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Test Method Development for Environmental Durability of Composite Bonded Joints

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THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

- Principal Investigators: **Dr. Dan Adams,**
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  Air Force Research Laboratory: Jim Mazza

Outline

- Overview: Environmental durability testing of metal bonded joints

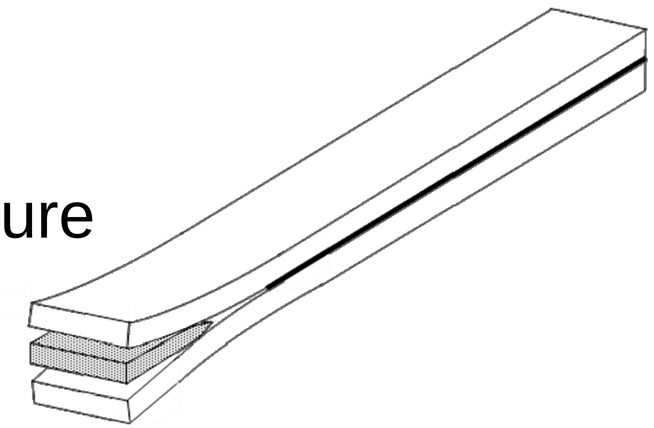
- Candidate environmental durability test methods for composite bonded joints
  - Static wedge test
  - Traveling wedge test
  - Back-bonded Double Cantilever Beam (DCB) test

- Current Status and Upcoming Work

Our Earlier Research Focus:
Improving ASTM D3762 Metal Wedge Test

ASTM D 3762: "Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)"

- Able to asses 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

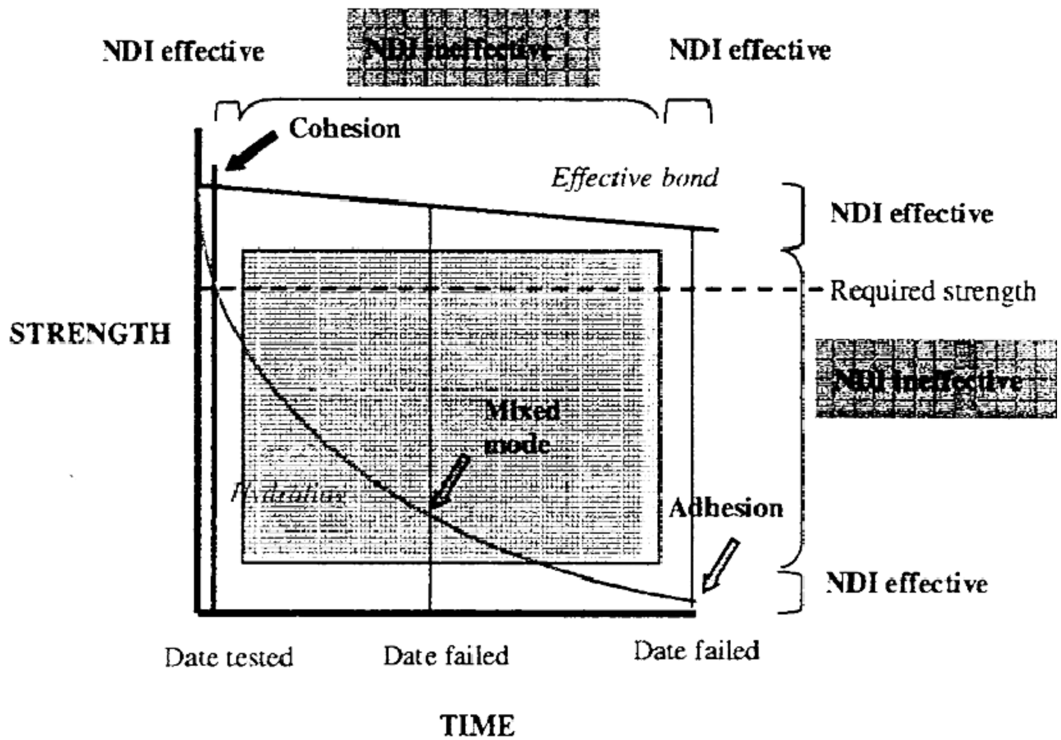
- **Aluminum when exposed to oxygen forms an aluminum oxide surface layer**

