JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Development of Environmental Durability Test Methods for Composite Bonded Joints

Heather McCartin
Dan Adams, Larry DeVries

University of Utah

JAMS 2017 Technical Review
March 21, 2017

THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

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

Graduate Student Researchers:
  Heather McCartin

- FAA Technical Monitor:
  David Westlund
- Collaborators:
  Boeing: Kay Blohowiak, Will Grace, Charles Park
  Air Force Research Laboratory: Jim Mazza

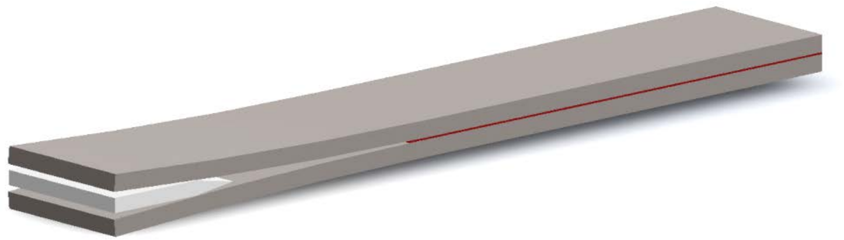
Current Activities:
Development of a Composite Wedge Test:

Additional Complexities:

- Variable flexural rigidity (E_f*I) of composite adherends
- Environmental crack growth dependent on adherend flexural rigidity
  - Flexural rigidity must be within an acceptable range

    or…
  - Must tailor wedge thickness for composite adherends

    or…
  - Must use another quantity to assess durability
- Restrictions in fiber orientation adjacent to bonded interface
- Failure in the composite laminate prior to failure in the adhesive or at the bondline



THE UNIVERSITY OF UTAH

Why Environmental Durability Tests of Composite Bonded Joints?

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

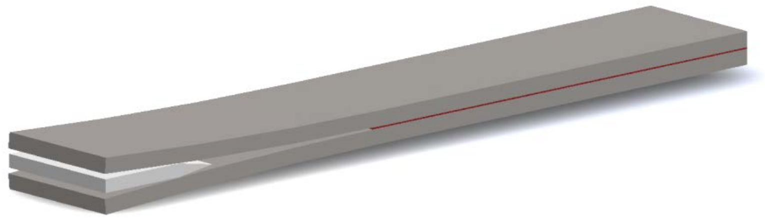
- **Ensure longer-term environmental durability of composite bonds**
- **Investigate effects of environmental exposure on performance of bonded composite joints**
  - **Failure mode: cohesion versus adhesion failure**
  - **Estimate fracture toughness reduction**
- **Evaluate effectiveness of surface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

Use of Fracture Toughness, G_c
To Assess Environmental Durability

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: $$\delta = \frac{t}{2} = \frac{P\,l^3}{3\,Ef\,I} = \frac{T\,a^3}{3\,Ef\,I}$$

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

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

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

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

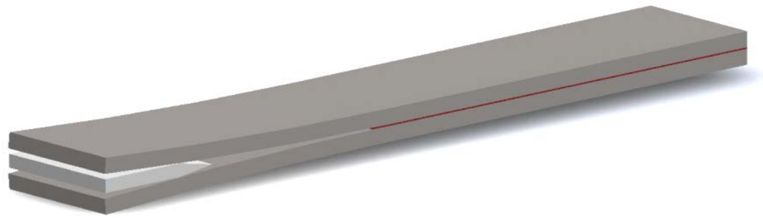
a = crack length
t = wedge thickness
h = adherend thickness
b = specimen width
T = load to deflect tip of beam
E_f = flexural modulus
G_c = fracture toughness

Use of Fracture Toughness, G_c
To Assess Environmental Durability

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: $$\delta = \frac{t}{2} = \frac{P\,l^3}{3\,Ef\,I} = \frac{T\,a^3}{3\,Ef\,I}$$

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

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

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

$$G_c = \frac{3\,Ef\,t^2\,h^3}{16\,a^4}\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]$$

Correction factor for crack tip rotation

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

Is it Really Necessary to Switch From Δa to G_c For Composite Adherends?

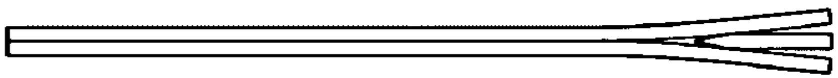
- Consider wedge testing using two adherend thicknesses:

  h = 0.06 in.   h = 0.12 in.

- Assume 50% reduction in G_c from 25 to 12.5 in-lb/in^2

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

For **h = 0.06 in.**



$a_{initial}$ = 0.88 in.

a_{final} = 1.05 in.

Total Growth Δa = 0.17 in.

For **h = 0.12 in.**

$a_{initial}$ = 1.48 in.

a_{final} = 1.76 in.

Total Growth Δa = 0.28 in.

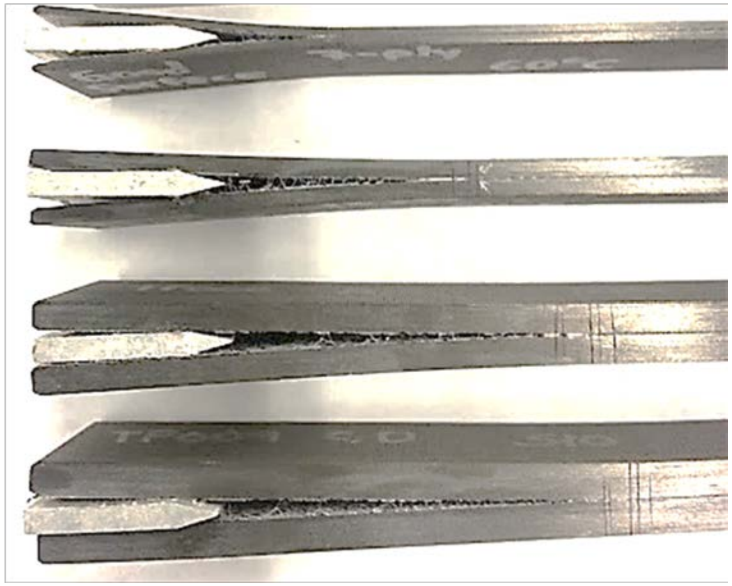
Changing the adherend flexural rigidity changes…

