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Development of Environmental Durability Test Methods for Composite Bonded Joints

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Heather McCartin, Zachary Sievert

University of Utah

FAA AMTAS Autumn 2018 Meeting
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FAA Sponsored Project Information

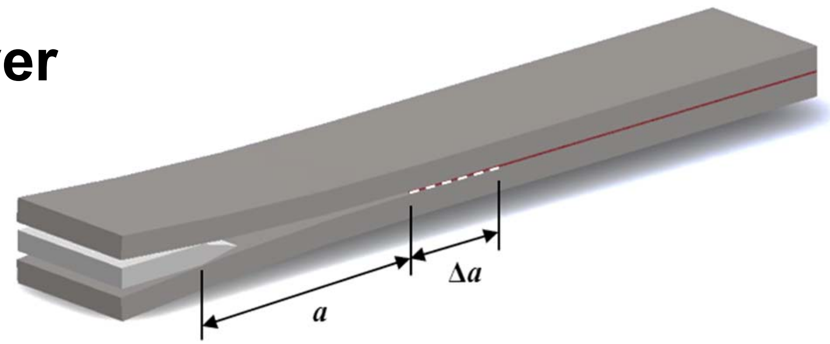
- Principal Investigators:
  - **Dr. Dan Adams**
- Graduate Student Researchers:
  - **Heather McCartin**
  - **Zach Sievert**
- FAA Technical Monitor:
  - **Ahmet Oztekin**
- Collaborators:
  - **Boeing: Kay Blohowiak, Will Grace, Charles Park**
  - **Air Force Research Laboratory: Jim Mazza**
  - **3M Corp: Maha DeSilva**

Outline

- Updates:
  - Revision of metal wedge test method (ASTM D3762)
  - ASTM Adhesive Bonding Task Group D14.80.01
- Primary focus: Environmental durability test methods for composite bonded joints
  - Composite wedge test development
  - Comparison of results with other test methods
  - “Smart Wedge” traveling wedge test concept

Background: The Metal Wedge Test

ASTM D3762: "Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)"



- **Bonded aluminum double cantilever beam loaded by forcing a wedge between adherends**
- **Assembly placed into test environment (ex: 50^0 C, 95% RH)**
- **Crack growth *Δa* due to environmental exposure measured following prescribed time**
- **Able to asses bond quality quickly by causing rapid hydration of oxide layers**

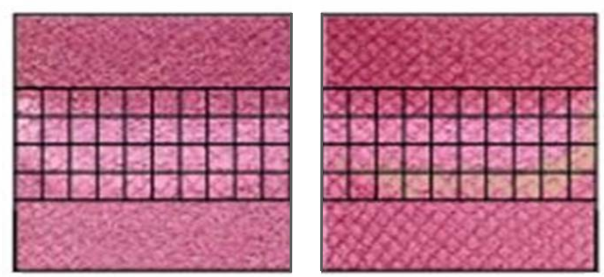
Revision of ASTM D3762:

Summary of Proposed Revisions

- **Correction of existing errors in standard**
- **Broadening of scope to include metals other than aluminum as adherends**
- **Provided additional guidance in specimen manufacturing**
- **Provided additional detail in test procedure**
- **Addition of requirement to estimate % cohesion failure in region of environmental crack growth**

