# TEST METHOD DEVELOPMENT FOR ENVIRONMENTAL DURABILITY OF BONDED COMPOSITE JOINTS


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# FAA Sponsored Project Information

- **Principal Investigators: Dr. Dan Adams**
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- **FAA Technical Monitor: Curt Davies**
- **Primary Collaborators:**
  - **Boeing: Kay Blohowiak and Will Grace**
  - **Air Force Research Laboratory: Jim Mazza**

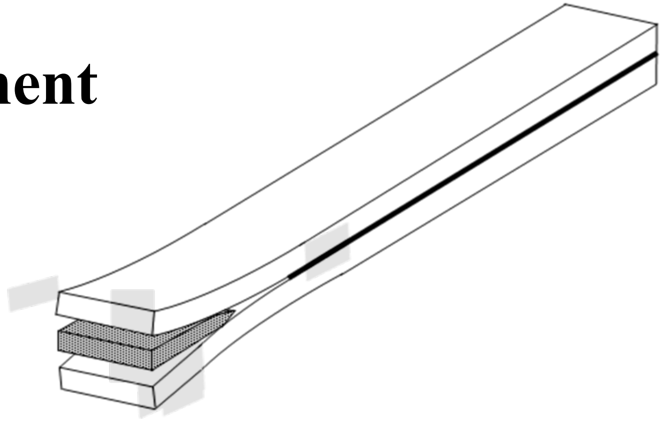
# OUTLINE

- **Background: Durability Testing of Metals Bonds**
  - Short duration testing to assess long term bond durability
- **Candidate Test Methods for Composites**
  - Wedge test
  - Traveling wedge test
  - Back Bonded Double Cantilever Beam
- **Current Status and Upcoming Work**

# Background:
## Environmental Durability Testing of Metal Bonds

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

- **Bonded aluminum double cantilever beam specimen is loaded by forcing a wedge between the adherends**
- **Wedge is retained in the specimen**
- **Assembly placed into a test environment**
  - **Aqueous environment**
  - **Elevated temperature**
- **Further crack growth is measured following a prescribed time period**



# Degradation of Metal Bonds: Hydration

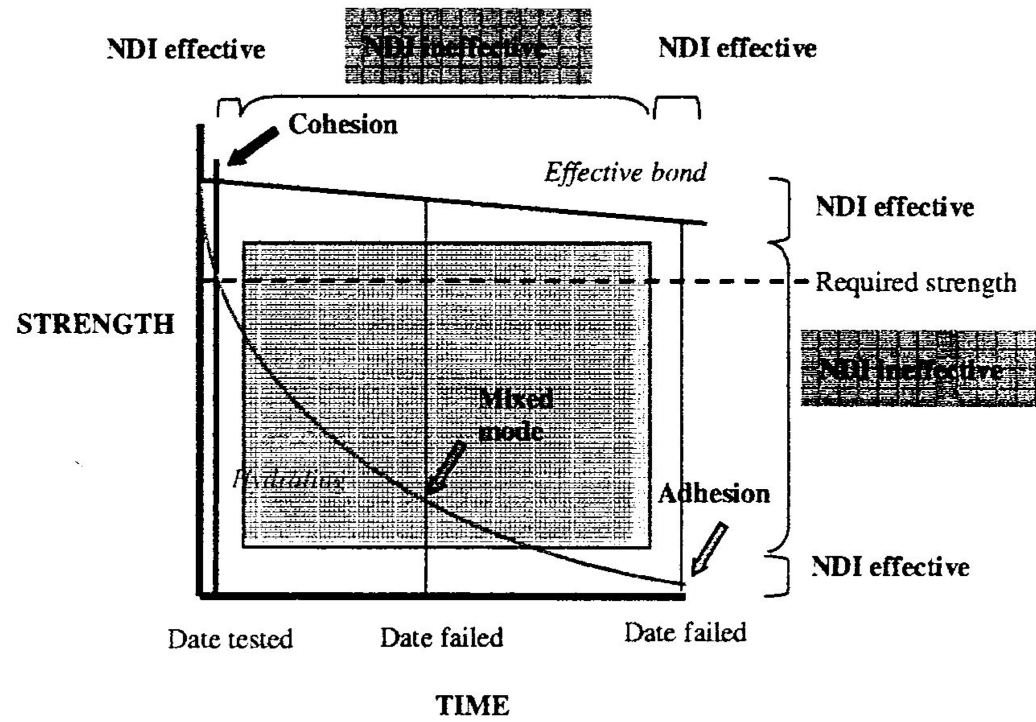
- **Aluminum when exposed to oxygen forms an aluminum oxide surface layer**

  $$4Al + 3O_2 \Rightarrow 2Al_2O_3$$

- **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)*

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# Environmental Durability of Composite Bonds
# Needs and Uses

- **Predict long term behavior of adhesive joints**
  - Failure mode – cohesion v. adhesion
  - Can we get more than a qualitative assessment?
- **Effects of surface preparation on durability**
  - Most common investigation
  - Process assessment
- **Comparison of adhesive durability**
- **Comparison of environment severity**
- **Establishment of acceptance criteria**

# Candidate Test Methods for Composites

**Static Wedge Crack Test**

- Minimal test related specimen prep conditions
- Quick and easy testing and turnaround
- Minimal data reduction time

**Travelling Wedge Test**

- Computer controlled testing
- Potential for full test automation
- Many crack propogation events per specimen