- Initial crack length, a   **- Environmental crack growth, Δa**

Experimental Investigation:

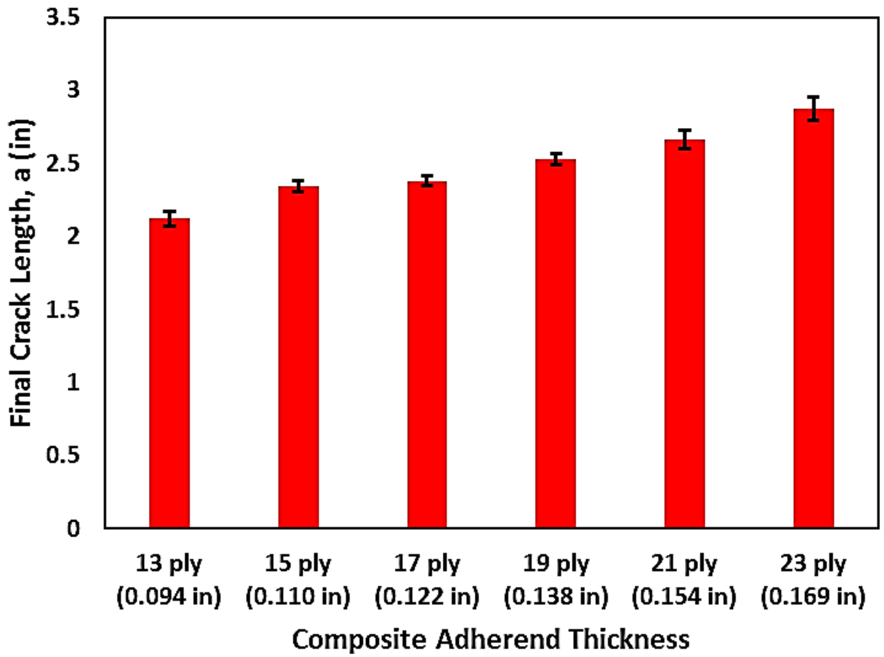
Composite Wedge Test Development

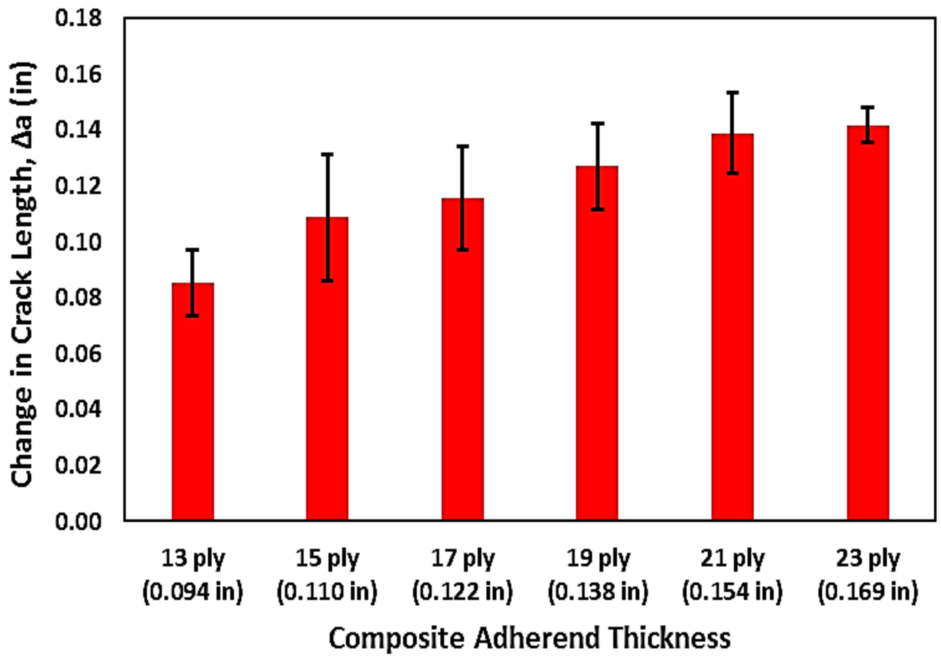
- **Unidirectional IM7/8552 carbon/epoxy adherends**
- **AF163-2K film adhesive**
- **"Ideal Bond": Grit-blast & acetone wipe bond surfaces**
- **Multiple adherend thicknesses to produce different flexural rigidities (E_f * I)**
    - **13, 15, 17, 19, 21, 23 ply thicknesses**
    - **(0.10 to 0.17 in thick adherends)**
- **122°F (50°C) and 95% humidity environment for 5 days**



