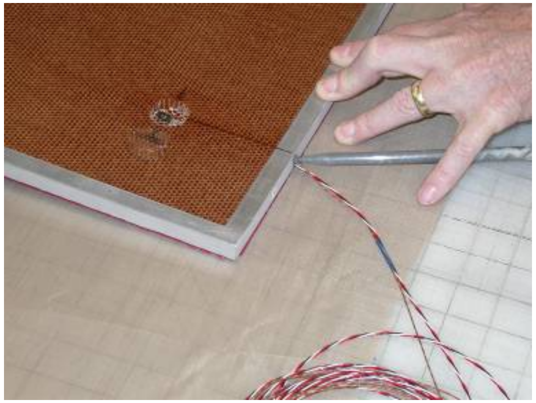
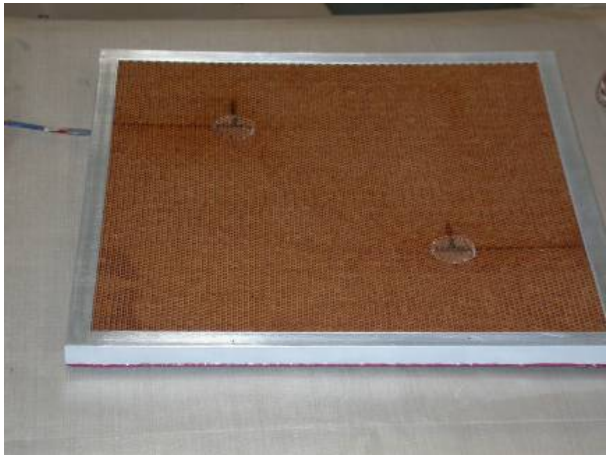


- Leadwire passage in aluminum frame sealed with epoxy

- Honeycomb 'caps' placed over instrumented sites



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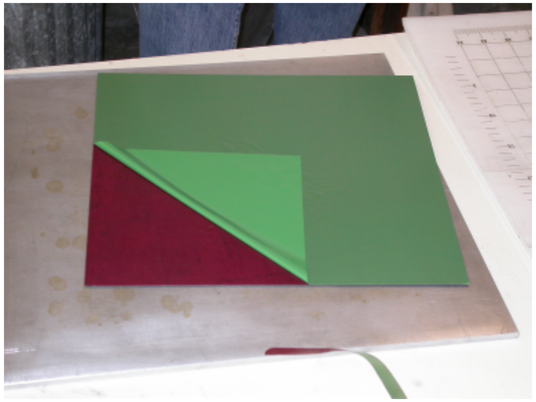


•Second facesheet bonded to panel using thin-film adhesive…

…and hot press

Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)

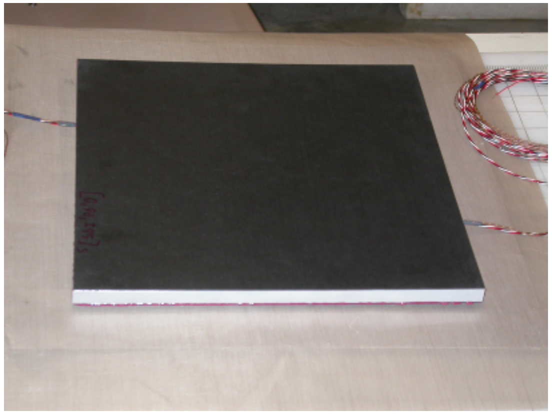
- Completed panel mounted in humidity chamber and exposed to constant environmental conditions for 12 months:

  - 40ºC (104ºF)

