Test Method Development for Environmental Durability of Composite Bonded Joints

Dan Adams, Larry DeVries
Nicholas Brown, David Ricsi, Karli Gillette

University of Utah

2014 Technical Review
FAA Sponsored Project Information

- Principal Investigators: Dr. Dan Adams, Dr. Larry DeVries

Graduate Student Researchers:
  Nicholas Brown
  David Ricsi

- FAA Technical Monitor:
  Curt Davies

- Collaborators:
  Boeing: Kay Blohowiak and Will Grace
  Air Force Research Laboratory: Jim Mazza
Outline

• Overview: Environmental durability testing of metal bonded joints

• Candidate environmental durability test methods for composite bonded joints
  – Static wedge test
  – Traveling wedge test
  – Back-bonded Double Cantilever Beam (DCB) test

• Current Status and Upcoming Work
Our Earlier Research Focus:
Improving ASTM D3762 Metal Wedge Test


- Able to assess quality of bond quickly by causing rapid hydration of oxide layers
- Bonded aluminum cantilever beam loaded by forcing a wedge between adherends
- Wedge is retained in specimen
- Assembly placed into test environment
- Crack growth due to environmental exposure is measured following a prescribed time period
Background: Environmental Durability
Degradation of Metal Bonds Due To Hydration

- Aluminum when exposed to oxygen forms an aluminum oxide surface layer
  \[ 4\text{Al} + 3\text{O}_2 \rightarrow 2\text{Al}_2\text{O}_3 \]

- Aluminum oxide layer hydrates when exposed to water
  \[ \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} \rightarrow 2\text{Al(OH)}_3 \]

- Hydration causes bond degradation (metal adherends)

*Davis and McGregor, "Assessing Adhesive Bond Failures: Mixed-Mode Bond Failures Explained" (2010)*
Why Environmental Durability Tests of Composite Bonded Joints?

“There is currently no known mechanism similar to metal-bond hydration for composites”

- Ensure longer-term environmental durability of composite bonds
- Investigate effects of environmental exposure on performance of bonded composite joints
  - Failure mode: cohesion versus adhesion failure
  - Estimate fracture toughness reduction
- Assess effectiveness of surface preparation
Environmental Durability Testing of Composites: Candidate Test Methods

- Static Wedge Crack Test
- Traveling Wedge Test
- Boeing Back-Bonded DCB

Van Voast et al., SAMPE 2013
Development of a Composite Wedge Test: Additional Complexities

- Variable flexural stiffness of composite adherends
  - Environmental crack growth dependent on adherend flexural stiffness
    - Must be within an acceptable range
    Or
    - Must tailor wedge thickness for composite adherends
- Restrictions in fiber orientation adjacent to bonded interface
- Failure in the composite laminate prior to failure in the adhesive or at the bondline
Consider composite adherends as cantilever beams

- Measured values of crack length, \( a \)
- Known value of beam deflection, \( \delta \)

\[ \delta = t/2 \] (half of wedge thickness)

Tip deflection of a cantilever beam:

\[
\delta = \frac{t}{2} = \frac{P l^3}{3 E_f I} = \frac{T a^3}{3 E_f I}
\]

- \( \delta \) = tip deflection
- \( t \) = wedge thickness
- \( h \) = adherend thickness
- \( b \) = specimen width
- \( a \) = crack length
- \( E_f \) = flexural modulus
- \( T \) = load to deflect tip of beam
- \( G_c \) = fracture toughness

Strain energy due to bending:

\[ U = \frac{1}{2} T \delta \]

Strain energy release rate:

\[ G_c = \frac{dU}{da} \]

\[
G_c = \frac{3 E_f t^2 h^3}{16 a^4}
\]
Effect of Flexural Stiffness of Composite Adherend on Crack Growth

Wedge testing using with two different adherend thicknesses:

- Same composite material, same laminate (same $E_f$)
- Two laminate thicknesses: $h = 0.06$ in. and $h = 0.12$ in.
- Assume 50% reduction in $G_c$ from 25 to 12.5 in-lb/in²

\[
G_c = \frac{3 E_f t^2 h^3}{16 a^4}
\]

For $h = 0.06$ in.
\[
\begin{align*}
a_{\text{initial}} &= 0.879 \text{ in.} \\
a_{\text{final}} &= 1.046 \text{ in.} \\
\text{Total Growth} &= 0.17 \text{ in.}
\end{align*}
\]

For $h = 0.12$ in.
\[
\begin{align*}
a_{\text{initial}} &= 1.479 \text{ in.} \\
a_{\text{final}} &= 1.759 \text{ in.} \\
\text{Total Growth} &= 0.28 \text{ in.}
\end{align*}
\]

Changing adherend flexural stiffness changes...
- Initial crack length
- Environmental crack growth
Effect of Adherend Flexural Stiffness:
Experimental Investigation

• Unidirectional IM7/8552 carbon/epoxy adherends
• AF163-2K film adhesive
• Grit-blast & solvent wipe surface preparation
• Four adherend thicknesses to produce different $E_f$
  • Thick adherends: maximize crack growth (25 ply)
  • Match thickness of aluminum - 1/8 in. adherends (20 ply)
  • Match EI of aluminum adherends (13 ply)
  • Thin adherends: minimize crack growth (7 ply)
• 122°F (50°C) and 95% humidity environment for 6 days
Static Wedge Test Results: Effects of Composite Adherend Thickness

- Crack Length, in.
- Time (days)

7 ply, 13 ply, 20 ply, 25 ply

Ambient 122F / 95% RH
Increasing adherend thickness (and flexural modulus)...