Effects of Composite Adherend Thickness: Crack Length and Growth Measurements

122°F (50°C) and 95% humidity environment

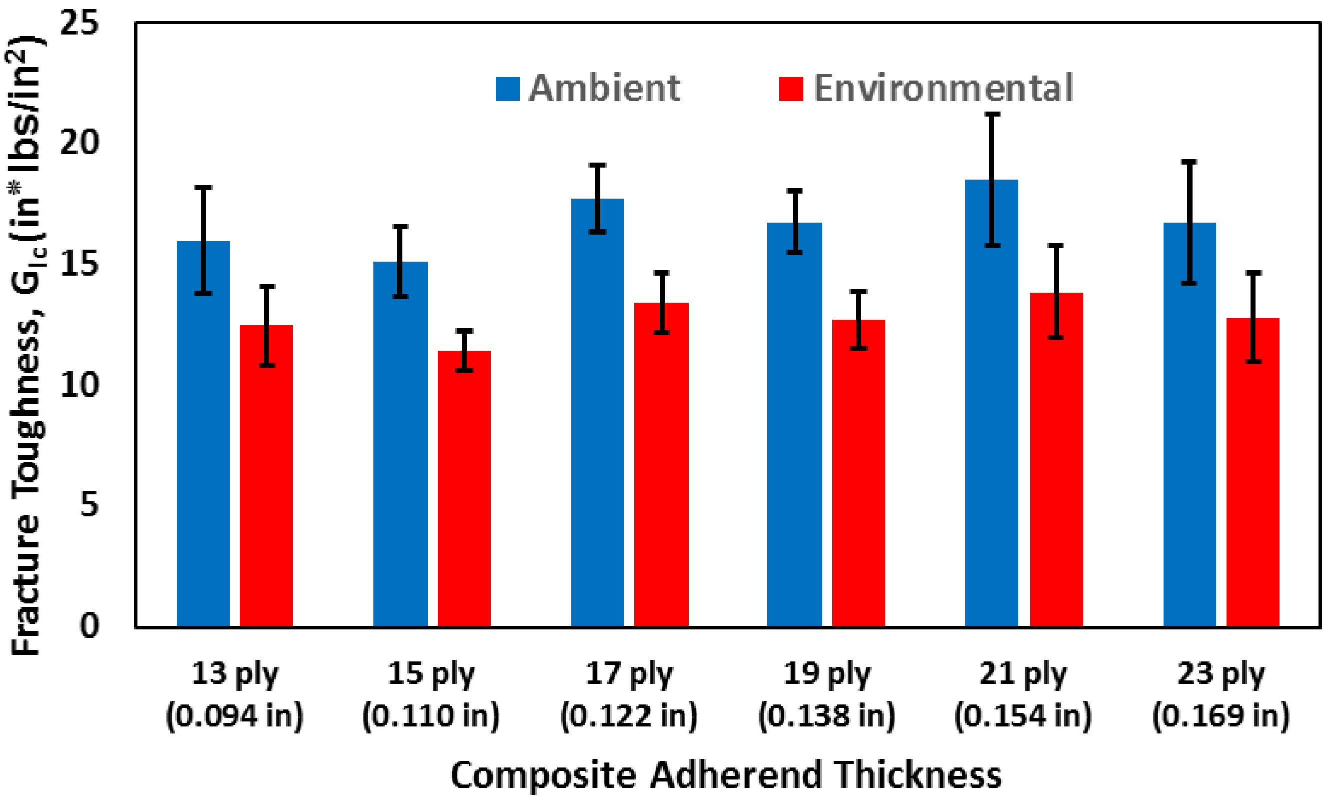




Increasing adherend thickness (and flexural stiffness)…

- **Increases crack length, a**
- **Increases crack growth, Δa**

Effects of Composite Adherend Thickness: Fracture Toughness Values

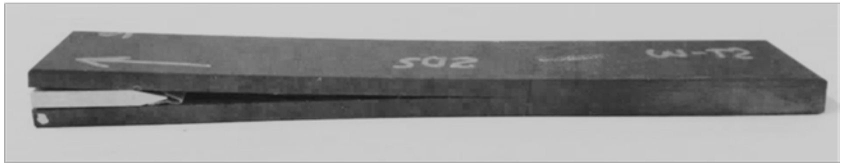


- **Apparent facture toughness values remain relatively constant**
- **Provides estimate of fracture toughness at ambient conditions**

THE UNIVERSITY OF UTAH

Composite Wedge Test Development:
Comparisons With DCB Test

- Comparison of G_c values
  - Wedge test: Gc calculated based on crack length
  - DCB: Gc calculated following ASTM D5528
- IM7/8552 carbon/epoxy unidirectional laminates
- Two test environments
  - Room temperature/ambient
  - 122°F (50°C) and 95% humidity
- Two "bond" conditions
  - AF163-2K film adhesive
  - 8552 epoxy (no adhesive)