  - 55% RH

  - from 5 Aug '08 to 4 Aug '09

  - Sensors monitored continuously (i.e., every 30 minutes) using LabView



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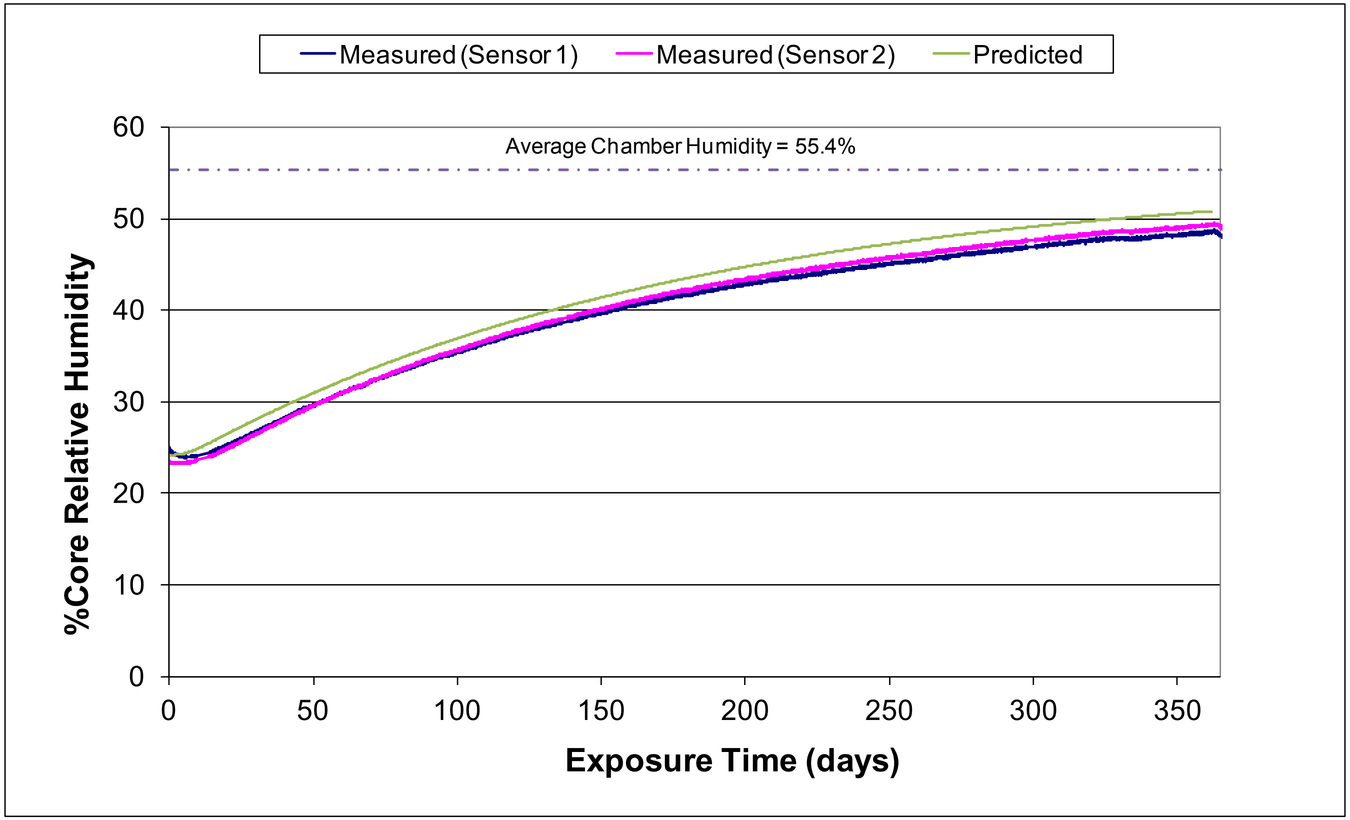

Effects of Moisture Diffusion in Sandwich Composites

Motivation and Key Issues:

- Honeycomb panels mounted on transport aircraft routinely experience pronounced thermal cycles:

  (ground level temperatures) ↔ (-60ºF at 35,000 ft)

- Implication: Over long times internal core humidity will increase to a level at which a condense-freeze-thaw-evaporate cycle may occur during each flight….may represent a long-term durability issue