**Boeing Back Bonded DCB**

- Quicker saturation time
- Good agreement with standard DCB testing
- Widely accepted

# Development of a Composite Wedge Test: Expected Complexities

***Complexities associated with a composite wedge test include:***

- **Variable flexural stiffness of composite adherends**
  - Must be within a specific range

    **OR**
  - Must tailor wedge thickness for specific composite adherends
- **Restrictions in fiber orientation adjacent to bonded interface**
- **Failure in the composite laminate instead of/in addition to failure at the adhesive bondline**

# Summary of Previous Research: Static Wedge Test with Composite Adherends

**Bardis and Kedward, 2004**

- "*Static wedge tests provided long-term durability data in a relatively short period of time*"
- Further static wedge testing needed to "*…determine if the test is indeed sensitive to minor differences*" in surface preparation

**K.B. Armstrong, 1996**

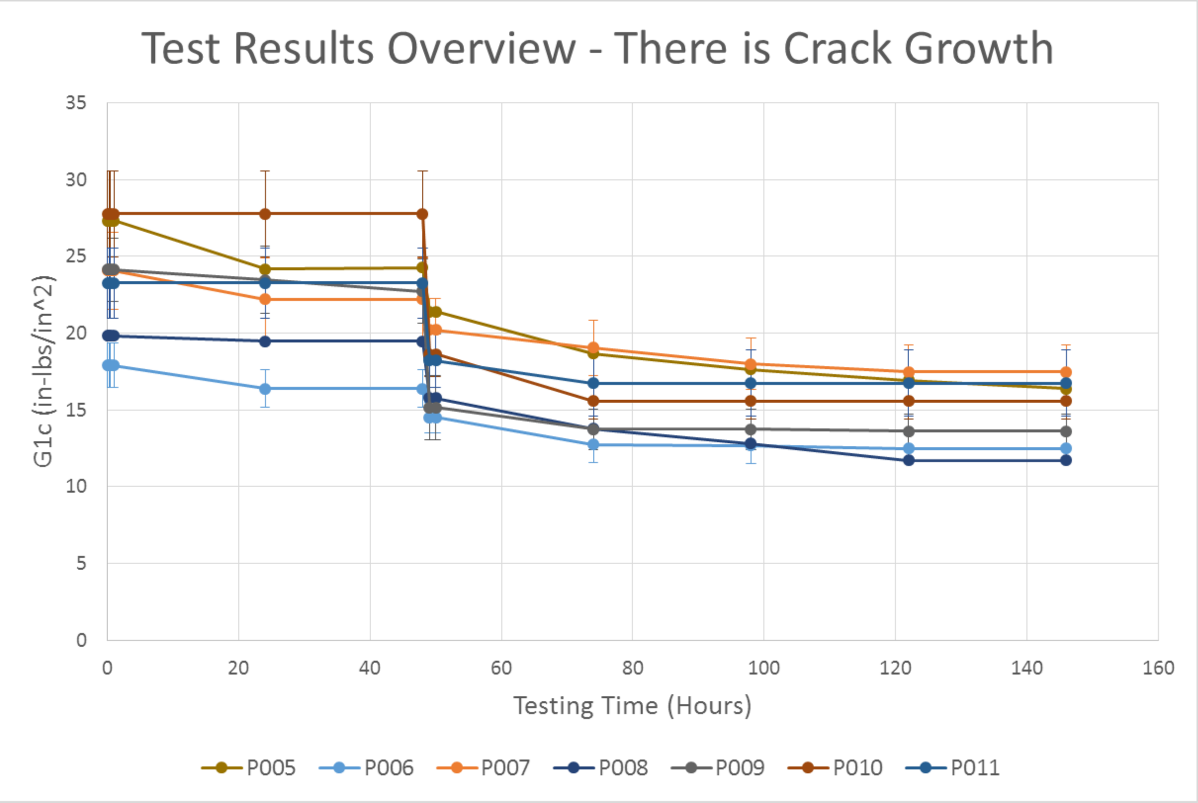
- Used wedge test to examine bond durability of adhesively bonded joints made from "dry and water-immersed and dried" CFRP adherends.
- Found that the wedge test can effectively discriminate between bonds of different surface preps, and different pre-bonding adherend conditions such as water immersed and dried samples versus dry samples.

# Development of a Composite Wedge Test: Initial Investigations

- **Investigate environmental crack growth sensitivity to thickness and flexural stiffness of composite adherends**
  - IM7/8552 Carbon/epoxy
  - Unidirectional laminates
  - Two adherend thicknesses investigated
    - Match thickness of aluminum
    - Match EI of aluminum
  - AF163-2K adhesive

# Results of Initial Investigation:
# Composite Wedge Test

- 4 specimen thicknesses
  - .142 in - .048 in
- 4 surface preparations
- Growth after environmental exposure in every case.