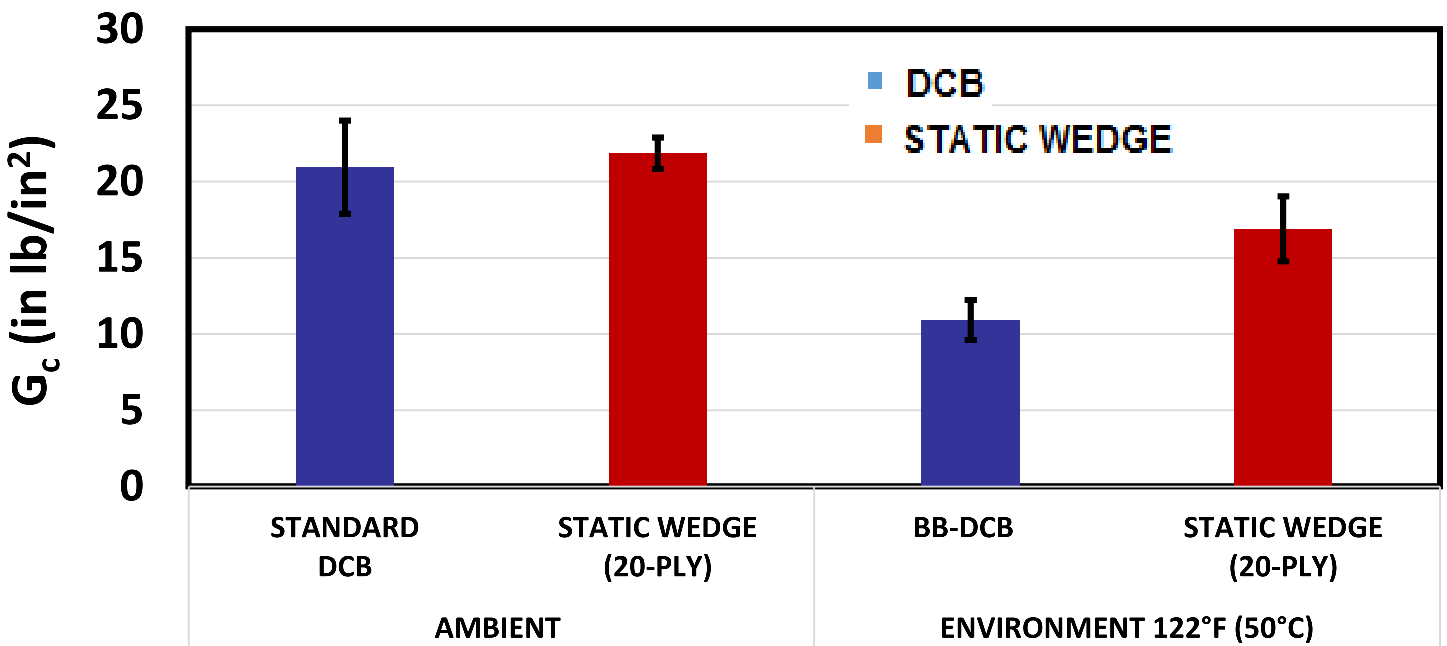


Composite Wedge Test

Double Cantilever Beam (DCB) Test

Back-Bonded DCB vs. Static Wedge Test: Initial Fracture Toughness Comparisons

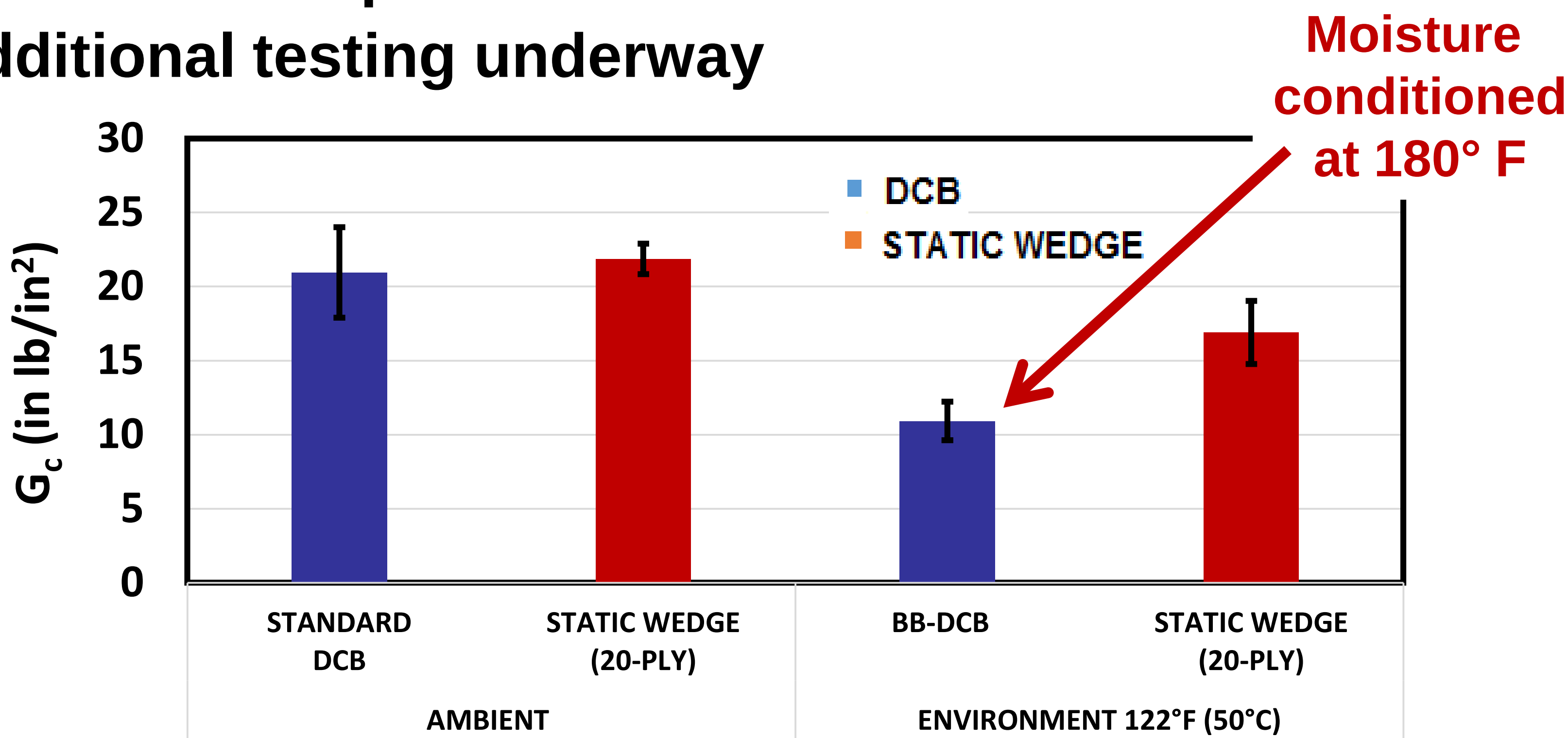
- Higher fracture toughness values at ambient conditions
- Good agreement at ambient conditions
- Significant differences at environment using back-bonded DCB specimens
- Additional testing underway



THE UNIVERSITY OF UTAH

Back-Bonded DCB vs. Static Wedge Test: Initial Fracture Toughness Comparisons

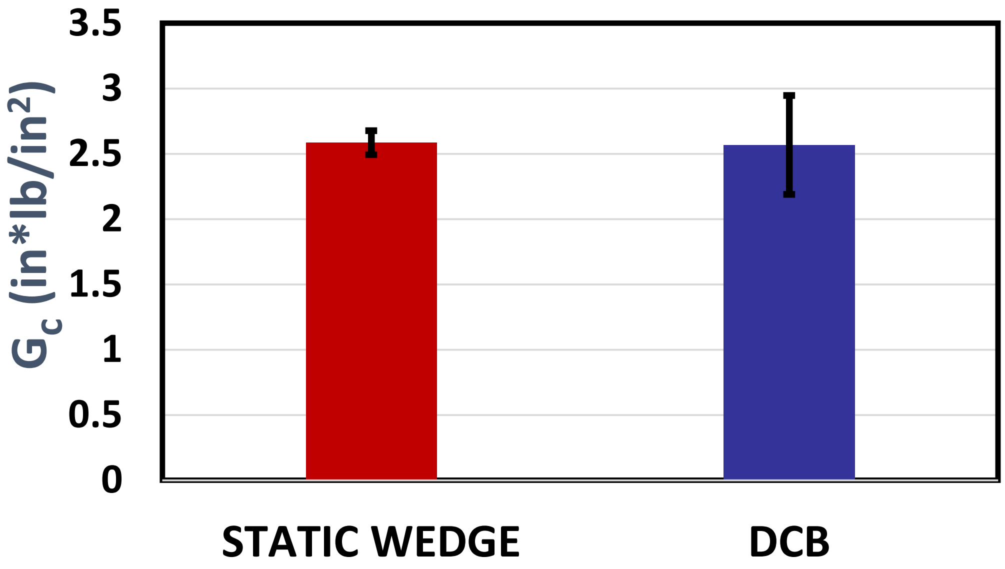
- Higher fracture toughness values at ambient conditions
- Good agreement at ambient conditions
- Significant differences at environment using back-bonded DCB specimens
- Additional testing underway