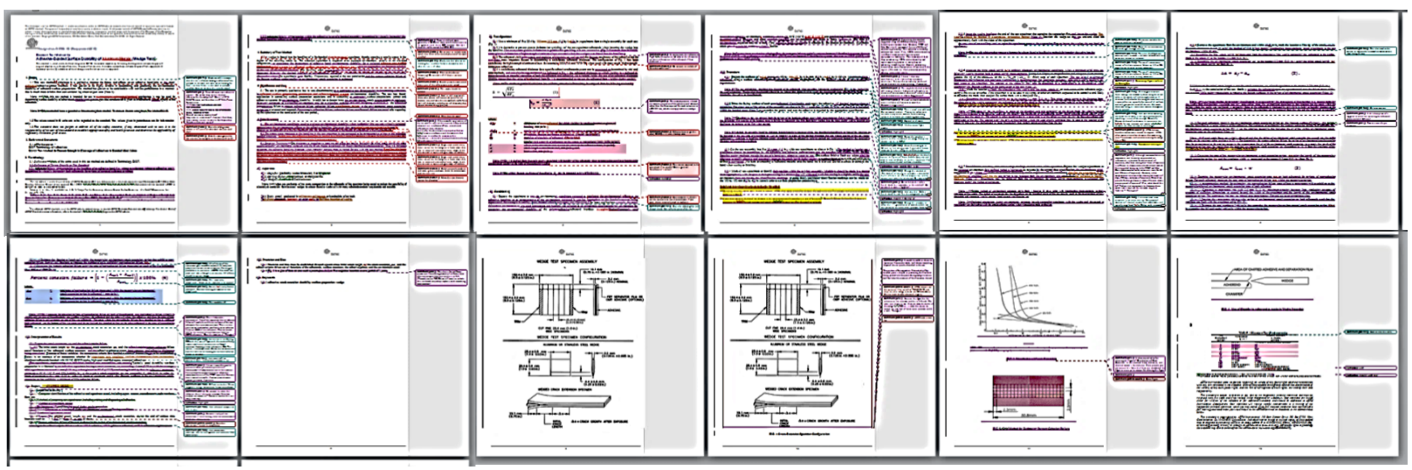
$\boldsymbol{Percent\ cohesion\ failure}$:

$$\left[1 - \left(\frac{A_{nc1} + A_{nc2}}{A_{ext}}\right)\right] x\ 100\%$$



Revision of ASTM D3762:
Current Status

- Completed extensive revision of standard
- Initial D14.80 subcommittee balloting April 2018
- Addressed concerns: negative votes and comments
- Currently reballoting at concurrent D14.80 subcommittee and D14 main committee levels



Collaborations with ASTM D14 (Adhesives):
D14.80.01 Task Group

- Includes ASTM D14 (Adhesives) and ASTM D30 (Composites) committee members
- Meets concurrently with ASTM D30 to allow for greater participation
- Balloting through D14.80 subcommittee and D14 main committee
- Technical contact(s) from D30 to attend D14 meetings and provide TG status reports

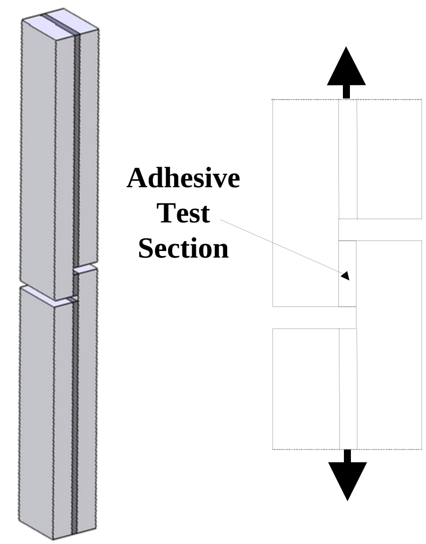
Current Activities

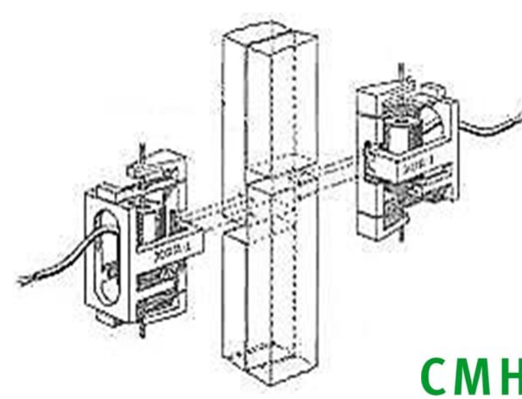
- ASTM D3762 Metal Wedge Test revision
- ASTM D5656 Thick Adherend Lap Shear Test revision
- Bonded composite fracture mechanics test evaluation
- Composite Wedge Test development/standardization