Effects of Moisture Diffusion in Sandwich Composites

Objective: Determine if condense-freeze-thaw-evaporate cycle within core region cycle is detrimental. Specifically, subject representative honeycomb sandwich panels to high humidity and thermal cycles, and then measure if any

- Damage to facesheets, bondline, or core occurs (using optical microscopy)

- Change in effective bending stiffness occurs (using 4-point bending test)

- Change in strain-energy release rate G_{ic}, occurs (using single single cantilever beam specimen under development by CMH-17 Sandwich Disbond Task Group

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Effects of Moisture Diffusion in Sandwich Composites

- **Principal Investigator**
  - Mark Tuttle
- **Students**
  - William Smoot, Sung Lin ‘Jason’ Tien, Shuyu ‘Frank’ Xia
- **FAA Technical Monitor**
  - Lynn Pham
- **Industry Participation**
  - Bill Avery/The Boeing Company
  - Dan Holley and Chris Praggastis/3M
  - Bob Fagerlund/Bell Helicopter
- **Study Initiated in September 2015**

Effects of Moisture Diffusion in Sandwich Composites

<u>Technical Approach (some details still TBD):</u>

- Produce 20, 2 in x 12 in specimens with 4-ply *woven* facesheets with $[45/0/0/45]_T$ stacking sequence:

  - 5 specimens: inspect using optical microscopy and measure as-produced RT properties
  - 5 specimens: cycle as-produced panels between RT and -60ºF, then inspect using optical microscopy and measure RT properties
  - 10 specimens: increase core humidity to ~70%RH (expect to require about 4 mos exposure time)
    - 5 specimens : inspect using optical microscopy and measure RT properties
    - 5 specimens : cycle between room temp and -60ºF, then measure RT properties

Effects of Moisture Diffusion in Sandwich Composites

Technical Approach (some details TBD):

- Materials:
  - Cycom 970/PWC graphite/epoxy (certified to BMS 8-256), based on:
    - Cytec 970 epoxy resin
    - Torayca T300 3K woven fabric
  - Hexcel HRH-10 1/8-3.0 Nomex honeycomb core, ½ in thick
  - 3M AF 163-2k film adhesive

- Fabrication:
  - $[45/0/0/45]_T$ facesheets first produced using an autoclave cure
  - Secondary bonding operation used to bond facesheets to core
  - All cured materials stored in humidity chamber at 122ºF and ~7%RH to minimize initial moisture content

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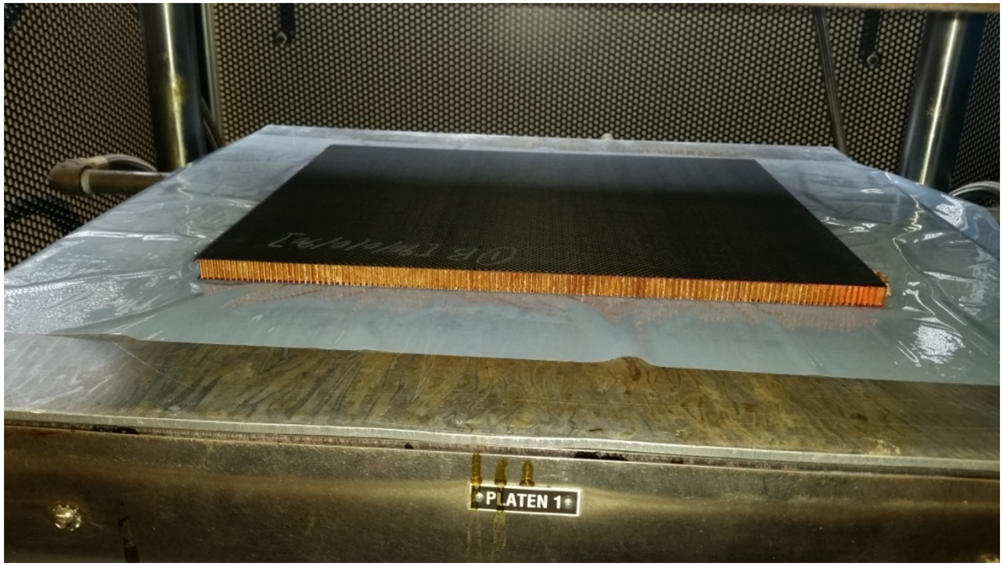