# Further Development of a Composite Wedge Test: Adherend Thickness

**Using the same wedge geometry as ASTM D3762, the amount of crack growth is expected to be dependent on flexural stiffness of the composite adherends**

- Require acceptable lengths of crack growth:
  - Minimal growth – sufficient for measurement
  - Maximal growth – specimen remains bonded
- Provide adequate resolution in crack length to distinguish between high and low durability composite bonds

# Development of a Composite Wedge Test: Adherened Thickness

## Estimate the total crack growths for a given specimen thickness:

Tip deflection of a cantilever beam: $\delta = t/2 = Pl^3/3EI = Ta^3/3EI$ and $T = EBh^3 t/8a^3$

Energy of bending equation $U = 1/2\, T\delta$

Strain energy release rate: $G_c = -dU/da$

$G_c = 3Et^2 h^3/16a^4$

**Which gives:** $a = \sqrt[4]{3Et^2 h^3/16G_{1c}}$

$T$ = load to deflect tip of beam
$G_{1c}$ = Strain Energy Release Rate
E = Young's Modulus
t = wedge thickness
h = adherend thickness
A = crack length

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# Development of a Composite Wedge Test: Adherend Thickness

**Calculations suggest the total crack growth will be between 0.12in and .28in for adherends from 0.04in to 0.12in for a 50% reduction in** $G_{c}$ **from** $25\, in-lbs/in^{2}$ **to** $12.5\, in-lbs/in^{2}$ **.**

For h = 0.04in

$a_{initial} = 0.649$ in

$a_{final} = 0.772$ in

Total Growth = .123 in

For h = 0.12in

$a_{initial} = 1.479$ in

$a_{final} = 1.759$ in

Total Growth = .28 in

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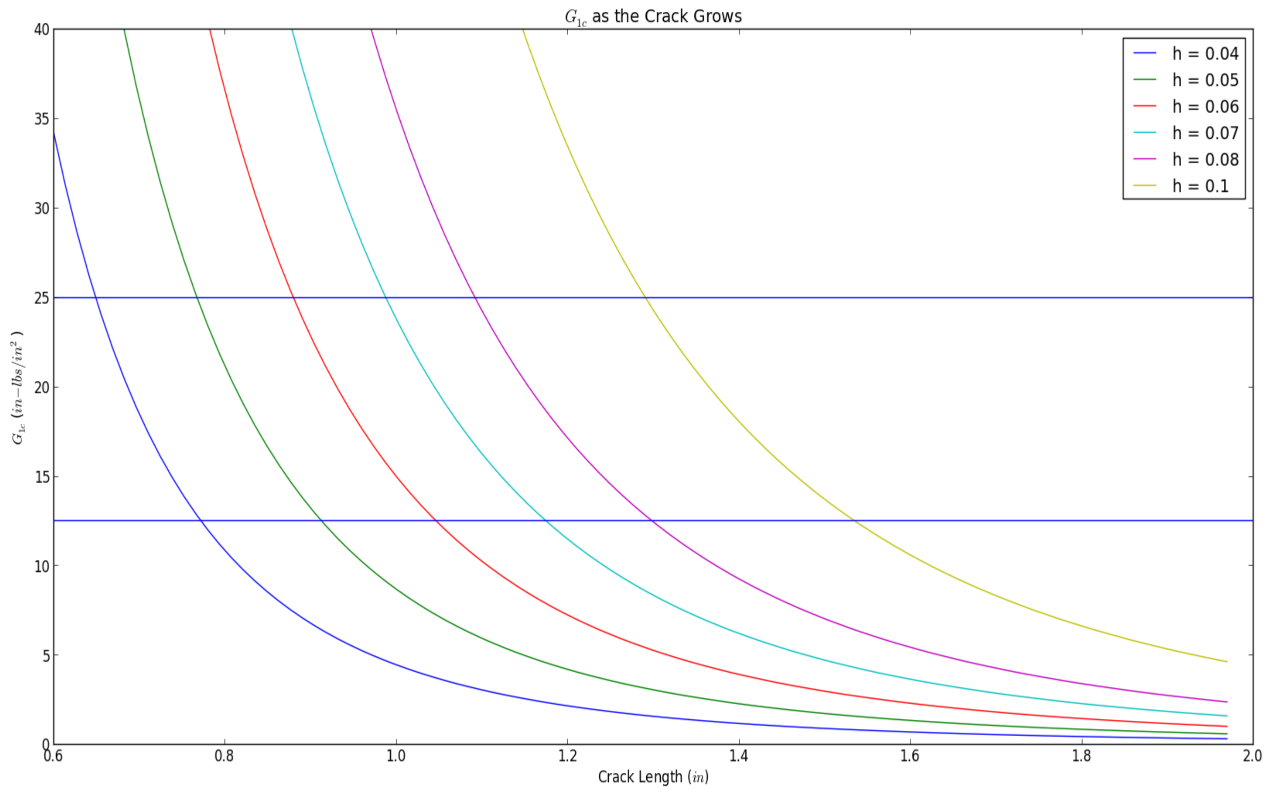
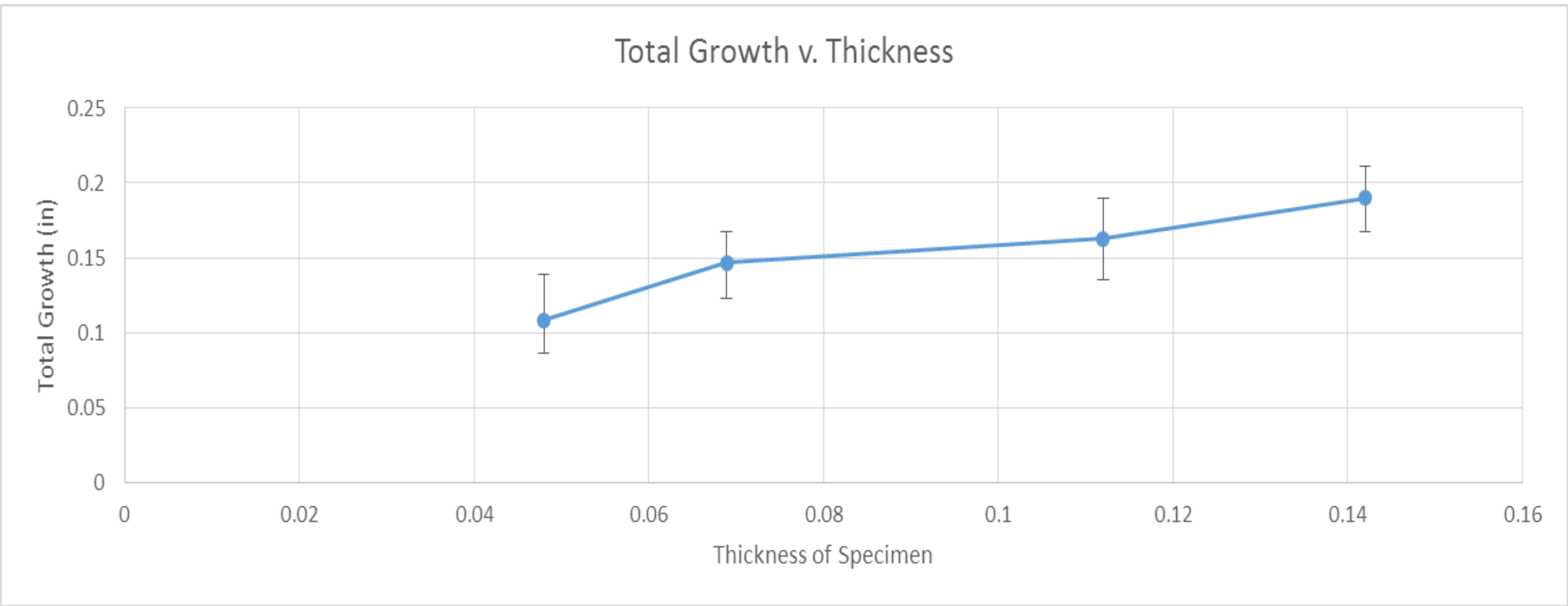
# Development of a Composite Wedge Test: Adherend Thickness