Current Activities:
ASTM D14.80.01 Task Group

Improvements to ASTM D5656–Thick Adherend Lap Shear Test

- **Best practices for shear strain measurement**
  - Identify suitable replacement(s) for obsolete KGR-1 extensometer
  - Optimal attachment points for shear strain measurement
- **Initial round-robin investigation completed**
  - Two paste adhesives
  - Four adhesive thicknesses
  - Three labs/measurement methods
- **In conjunction with CMH-17 Testing Working Group**



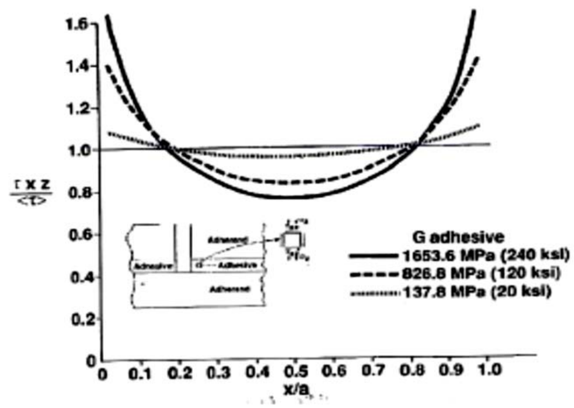


CMH-17 COMPOSITE MATERIALS HANDBOOK

Current Activities:
ASTM D14.80.01 Task Group

Improvements to ASTM D5656–Thick Adherend Lap Shear Test (Con'd)

- **Follow-on round-robin investigation in planning stage**
  - AFRL specimens, single film adhesive
- **Evaluation of candidate shear strain measurement methods**
  - Epsilon extensometer
  - NIAR extensometer attachment
  - Digital Image Correlation (DIC)
  - Others
- **Update ASTM D5656 Standard**
- **Balloting through ASTM D14.80**



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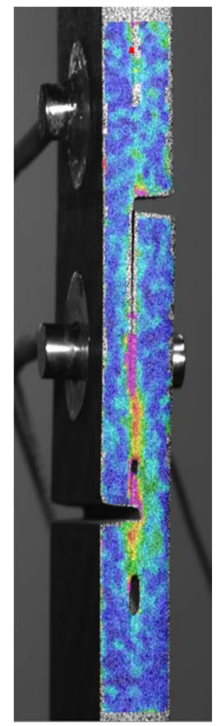

R. Cole, NRC Canada

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- **Updates:**
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  - Comparison of results with other test methods
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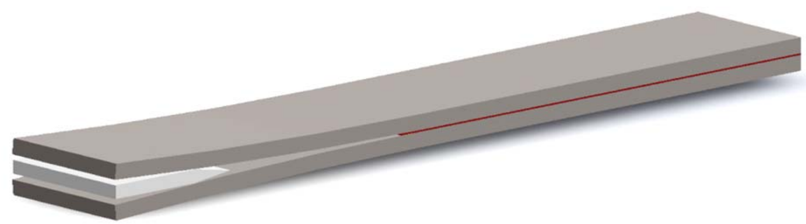
Overview:
Development of a Composite Wedge Test:

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



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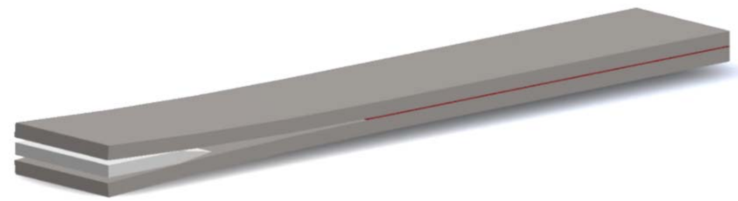
Use of Fracture Toughness, G_c To Assess Environmental Durability