  $4Al + 3O_2 \Rightarrow 2Al_2O_3$

- **Aluminum oxide layer hydrates when exposed to water**

  $Al_2O_3 + 3H_20 \Rightarrow 2Al(OH)_3$

- **Hydration causes bond degradation (metal adherends)**



Davis and McGregor, "Assessing Adhesive Bond Failures: Mixed-Mode Bond Failures Explained" (2010)

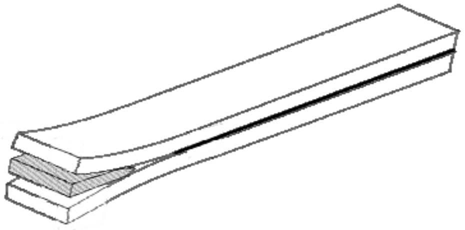
Why Environmental Durability Tests of Composite Bonded Joints?

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

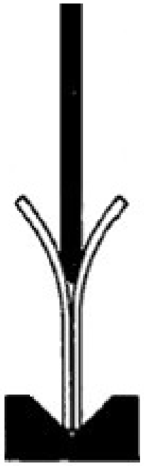
- **Ensure longer-term environmental durability of composite bonds**
- **Investigate effects of environmental exposure on performance of bonded composite joints**
  - **Failure mode: cohesion versus adhesion failure**
  - **Estimate fracture toughness reduction**
- **Assess effectiveness of surface preparation**

Environmental Durability Testing of Composites: Candidate Test Methods

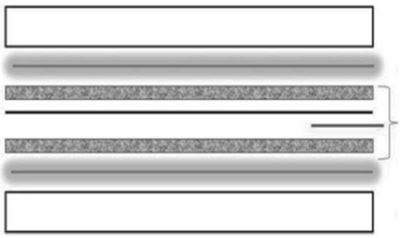
- **Static Wedge Crack Test**



- **Traveling Wedge Test**



- **Boeing Back-Bonded DCB**

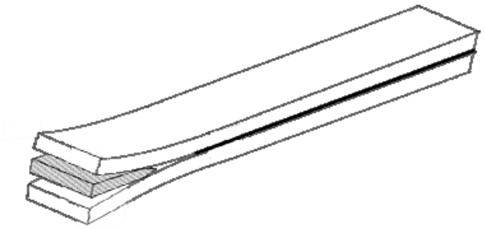


Van Voast et al., SAMPE 2013

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**

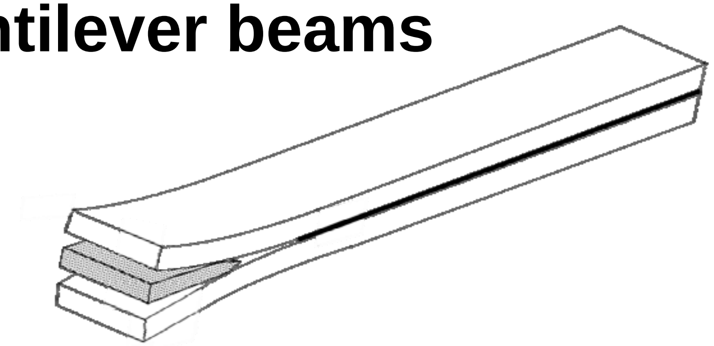
- **Failure in the composite laminate prior to failure in the adhesive or at the bondline**

Estimate of Fracture Toughness, G_c Using Static Wedge Test

Consider composite adherends as cantilever beams

- **Measured values of crack length, a**
- **Known value of beam deflection, δ**

δ = t/2 (half of wedge thickness)



Tip deflection of a cantilever beam: $$\delta = \frac{t}{2} = \frac{P\,l^3}{3\,E_f\,I} = \frac{T\,a^3}{3\,E_f\,I}$$

$$T = \frac{E_f\,b\,h^3\,t}{8\,a^3}$$

Strain energy due to bending: $U = \frac{1}{2} T\,\delta$

Strain energy release rate: $G_c = \frac{dU}{da}$

$$G_c = \frac{3\,E_f\,t^2\,h^3}{16\,a^4}$$

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

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

$$G_c = \frac{3\, E_f\, t^2\, h^3}{16\ a^4} \quad \Rightarrow \quad a = \sqrt[4]{\frac{3\, E_f\, t^2\, h^3}{16\ G_c}}$$

For h = 0.06 in.

$a_{initial}$ = 0.879 in.

a_{final} = 1.046 in.

Total Growth = 0.17 in.

For h = 0.12 in.

$a_{initial}$ = 1.479 in.

a_{final} = 1.759 in.