- $G_{Ic}$ curves for different thickness adherends
- Horizontal lines drawn at the estimated initial and final values of $G_{Ic}$.
- Thicker specimens are tested in a section of the curve that has a lower average slope.



# Development of a Composite Wedge Test: Adherend Thickness

**Tests showed agreement with thicker specimen = more crack growth.**

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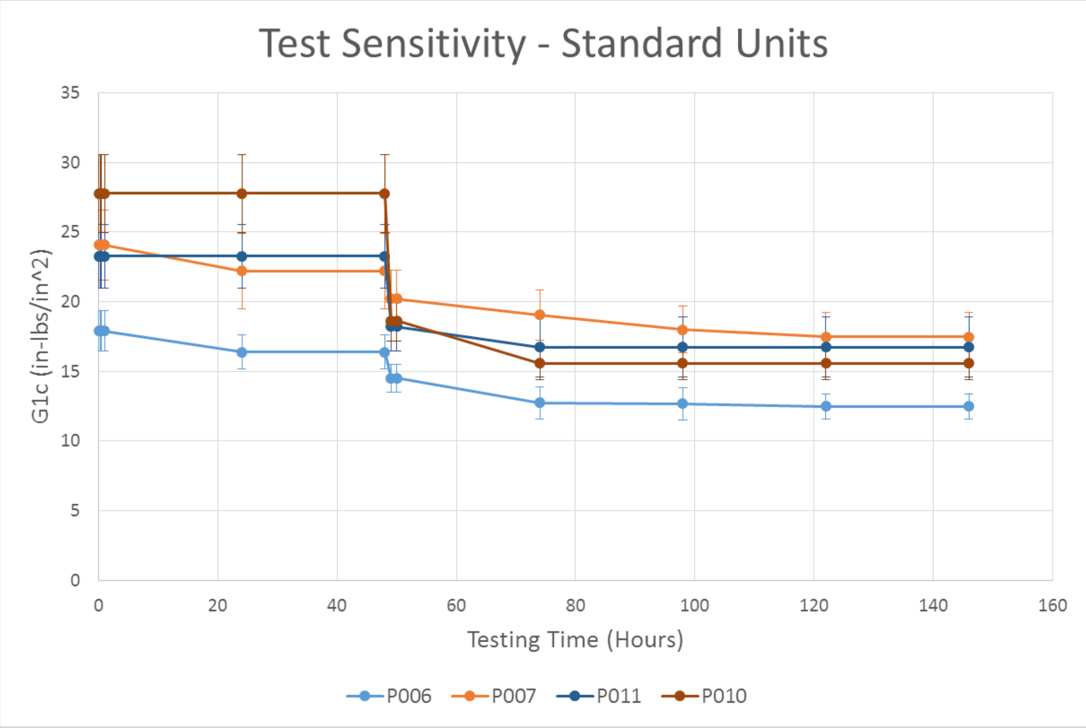
# Development of a Composite Wedge Test: Work In Progress – Surface Prep Sensitivity

- P010 – Cured against the released mold, acetone wipe, grit blast, acetone wipe, dry cycle, bond.
- P011 – Cured against semi-permanent release agent coated metal mold. After grit blast it was wiped once, with one acetone saturated wipe.
- P007 – Cured against PTFE released Peel Ply, Acetone wipe prior to bonding
- P006 – Cured against silicone released peel ply – no further surface preparation.