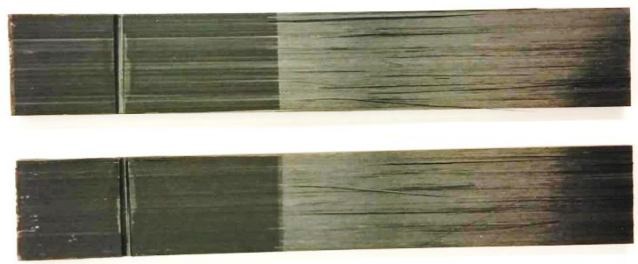
THE UNIVERSITY OF UTAH

Comparison With DCB Test:
Composite Specimens – No Adhesive

- Initial results at RT/Ambient conditions
- Similar appearance on fracture surfaces
- Further testing underway at RT/Ambient and 50°C (122°F) / 95% RH using back-bonded DCB specimens



Composite Wedge Test Specimen



Double Cantilever Beam (DCB) Specimen

Determination of Flexural Modulus, E_f:
Effects of Environmental Exposure

- **Require value of flexural modulus, E_f, for calculating fracture toughness,**

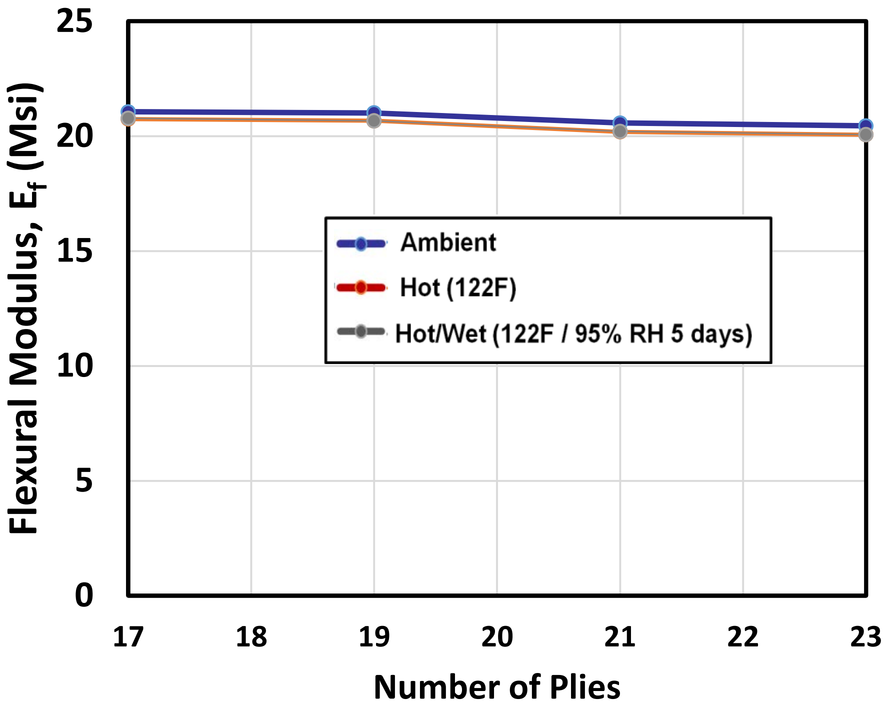
$$G_c = \frac{3\, E_f\, t^2\, h^3}{16\, a^4}\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]$$

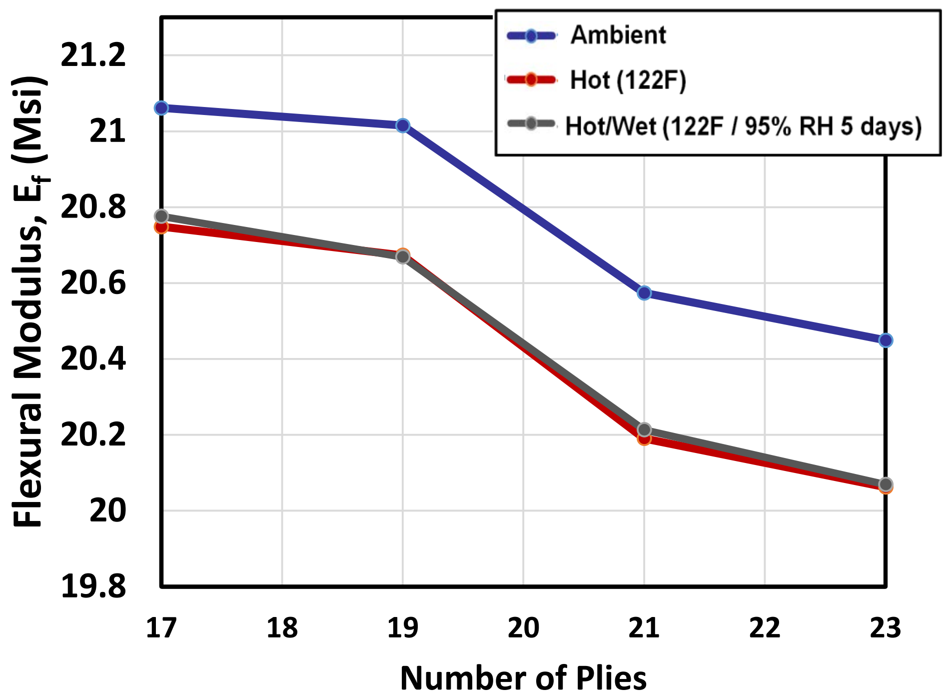
- **E_f value should be representative of that experienced during wedge testing**
  - **Initial crack stabilization at room temperature/ambient conditions**
  - **Environmental crack growth at hot/wet conditions (122° F/95% RH)**
- **Can be measured using three-point flexure testing**

- How does environmental exposure affect E_f?