Total Growth = 0.28 in.

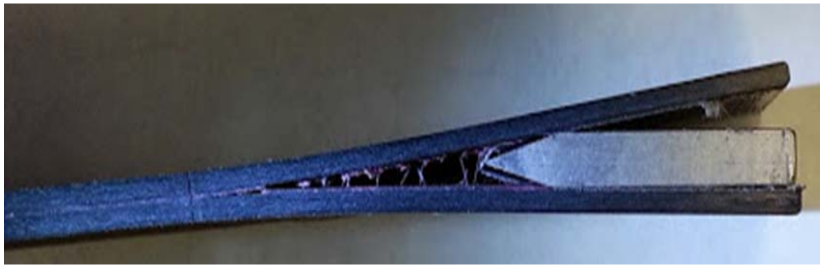
Changing adherend flexural stiffness changes…

- Initial crack length

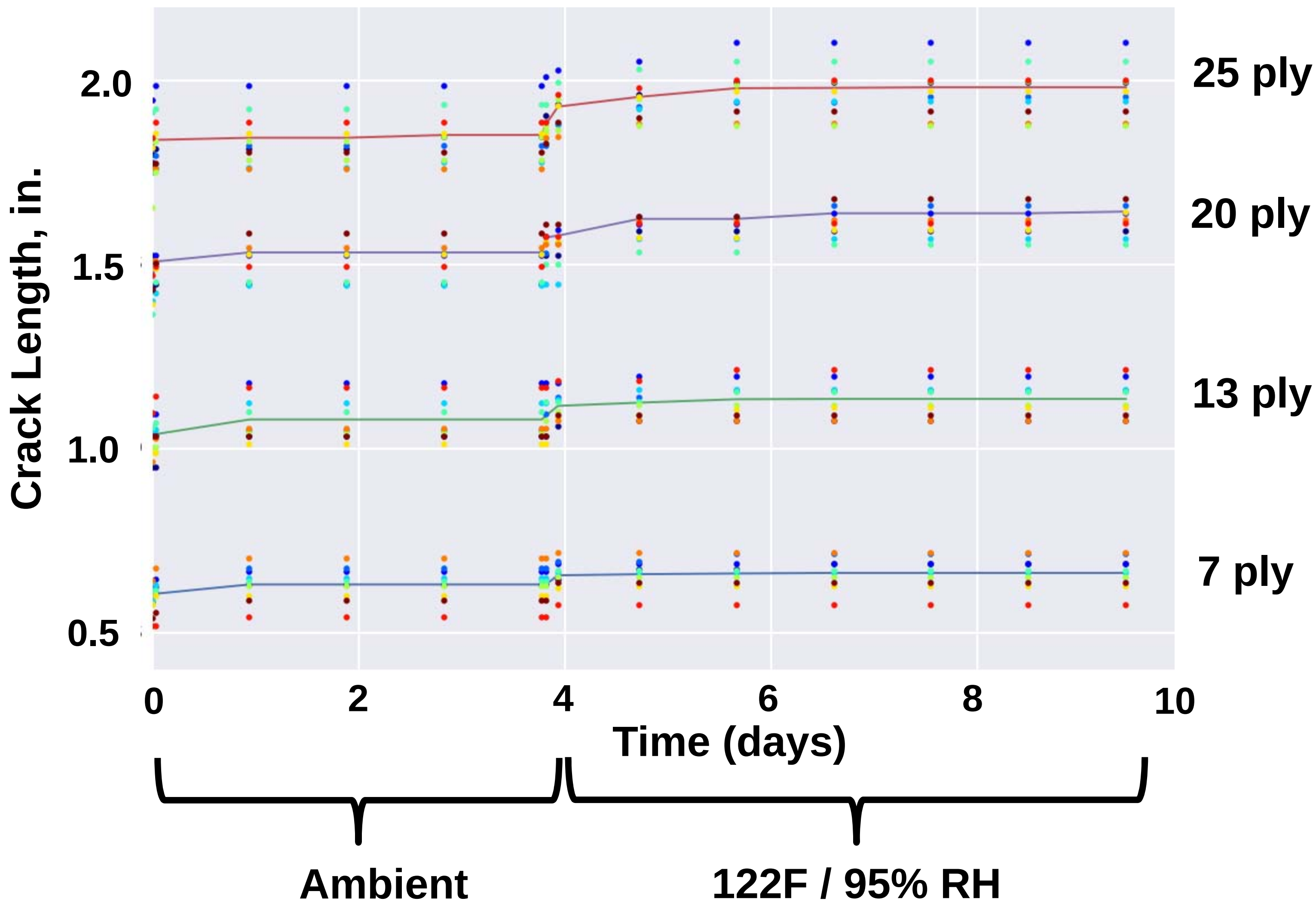
- Environmental crack growth