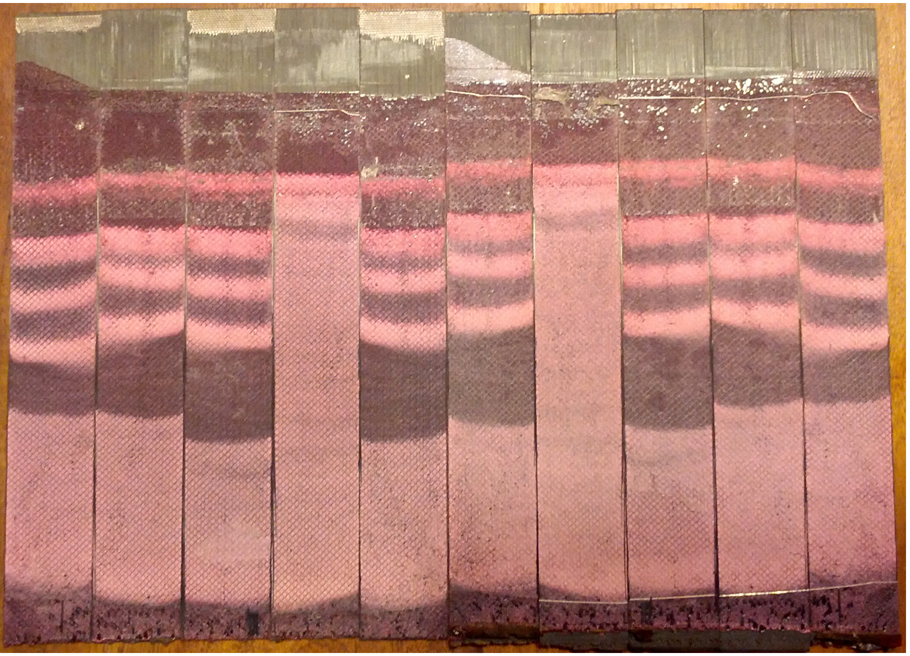
# Development of a Composite Wedge Test: Increasing Testing Area

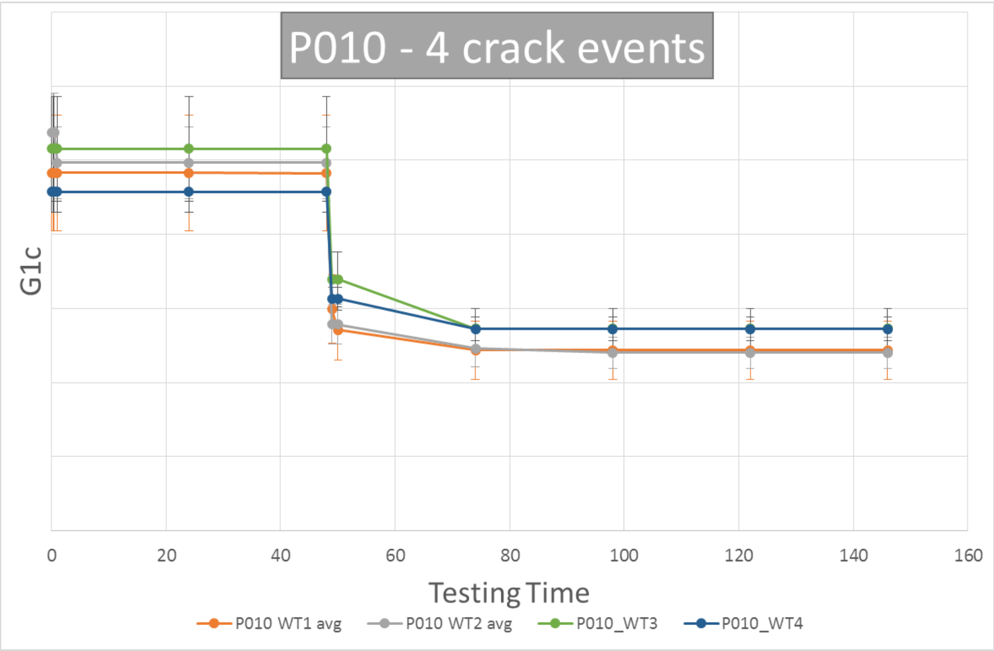
**Classic static wedge tests only interrogate a small area.**

- Inconsistencies in the surface preparation missed.
- Predictions on bond performance are made based on limited data.
- Better characterization of surface preparation consistency.