- Increases crack length
- Increases crack growth
Composite Wedge Test Development: Current and Upcoming Work

- Investigate temperature sensitivity of test results
- Investigate “non-ideal” surface preparation conditions
  - Released and unreleased nylon peel ply
    - Grit blasted, hand sanded
  - Released and unreleased polyester peel ply
    - Grit blasted, hand sanded
- $G_{1c}$ correlation between static wedge, travelling wedge and DCB tests
Traveling Wedge Test for Environmental Durability Assessment

- Longer version of static wedge specimen
- Moisture saturation of bonded composite specimen prior to testing
- Wedge driven continuously through adhesive bondline at elevated temperature using testing machine
- Assessment of relatively large bond area
- Can provide an estimate of $G_c$
- Limited prior usage/investigation for environmental durability assessment
Traveling Wedge Test: 
Test Methodology

- Moisture saturation of specimen prior to testing at elevated temperature
- Wedge insertion similar to static wedge test
- Record position of crosshead of test machine associated with initial wedge position in specimen
- Record crosshead displacement associated with prescribed increments of crack extension (5 mm)
- Determine crack length beyond wedge, \( a \)
- Calculate \( G_c \) as for static wedge test

\[
G_c = \frac{3 E_f t^2 h^3}{16 a^4}
\]
Traveling Wedge Test: Initial Assessment

- **Unidirectional IM7/8552 carbon/epoxy adherends**
  - Thin adherends: (3 ply, 0.024 in.)
    - Preferred for shorter moisture saturation time
    - Of concern due to short crack length
  - Thick adherends: (20 ply, 0.144 in.)
    - More representative of static wedge and DCB specimens
    - Long moisture saturation time (reduced if “back-bonded”)
- **AF163-2K film adhesive**
- **Two surface preparations investigated**
  - “Ideal”: Grit-blast & acetone wipe
  - “Non-ideal”: Nylon peel ply
Traveling Wedge Test:
Initial Results Using Thick Adherends

“Ideal” bond (grit blasted) at room temp/ambient conditions
- Cohesion failure
- Stable crack growth
- Repeatable results
“Non-Ideal” bond (Nylon peel ply) at room temp/ambient

- Adhesion failure
- “Stick-slip crack growth behavior
Traveling Wedge Test: Initial Results Using Thin Adherends

“Ideal” bond (grit blasted) at elevated temp/wet conditions

- Moisture saturation in ~3 weeks
- Tested at 122°F (50°C)
- Significant interlaminar failure
Traveling Wedge Test Assessment: Current and Upcoming Work

- Further evaluation of adherend thickness effects
- Testing of additional “non-ideal” surface preparations conditions
- Comparison of $G_c$ estimates with static wedge, and back-bonded DCB tests
Environmental Durability Testing: Boeing Back-Bonded DCB Test

- Bond thin adherends with desired surface preparation and adhesive
- Moisture saturate thin bonded composite specimen
- Bond doubler panels to thin specimens to produce full DCB specimen thickness
- Test at elevated temperature conditions

Van Voast, Blohowiak, Osborne and Belcher, “Rapid Test Methods for Adhesives and Adhesion” (SAMPE 2013)
Boeing Back-Bonded DCB Test: Current and Upcoming Work

• Testing of “ideal” and “non-ideal” surface conditions

• Investigate effects of test temperature

• Provide baseline $G_c$ values for comparison with static wedge, and traveling wedge testing
Environmental Durability Testing of Composites: Summary of Candidate Test Methods

Static Wedge Crack Test
- Simple to perform
- Several tests performed concurrently
- Estimate $G_c$ at both ambient and hot/wet conditions
- Extended time in environmental chamber
- Small bond area assessed

Traveling Wedge Test
- Relatively large bond area may be assessed
- Estimate $G_c$ at hot/wet conditions
- Single specimen tested at a time
- Moderate to relatively long moisture conditioning

Boeing Back-Bonded DCB
- Accurate, well accepted measure of $G_c$
- Single specimen tested at a time
- Moderate moisture conditioning time
SUMMARY

Benefits to Aviation

• Improved environmental durability test method for metal bonds (metal wedge test, ASTM D3762)

• Composite wedge test for assessing the environmental durability of composite bonds

• Evaluation of candidate test methods for assessing the environmental durability of adhesively bonded aircraft structures

• Dissemination of research results through FAA technical reports and conference/journal publications