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



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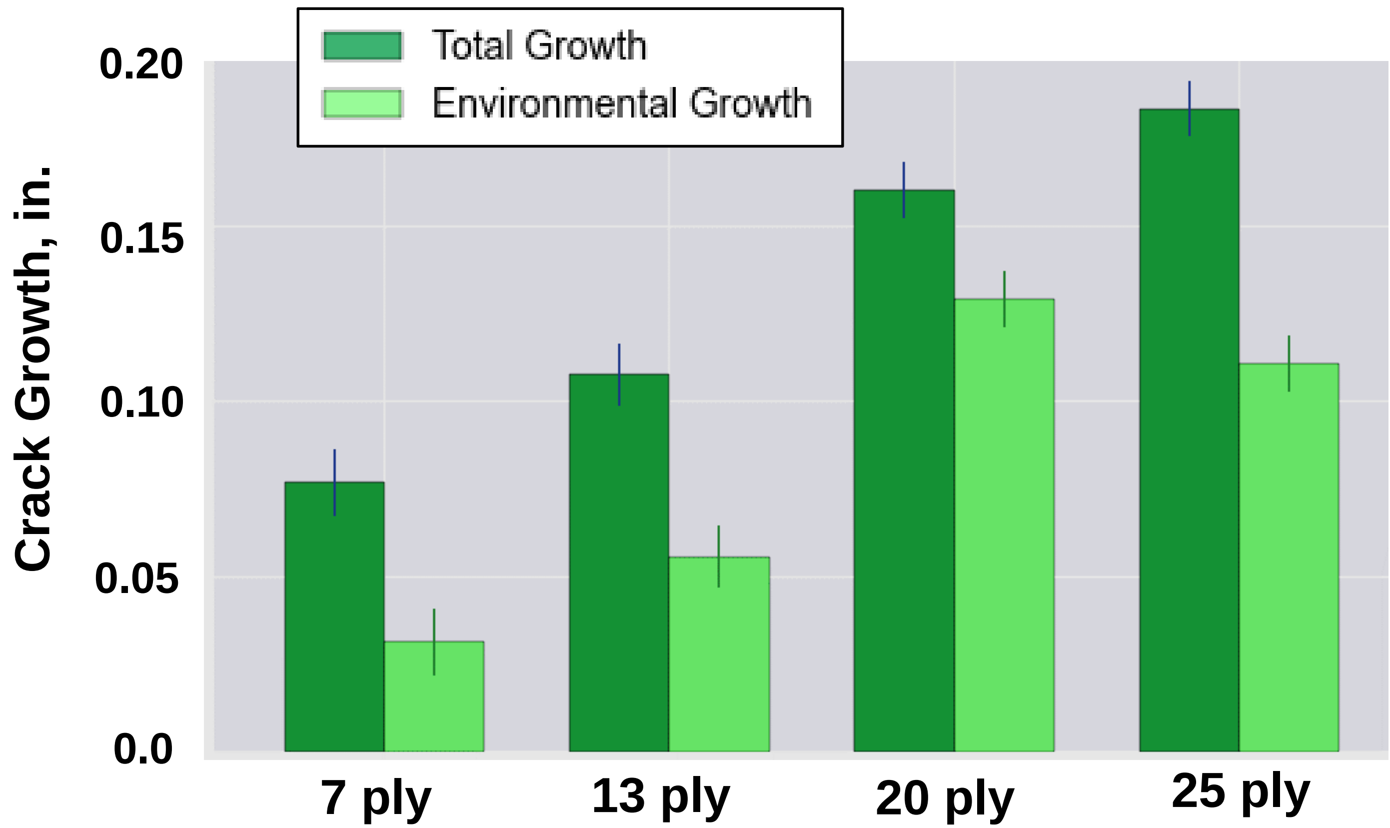
Summary of Results:
Effects of Composite Adherend Thickness