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

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

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

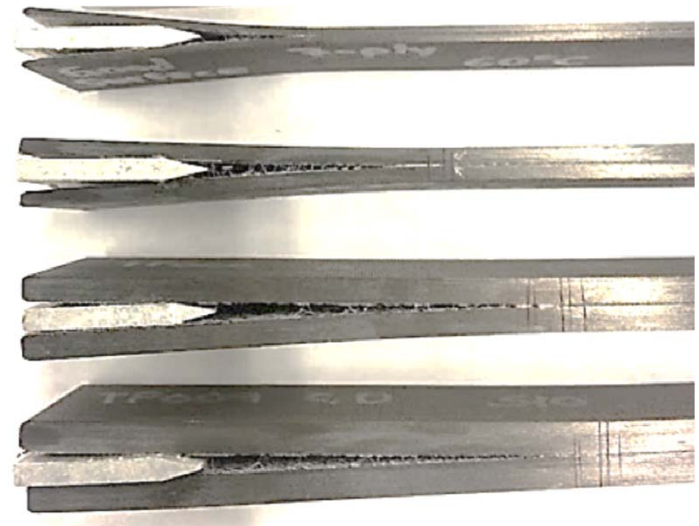
Strain energy release rate: $G_c = \frac{dU}{dA}$

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

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

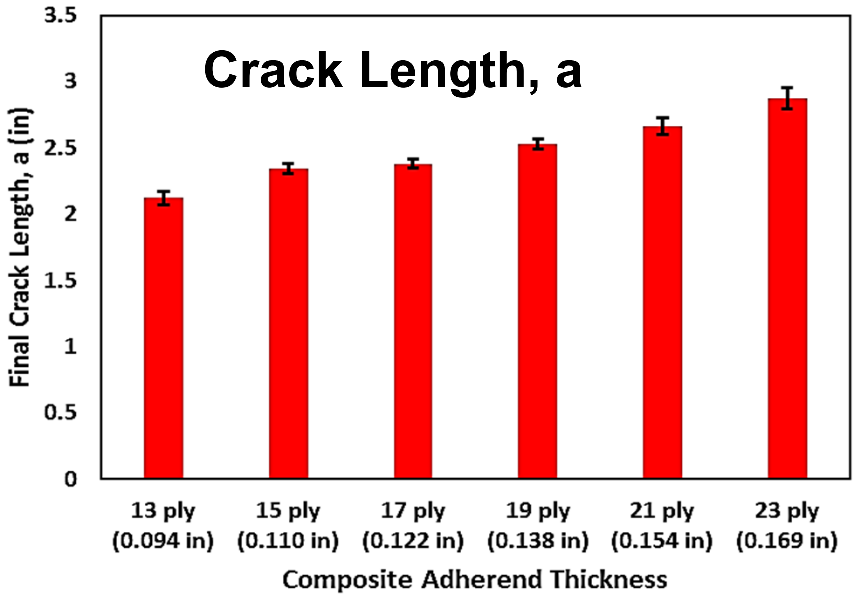
Experimental Investigation:
Composite Wedge Test Development