- Can RT/ambient E_f measurement be used?

Flexural Modulus (E_f) of Composite Adherends: Environmental Conditioning Effects



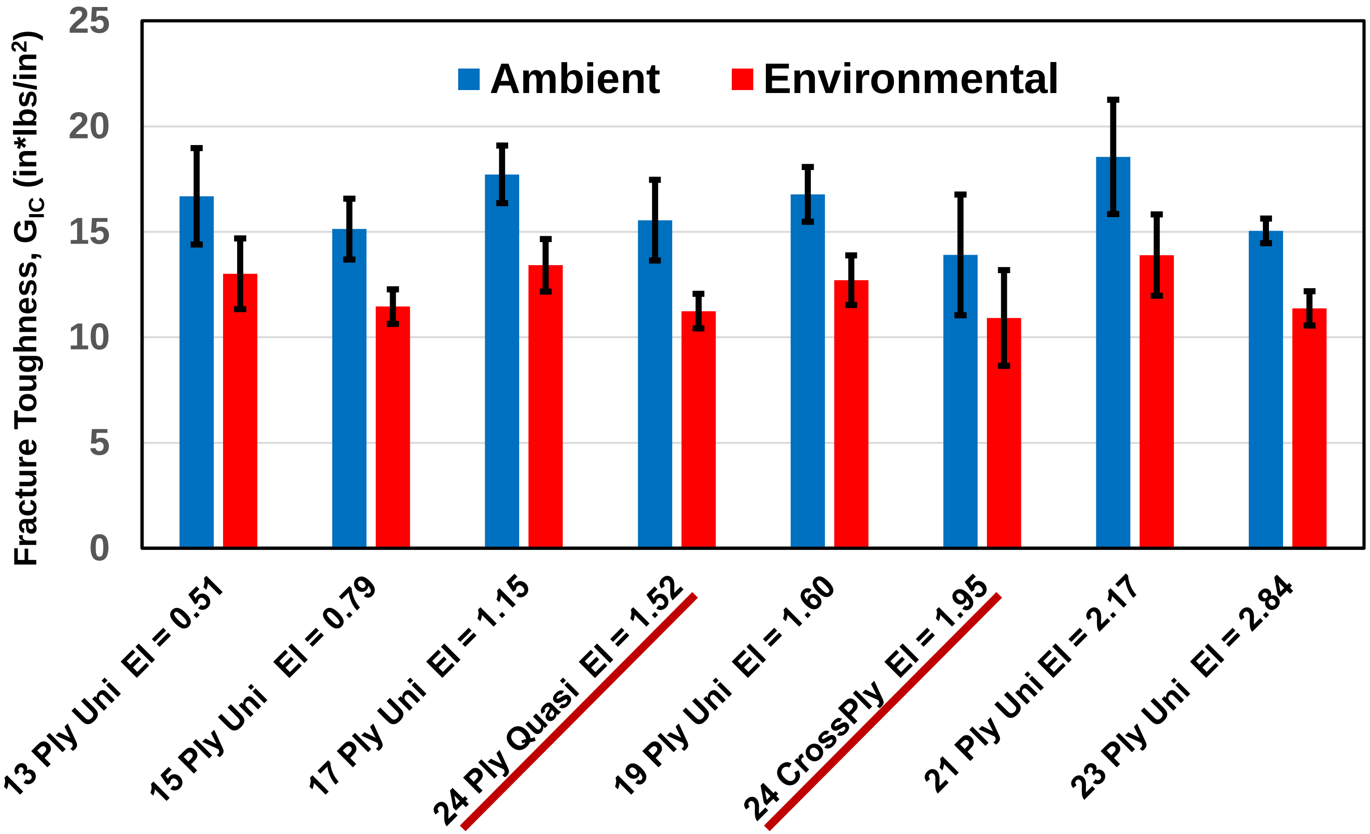


- **Less than 2% reduction in E_f due to conditioning environment (122 ^{0}F, 95% RH for 5 days)**
- ***Flexure testing of adherends at RT/Ambient conditions appears suitable for E_f determination***

Composite Wedge Test Development:
Testing of Multidirectional Laminates

- **Use of cross-ply and quasi-isotropic laminates**
- **Adherend thicknesses selected to fall within range of flexural rigidities (E_f*I) for unidirectional laminates**
- **Same adhesive and surface preparation conditions as for unidirectional laminates**

Wedge Testing of Multidirectional Laminates: Fracture Toughness Values



- G_{IC} values from quasi-isotropic and crossply laminates consistent with previous unidirectional laminates
- Further testing of multidirectional laminates underway

THE UNIVERSITY OF UTAH

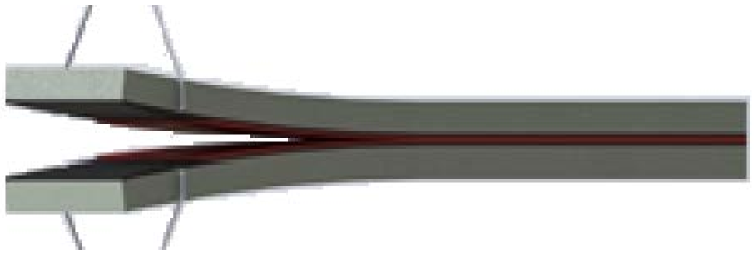
Fracture Toughness Determination Using Flexural Rigidity (E_f I) of Wedge Specimen