Increasing adherend thickness (and flexural modulus)…

- **Increases crack length**
- **Increases crack growth**

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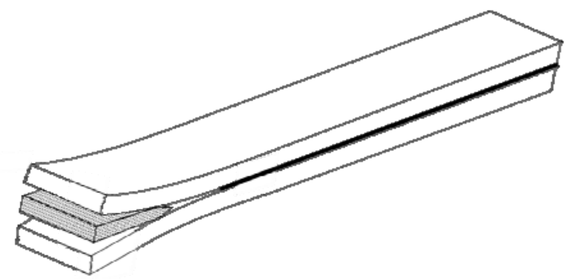
Composite Wedge Test Development: Current and Upcoming Work

- **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**

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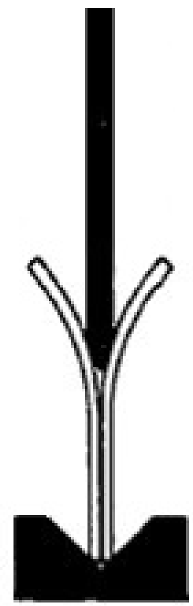
Traveling Wedge Test for Environmental Durability Assessment

- 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



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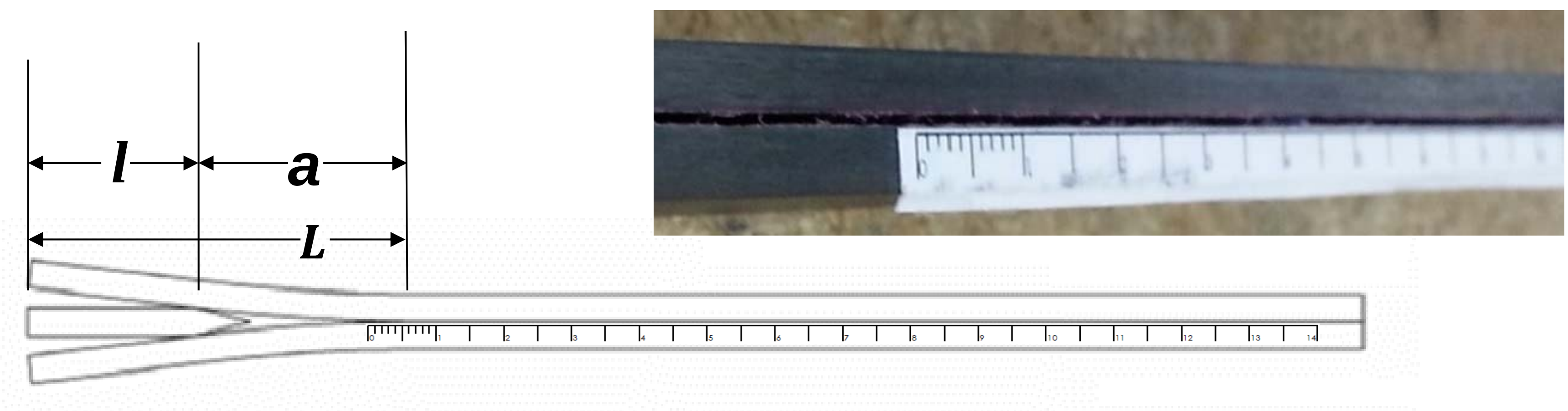
Traveling Wedge Test:

