Effects of Moisture Diffusion in Sandwich Composites

2016 Technical Review
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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)
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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
\[ P_0 = 100 \text{ kPa} = 14.7 \text{ psi} \]

Configuration at 35,000 ft
\[ P_0 = 24 \text{ kPa} = 3.5 \text{ psi} \]
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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
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Motivation and Key Issues:

- Significant moisture transport via diffusion typically requires months or years, depending on:
  - Temperature
  - Thickness and material properties
  - External humidity level
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Motivation and Key Issues:

Moisture diffusion in solid 48-ply Gr-Ep laminate; 160°F, 85%RH (W. Seneviratne and J. Tomblin, JAMS 2012)
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Motivation and Key Issues:

Moisture diffusion in honeycomb sandwich panel:
- 12-ply Gr-Ep facesheets
- 0.5 in Nomex core
- 90°F, 80%RH
(Tuttle, AMTAS 2009)
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Motivation and Key Issues:

Moisture diffusion in honeycomb sandwich panel:
- 12-ply Gr-Ep facesheets
- 0.5 in Nomex core
- 90°F, 80%RH
- Core moisture content eventually equals external humidity
(Tuttle, AMTAS 2009)
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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

www.ohmicinstruments.com/
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Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)

- Leadwires inserted through honeycomb and aluminum frame
- Installation of embedded sensors
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Motivation and Key Issues:
Experimental verification (Tuttle, AMTAS 2009)

- Leadwire passage in aluminum frame sealed with epoxy
- Honeycomb ‘caps’ placed over instrumented sites
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Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)

- Second facesheet bonded to panel using thin-film adhesive...

...and hot press
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Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)

- Completed panel mounted in humidity chamber and exposed to constant environmental conditions for 12 months:
  - 40°C (104°F)
  - 55% RH
  - from 5 Aug ‘08 to 4 Aug ’09
  - Sensors monitored continuously (i.e., every 30 minutes) using LabView
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Motivation and Key Issues:

Experimental verification (Tuttle, AMTAS 2009)

![Graph showing moisture diffusion in sandwich composites](image-url)
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) $\leftrightarrow (-60^\circ F \text{ at } 35,000 \text{ ft})$

- 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
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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)
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
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Technical Approach (some details still TBD):

- 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
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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 122°F and ~7%RH to minimize initial moisture content
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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
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Schematic of experimental arrangement to measure $G_1$ for sandwich panels (under development by CMH-17 working group)
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Photos of test setup at NIAR
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Photos of test setup at NIAR
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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
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Thank You!

Questions, Comments, Suggestions?
End of Presentation.

Thank you.
Backup Slides
Predicting Moisture Diffusion

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

\[ \phi = D_z \frac{\partial c}{\partial z} \]

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

- \( \phi \) = 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:

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

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

\(\rho = \text{density, mass/volume}\)

\(M = \text{"moisture content"}\)

\[
M = \frac{(\text{current weight}) - (\text{dry weight})}{(\text{dry weight})} \times 100\%
\]
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$_2$O vapor in air assumed to follow a power law of the form*:

$$D_{air} = 0.03376 \left( \frac{T(\degree R)}{491.67(\degree R)} \right)^{1.81} \text{ in}^2 \text{ sec}^{-1}$$

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
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**

<table>
<thead>
<tr>
<th>Property</th>
<th>Gr/Ep (typical values)</th>
<th>Type 410, 2-mil Nomex (<a href="http://www.matweb.com">www.matweb.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_o$</td>
<td>0.010 $in^2/sec$</td>
<td>0.006 $in^2/sec$</td>
</tr>
<tr>
<td>$E$</td>
<td>10300 °R</td>
<td>9000 °R</td>
</tr>
<tr>
<td>$M_u$</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>0.054 $lbm/in^3$</td>
<td>0.026 $lbm/in^3$</td>
</tr>
</tbody>
</table>

**Note:** Properties reported for Gr/Ep vary widely. For example: $0.005 < D_o < 0.040$ $in^2/sec$