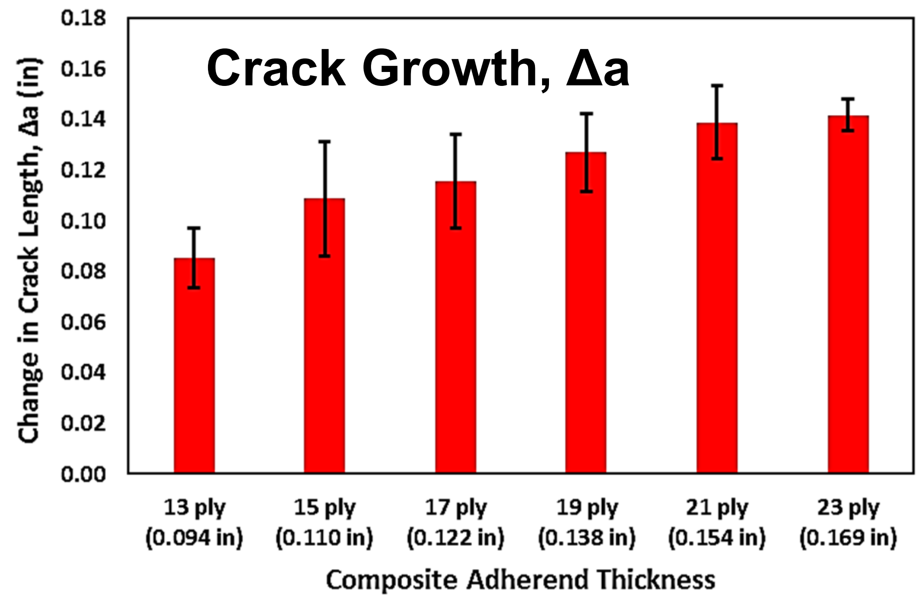
- **IM7/8552 carbon/epoxy adherends**
- **AF163-2K film adhesive**
- **"Ideal Bond": Grit-blast & acetone wipe bond surfaces**
- **Multiple adherend thicknesses to produce different flexural rigidities (E_f * I)**
    - **13, 15, 17, 19, 21, 23 ply thicknesses**
    - **(0.10 to 0.17 in thick adherends)**
- **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