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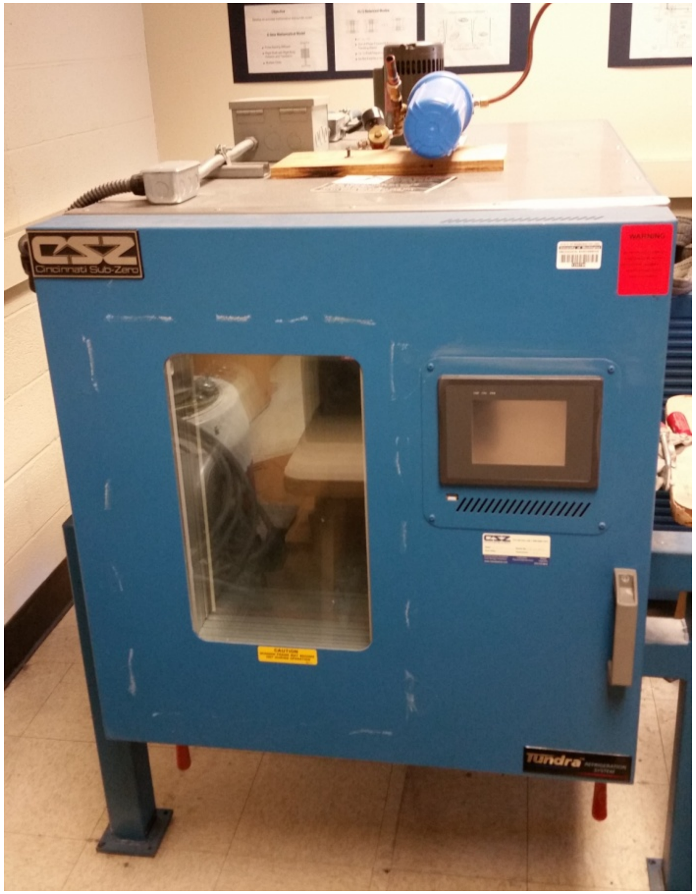

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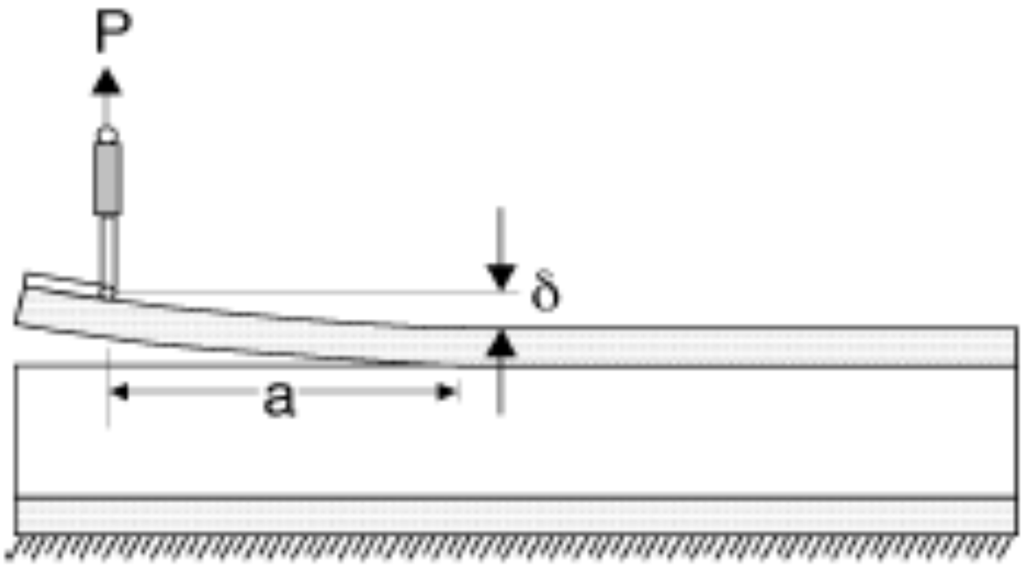
Effects of Moisture Diffusion in Sandwich Composites