- Express fracture toughness written in terms of E_f I:

$$G_c = \frac{9 E_f I \, t^2}{4 b \, a^4}$$

- Measure E_f I directly using post-tested wedge specimen under DCB type loading

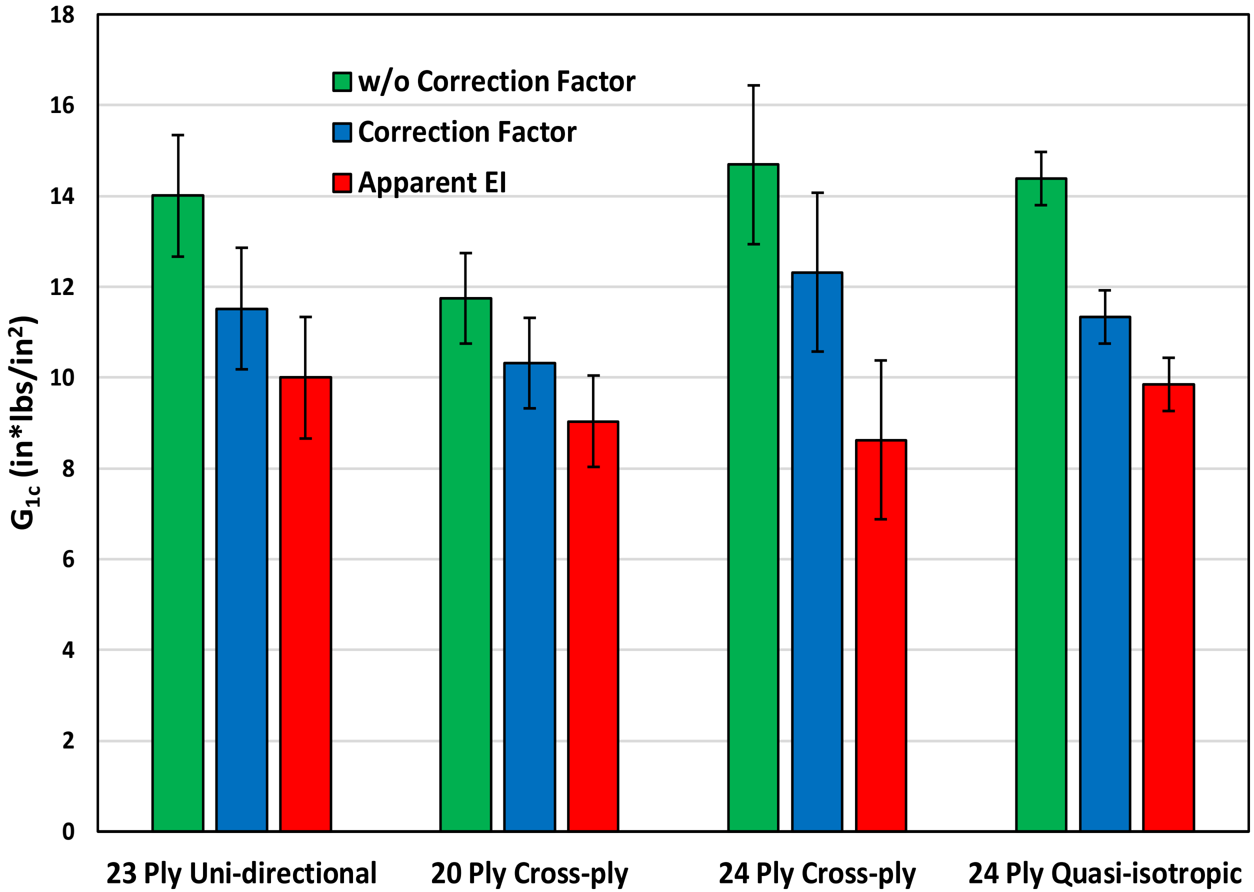
$$E_f I = \frac{2L^3}{3}\left(\frac{\Delta P}{\Delta \delta}\right)$$



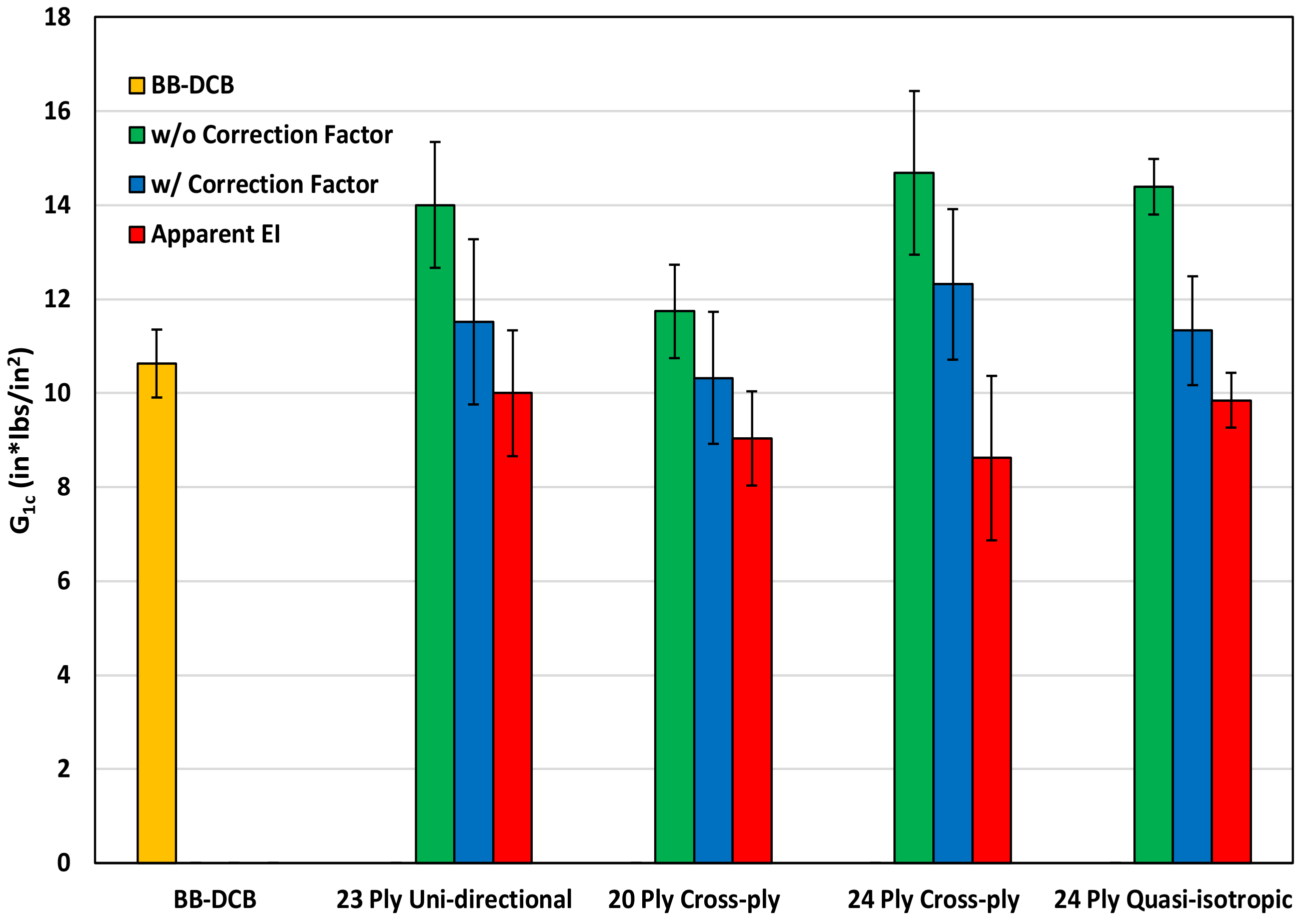
- Correction for crack tip rotation "built-in" to in-situ E_f I measurement