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**

$$G_c = \frac{3\, E_f\, t^2\, h^3}{16\, a^4}$$



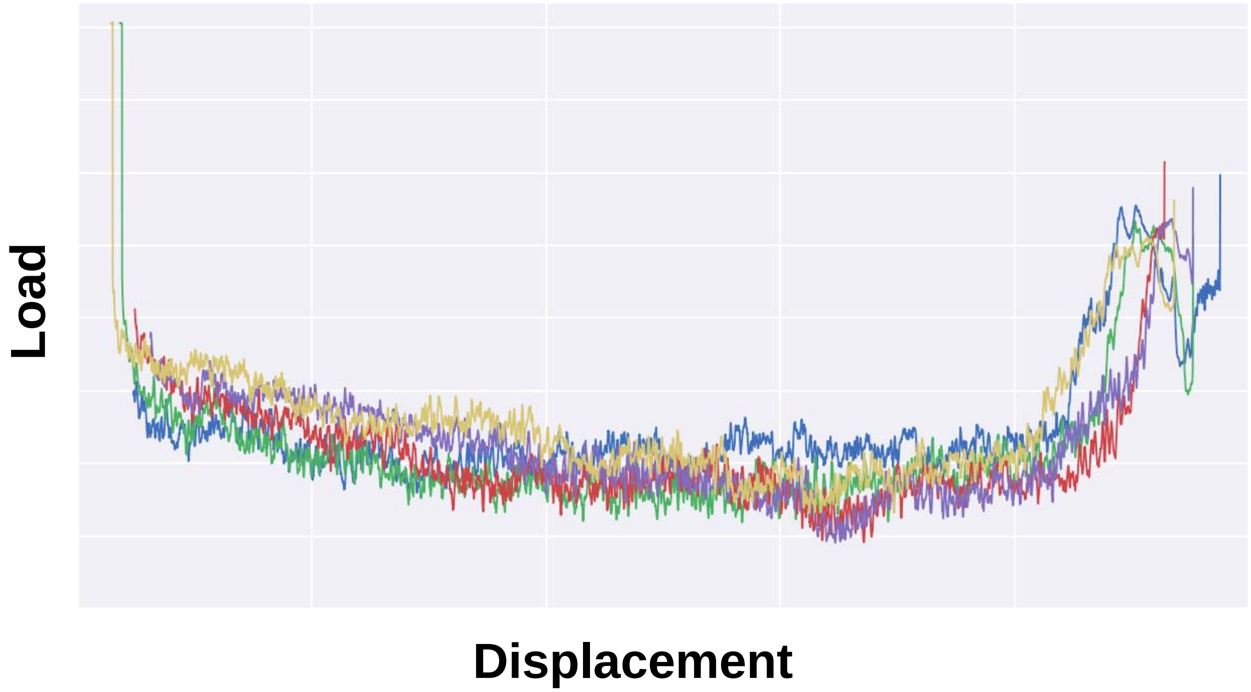
Traveling Wedge Test:
Initial Assessment

- **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

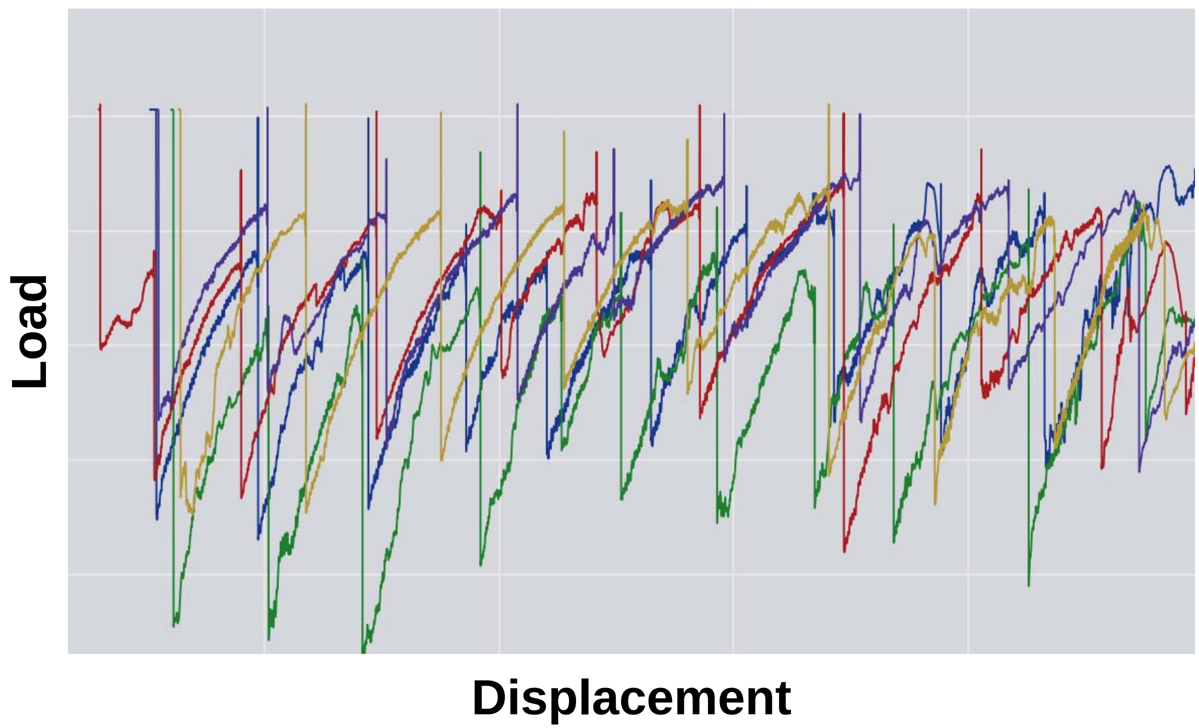
- **Cohesion failure**
- **Stable crack growth**
- **Repeatable results**