# Development of a Composite Wedge Test: Increasing Testing Area

- "Best bond" surface preparation
- Initial energy release rate length is very consistent.
- Environment reduced $G_{1c}$ is



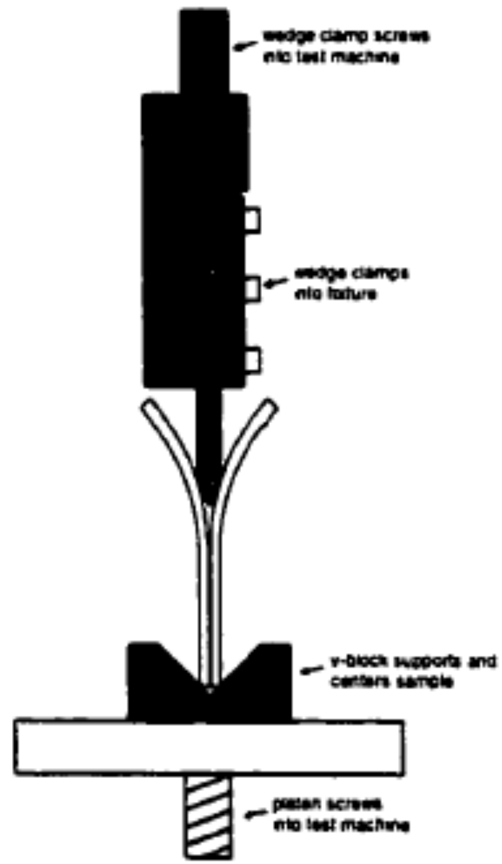


# Composite Wedge Test Development: Static Wedge Test - Future Plans

- **Investigate the resolution of the test with different adherend thicknesses.**
  - Does a thicker adherend show greater discrepancies between surface prep conditions?
- **Investigate temperature sensitivity of test**
- **Investigate testing with different adhesives**
- **Test different reduced durability conditions**
  - Released and unreleased nylon peel plies
  - Released and unreleased polyester peel plies
- **$G_{1c}$ correlation between static wedge, travelling wedge and DCB tests.**

# Composite Bond Durability Testing: Traveling Wedge Test – What is it?

- A wedge, in contact with the crack faces, is driven through specimen, splitting apart.
- Many fracture events occur in the span of one test.
- Observing the fracture events allows one to identify $G_{1c}$.




*Bardis, "Effects of Surface Preparation…" (2002)*

# Composite Bond Durability Testing: Traveling Wedge Test

**From The Literature:**

- Hulcher, 1999 – Used very thin specimens to compare traveling wedge test to DCB test for automated layup process optimization.
- Bardis, 2002 – Found excellent agreement between DCB and this test for determining $G_{1c}$.
- Dilliard, 2011 – Argues the test is only great for adhesives with significant stick slip behavior and that a correction factor – determined with FEA analysis is needed in computing $G_{1c}$.

# Composite Bond Durability Testing: Traveling Wedge Test

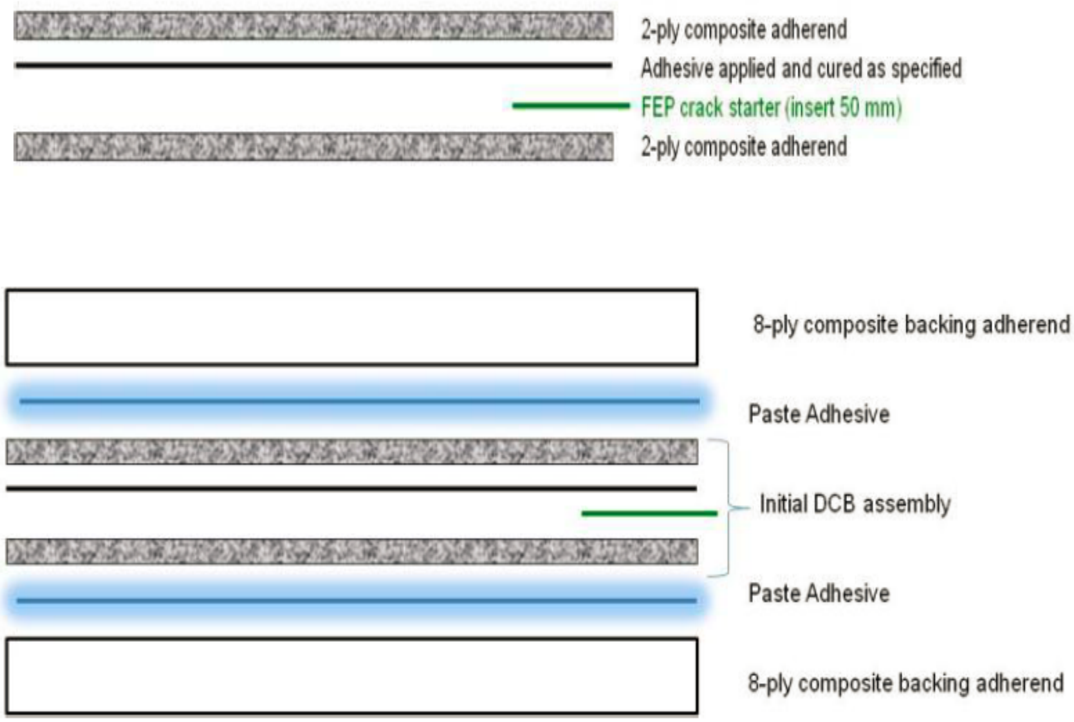
**Possible Advantages:**

- No extra hardware to change the behavior of the specimen
- No extra surface prep and bonding procedures that take time and can lead to undesired test results
- Only the crack length needs to be tracked during the test which makes it fairly simple to run.