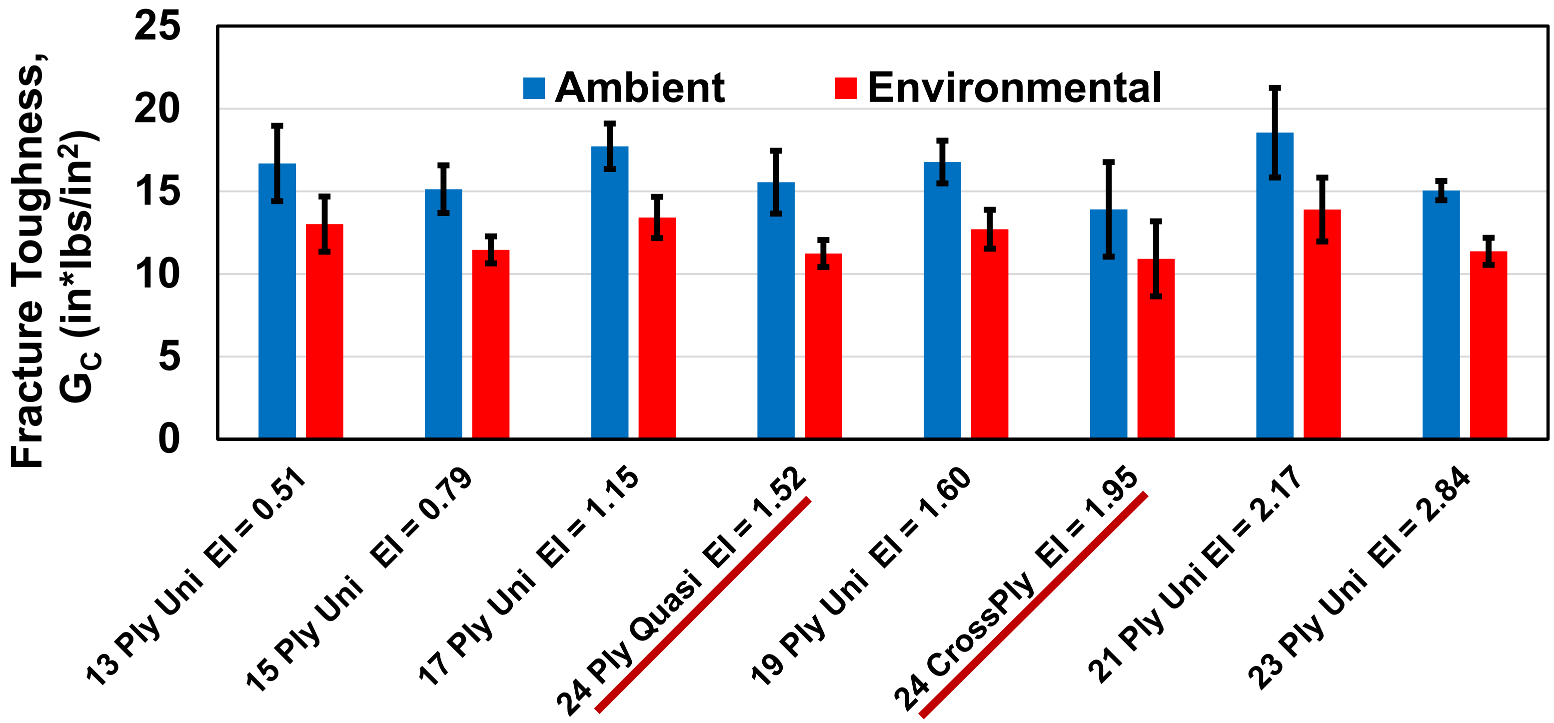




Increasing adherend thickness (and flexural stiffness)…

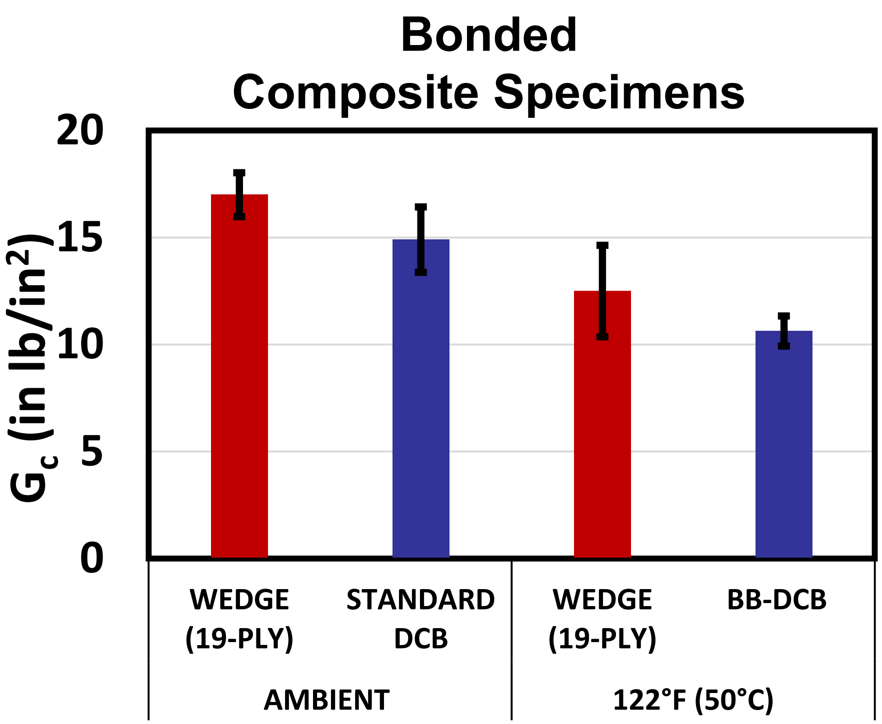
- **Increases crack length, a**
- **Increases crack growth, Δa**