Traveling Wedge Test:
Initial Results Using Thick Adherends (Con’d)

“Non-Ideal” bond (Nylon peel ply) at room temp/ambient

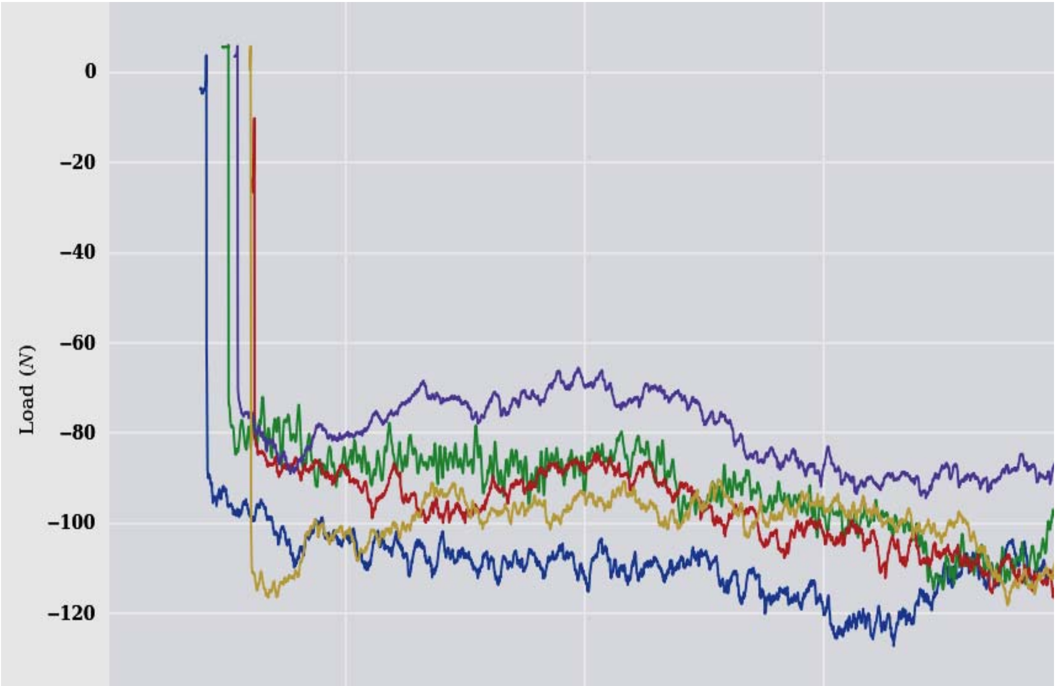
- **Adhesion failure**
- **“Stick-slip crack growth behavior**

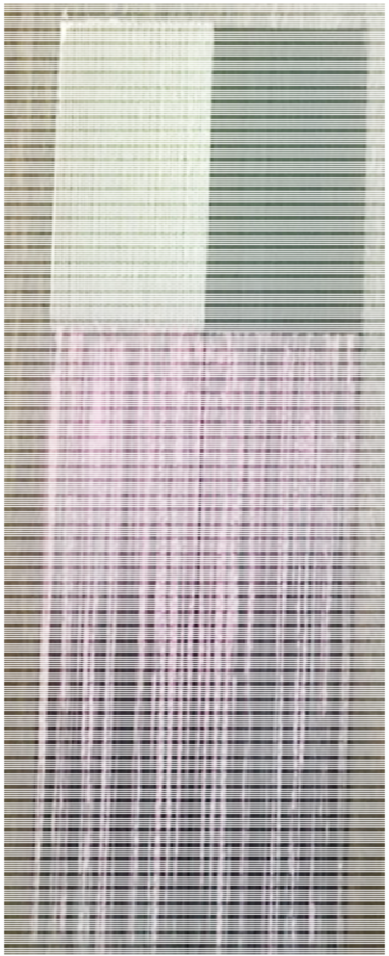


Traveling Wedge Test:
Initial Results Using Thin Adherends

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

- **Moisture saturation in ~3 weeks**
- **Tested at 122°F (50°C)**
- **Significant interlaminar failure**