Current Status

- Sufficient number of panels/specimens have been fabricated
- Single Cantilever Beam (SCB) text fixture nearing completion
  - Patterned after NIAR fixture
  - Similar to fixtures used by other members of CMH-17 Disbond working group
- Initial Testing to begin on/about 4 April
- Environmental conditioning to begin on/about 11 April

Effects of Moisture Diffusion in Sandwich Composites



Schematic of experimental arrangement to measure G_I for sandwich panels (under development by CMH-17 working group)

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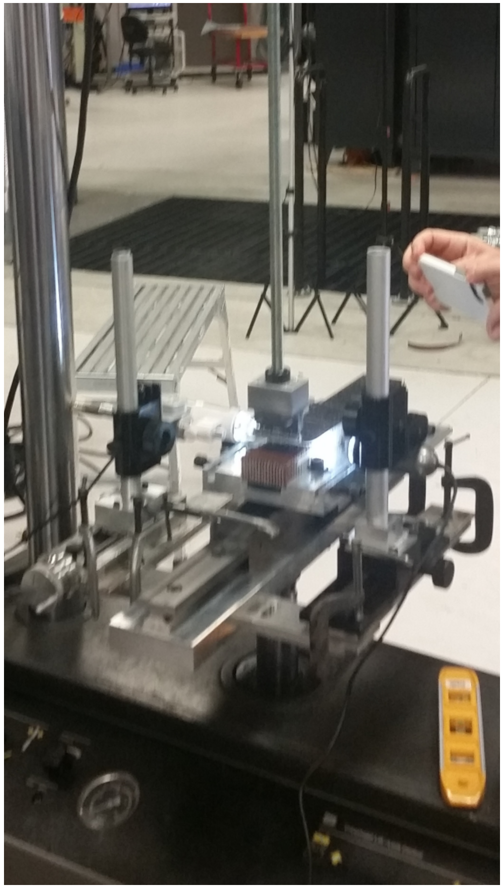