L = beam span (crack length)
P = load to deflect tip of beam
t = wedge thickness
h = adherend thickness
E_f = flexural modulus
I = moment of inertia

Initial Results:
G_c Using Flexural Rigidity ($E_f I$) of Wedge Specimen



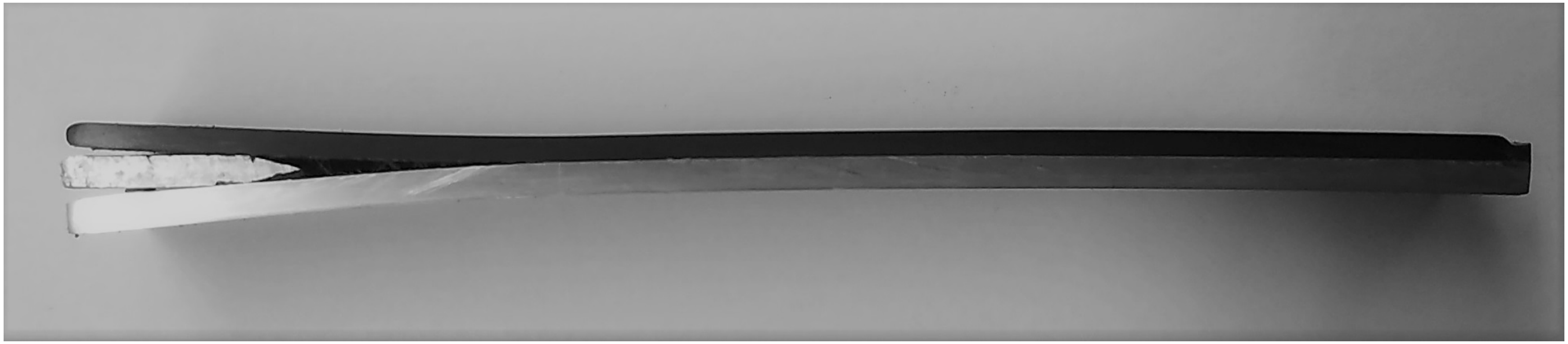
Initial Results:
G_c Using Flexural Rigidity (E_f I) of Wedge Specimen



Initial results in general agreement with back-bonded DCB tests

1. Variant Thickness Static Wedge
2. Variant Layup Static Wedge

3. What's Next?

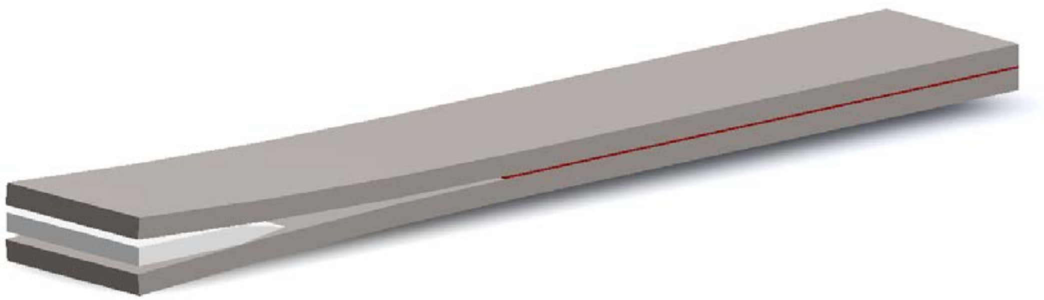


First run of environmental durability of aluminum-carbon fiber tests are complete and we have a slew of things to trouble shoot to bring fracture toughness values to you

- We will consider room-temperature cure
- Possibly multi-directional layup
- Surface prep on the aluminum
- Bond line quality

Composite Wedge Test Development:
Upcoming Work

- Determination of acceptable range of flexural rigidities (E_f * I) for composite adherends
  - Further investigate multidirectional laminates
  - Use of other composite materials
- Further investigate use of in-situ E_f * I measurement from wedge specimen for Gc determination
- Further comparisons with other test methods
- Investigate usage for metal-to-composite bonds



THE UNIVERSITY OF UTAH

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 other candidate test methods for assessing environmental durability of adhesively bonded aircraft structures

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

Thank you for your attention!

Questions?

THE UNIVERSITY OF UTAH