# Composite Bond Durability Testing: Future Plans – Traveling Wedge Test

- **Test durability by testing environmentally conditioned specimens using the travelling wedge test.**
  - **Use thin specimens (.020in)**
  - **Moisture saturate them prior to testing (ASTM D5229)**
  - **Run test in temperature chamber**
  - **Compare results to non-environmentally tested specimens.**
  - **Compare results to Boeing Back Bonded DCB test results.**

# Composite Bond Durability Testing: Boeing Back Bonded DCB - Intro



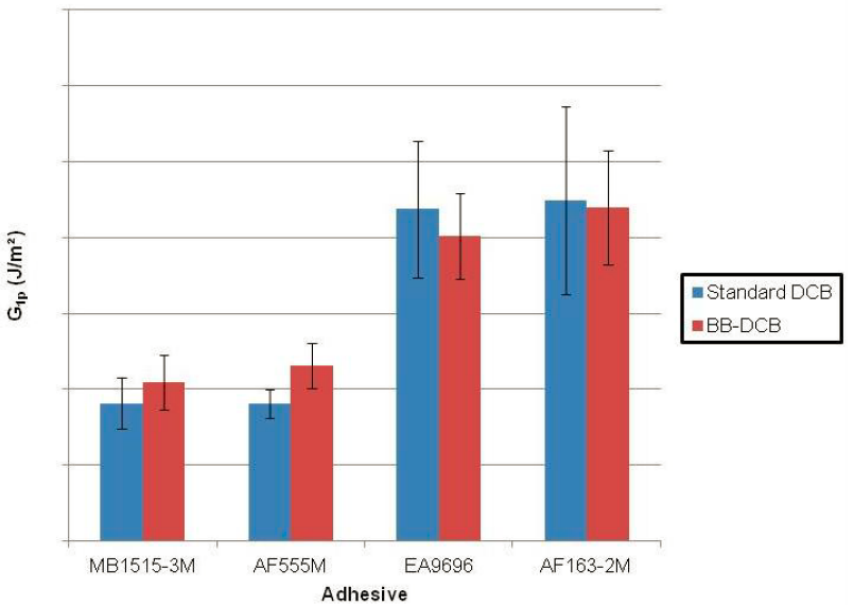

*Blohowiak et al., "SAMPE 2013 Rapid Test Methods for Adhesion" (2013)*

## Process:

1. Bond thin adherends that have the surface prep/adhesive combination that are to be tested.
2. Moisture saturate according to ASTM D5229
3. Bond doubler panels on to the thin specimens to bring them up to the appropriate stiffness for a DCB test.

# Composite Bond Durability Testing: Boeing Back Bonded DCB

### Standard DCB vs BB-DCB - 71°C Tested




*Blohowiak et al., "SAMPE 2013 Rapid Test Methods for Adhesion" (2013)*

## Current Findings:

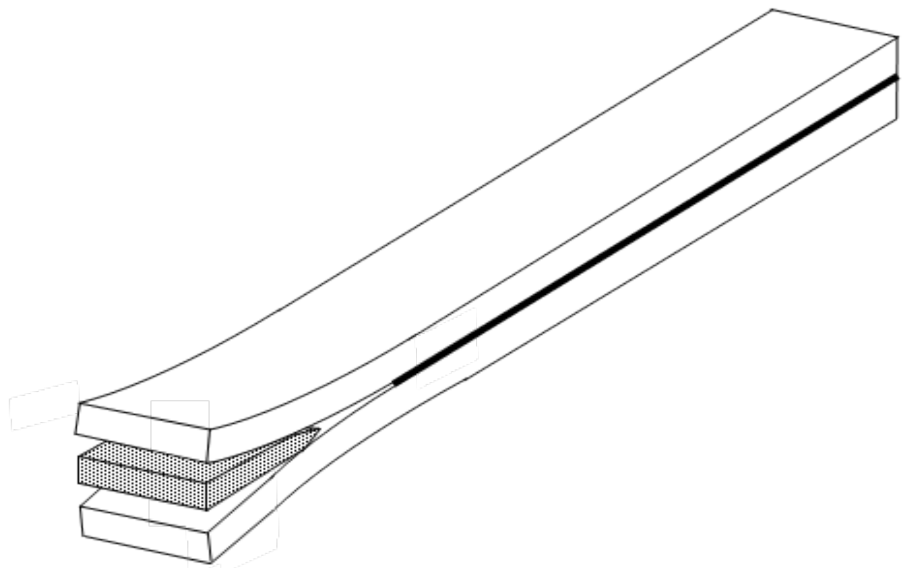
- Boeing has found:
  - "Results from BB-DCB are generally predictive of standard DCB results"
  - "Failure modes tend to be slightly worse for equivalent configurations"

# Composite Bond Durability Testing: Boeing Back Bonded DCB – Proposed Research

- Compare results from this test to results from the other two rapid durability tests discussed herein.
- Compare the ability of the tests to evaluate bond durability.
- Compare the tests to make a recommendation for a test that best assesses durability of adhesive bonds between composite adherends.