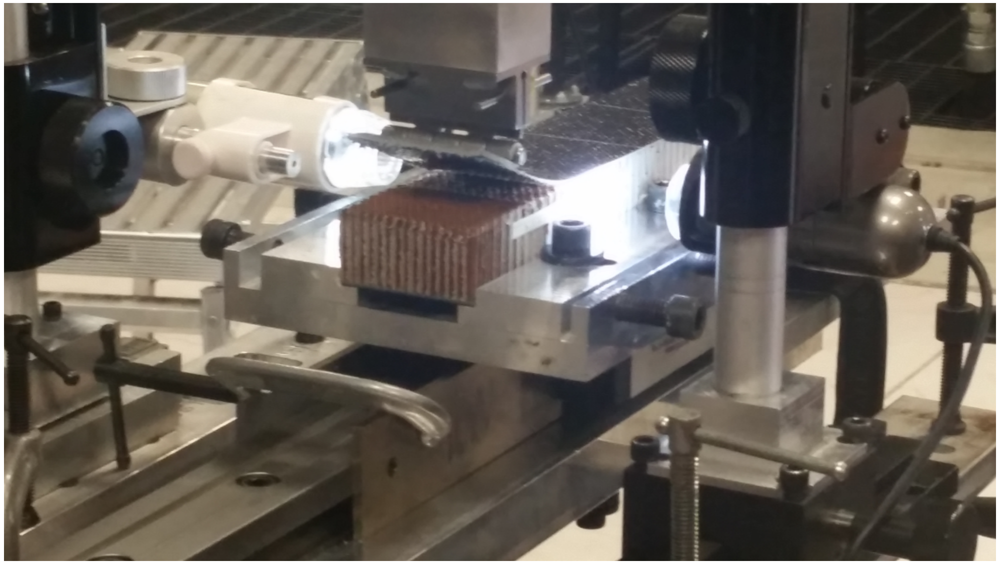

Photos of test setup at NIAR

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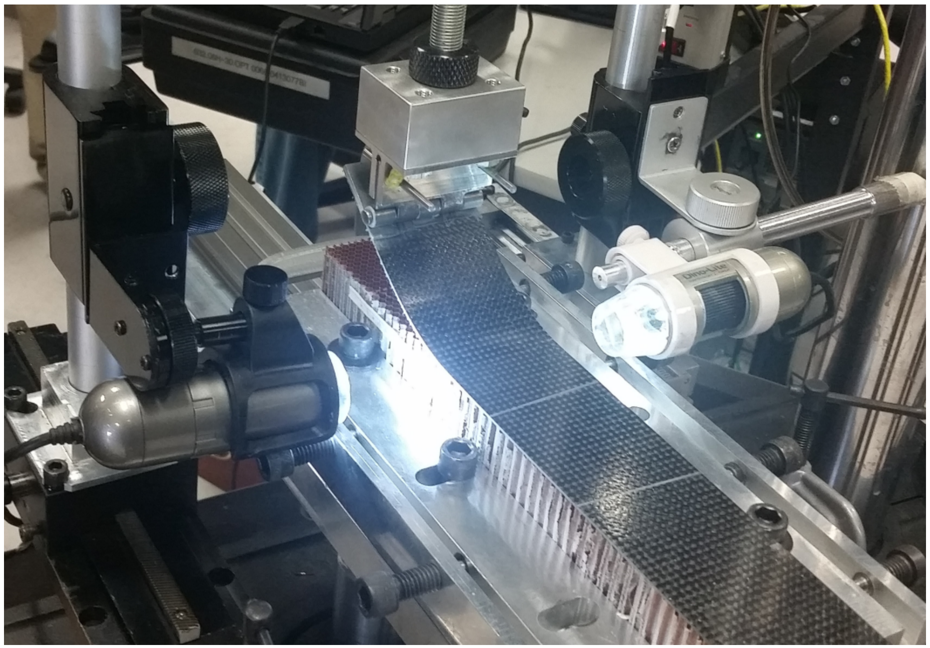

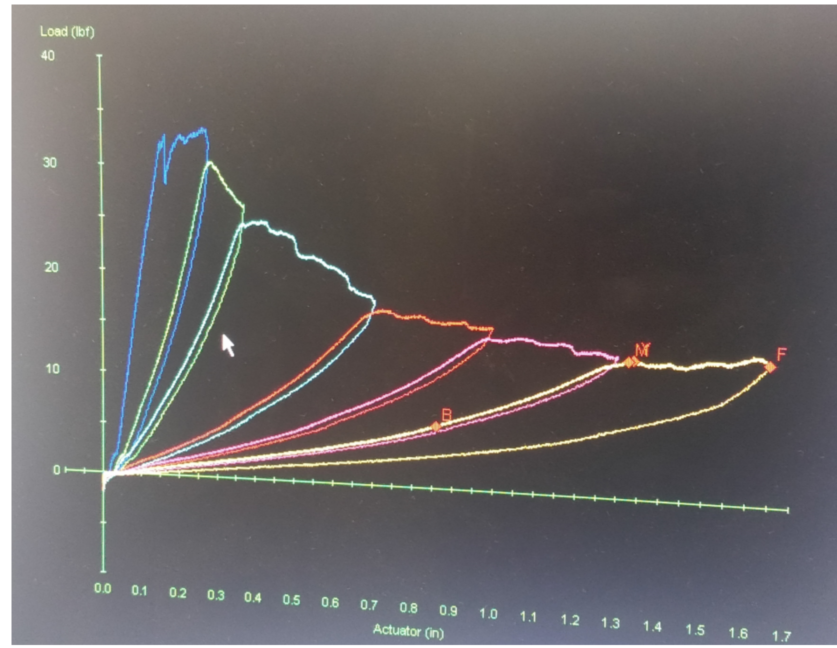

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Effects of Moisture Diffusion in Sandwich Composites

Benefit to Aviation:

- May identify a mechanism 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 Composites

Thank You!