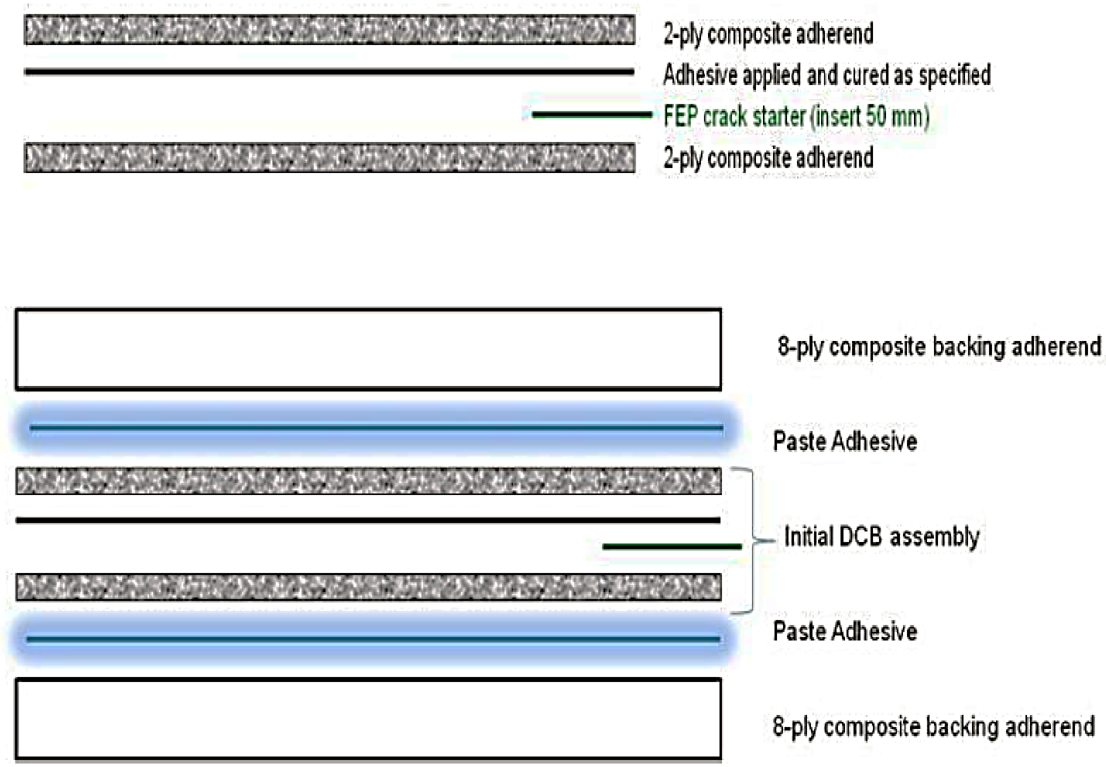


Traveling Wedge Test Assessment: Current and Upcoming Work

- **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**

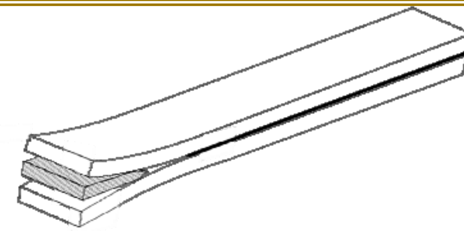


Van Voast, Blohowiak, Osborne and Belcher,
"Rapid Test Methods for Adhesives and Adhesion"
(SAMPE 2013)

Boeing Back-Bonded DCB Test: Current and Upcoming Work

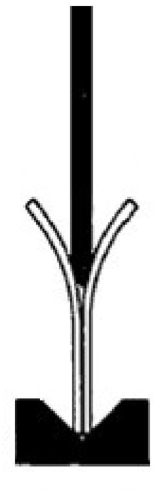
- Testing of “ideal” and “non-ideal” surface conditions
- Investigate effects of test temperature
- Provide baseline G_c values for comparison with static wedge, and traveling wedge testing

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

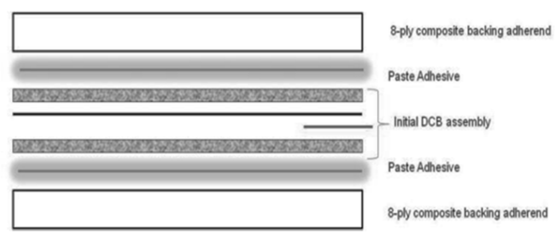


Traveling Wedge Test

- 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**