# Questions?

# Proposed Changes To Metal Wedge Test ASTM D3762



## Editorial Revisions

- Clarification of geometry
- Correction of procedure problems
- Improvement of figures

## Specimen Preparation

- Controlling bondline thickness
- Machining specimens from panel

## Testing Procedure

- Method of wedge insertion
- Measurement of initial crack length
- Specimen orientation during testing
- Specification of test environment

## Interpretation of Results

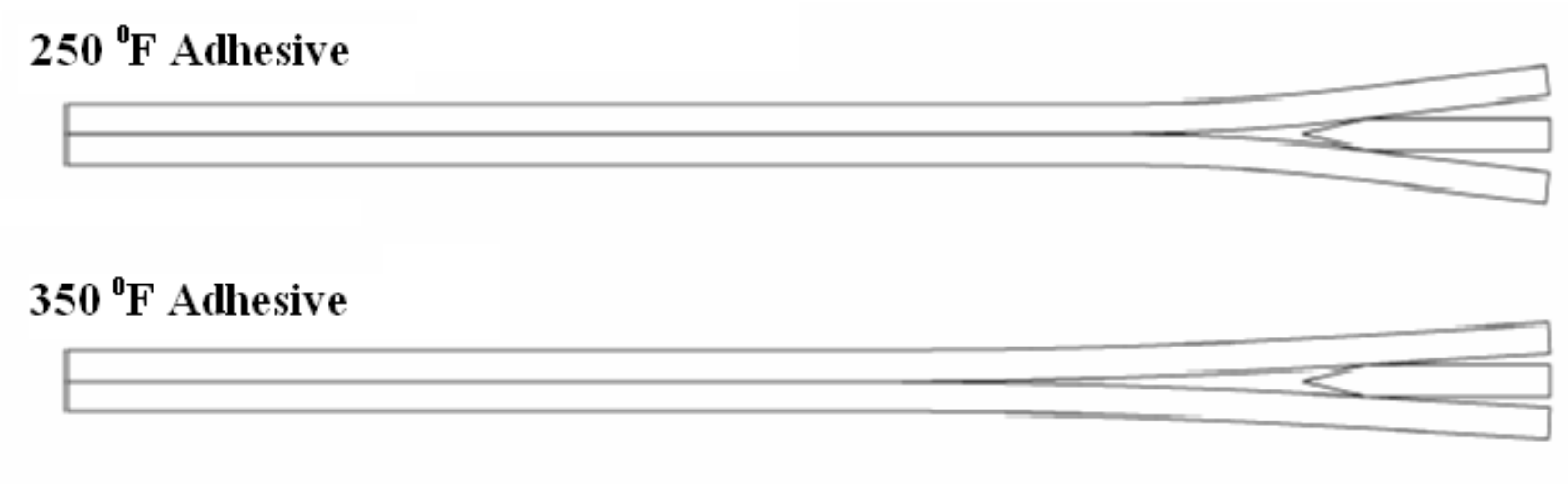
- Role of initial crack length
- Role of crack growth
- Role of failure mode in test area

# Variable Wedge Thickness

## Accounting for Different Classes of Adhesive

### Wedge test results can be misleading…

- Tough Adhesives ($250^0$F cure)
  - Shorter initial crack length
- Strong Adhesives ($350^0$F cure)
  - Longer initial crack length



# Variable Wedge Thickness:

## Effects of Different Initial Crack Lengths on Crack Extension

Assume 50% reduction in $G_c$ from environmental exposure

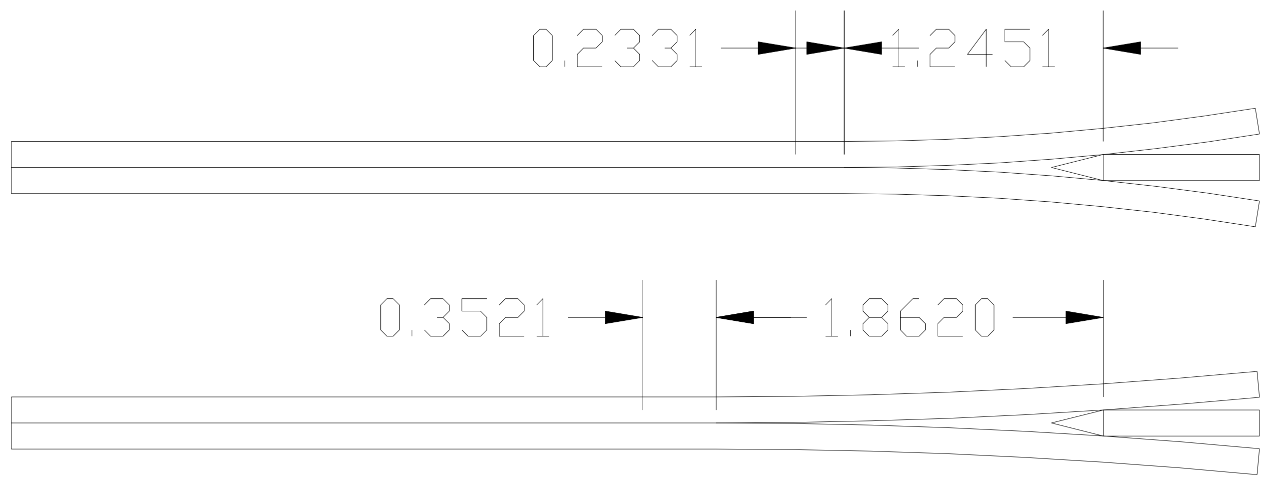
$G_{HIGH}$ = 25 in-lb/in$^2$ → 12.5 in-lb/in$^2$

$G_{LOW}$ = 5 in-lb/in$^2$ → 2.5 in-lb/in$^2$

$$a = \sqrt[1/4]{\frac{3\,h^2 t^3 E}{16\,G_c}}$$

$a_{0\ HIGH}$ = 1.25 in.

$a_{0\ LOW}$ = 1.86 in.




$\Delta a_{HIGH}$ = 0.235 in.

$\Delta a_{LOW}$ = 0.352 in.

**Same % reduction in Gc produces different crack extensions!**