Questions, Comments, Suggestions?

End of Presentation.

Thank you.

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Backup Slides

Predicting Moisture Diffusion

- Through-thickness (1-D) diffusion of moisture assumed to be governed by Fick's first and second laws:

$$\phi = D_z \frac{\partial c}{\partial z} \qquad\qquad \frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left[D_z \frac{\partial c}{\partial z}\right]$$

ϕ = rate of diffusion ("moisture flux") : units = mass/(area * time)

c = concentration : units = (mass/volume)

D_z = diffusivity : units = area/time

z = direction of diffusion : unit = length

t = time

Predicting Moisture Diffusion

- From an experimental point of view it is easier to deal with percent moisture by weight (*M*), rather than the concentration of moisture (*c*). Fick's first and second laws are restated as:

$$\phi = \frac{D_z \rho}{100} \frac{\partial M}{\partial z}$$

$$\frac{\partial M}{\partial t} = D_z \frac{\partial^2 M}{\partial z^2}$$

$$\rho = \text{density, mass/volume}$$

$$M = \text{"moisture content"}$$

$$M = \frac{\text{(current weight)} - \text{(dry weight)}}{\text{(dry weight)}} \text{X} 100\%$$

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Predicting Moisture Diffusion

- Temperature dependency of diffusion coefficient for solids (i.e., ply and core paper) assumed to follow a Arrhenius-type relationship:

$$D = D_o \exp\left(-\frac{E}{T}\right)$$

where: D_o, E = known material constants (differ for ply and core paper)

T = absolute temperature

Predicting Moisture Diffusion

- Temperature dependency of diffusion of H_20 vapor in air assumed to follow a power law of the form*:

$$D_{air} = 0.03376\left(\frac{T(^\circ R)}{491.67(^\circ R)}\right)^{1.81} \frac{in^2}{\sec}$$

* Massman, W.J., *Atmospheric Environment*, Vol 32 (6), pp 1111-1127 (1998).

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Predicting Moisture Diffusion

Estimated Core Density and Diffusivity

$$\rho_{core} = (V_{air})(\rho_{air}) + (V_{paper})(\rho_{paper})$$

$$D_{core} = (V_{air})(D_{air}) + (V_{paper})(D_{paper})$$

Predicting Moisture Diffusion

The moisture content (M) of any surface layer in contact with air can be related to the relative humidity according to (Springer, 1980):

$$M = M_u \left(\frac{\%RH}{100} \right)^b$$

- constant M_u = material property
- exponent b = 1 for most materials
- relationship used to define the boundary condition at all ply interfaces

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Predicting Moisture Diffusion

Preceding relations allows forward-difference solution to Fick's equations; summary

- (At all interior ply interfaces) moisture flux leaving ply *k* must equal moisture flux entering ply *k+1*

- (Boundary conditions): $M = M_u\left(\frac{\%RH}{100}\right)$

- (Initial conditions): Initial through-thickness moisture content assumed uniform (assumed = zero in '03)

- Time step increment of 1 minute

Predicting Moisture Diffusion

Properties Used in '03

Property	Gr/Ep (typical values)	Type 410, 2-mil Nomex (www.matweb.com)
D_o	0.010 *in²/sec* *(see note)*	0.006 *in²/sec*
E	10300 °*R*	9000 °*R*
M_u	0.02	0.03
Density, ρ	0.054 *lbm/in³*	0.026 *lbm/in³*

Note: Properties reported for Gr/Ep vary widely. For example:

$$0.005 < D_o < 0.040 \; in^2/sec$$