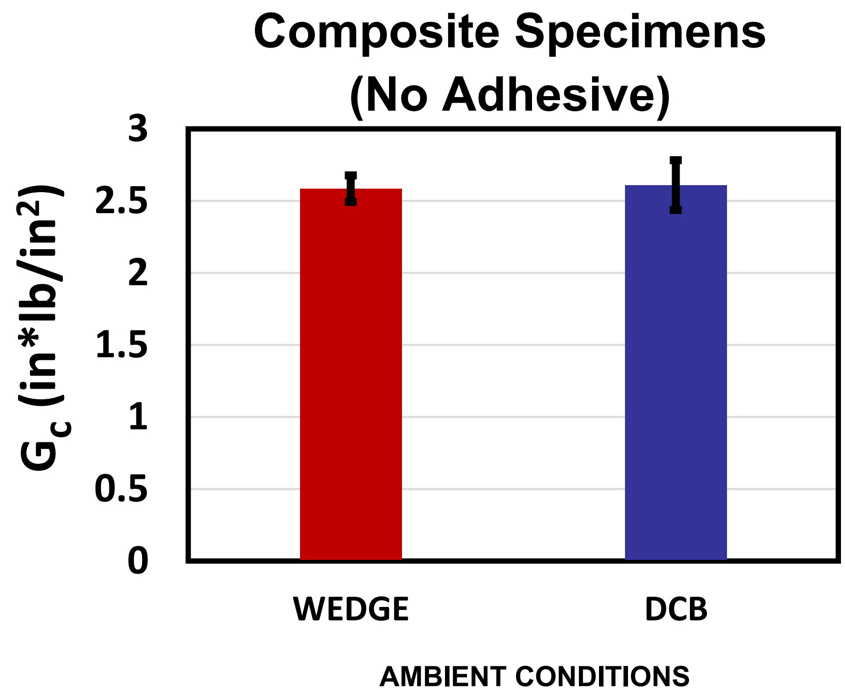
Wedge Testing of Multidirectional Laminates: Fracture Toughness Values



- Apparent facture toughness values remain relatively constant
- Provides estimate of fracture toughness at ambient conditions
- G_c values from quasi-isotropic and crossply laminates consistent with previous unidirectional laminates

Composite Wedge Test Development:
Comparisons With DCB Test



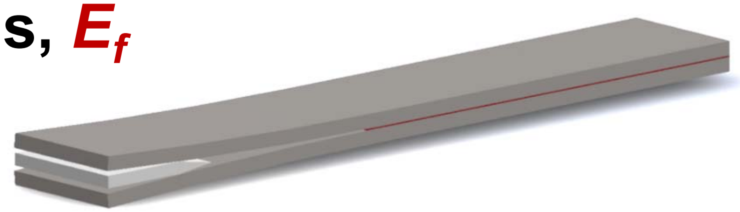


General agreement to date between double cantilever beam (DCB) and composite wedge test results

Calculation of G_c From Composite Wedge Test

G_C written in terms of flexural modulus, E_f

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



G_c = fracture toughness
E_f = flexural modulus
t = wedge thickness
h = adherend thickness
a = crack length

- Requires a measurement of flexural modulus E_f
  - Can obtain from three-point flexure testing of adherend material
- Requires a measurement of adherend thickness, h
- Requires a correction factor for crack tip rotation

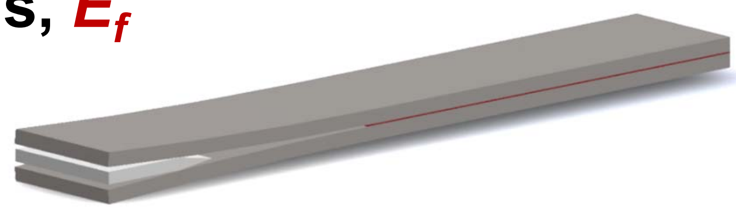
$$G_c = \frac{3E_f\,t^2\,h^3}{16\,a^4}\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]$$

Correction factor for crack tip rotation

Calculation of G_C:
*Why Not Measure E_f * I ?*

G_C written in terms of flexural modulus, E_f

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



G_c = fracture toughness
E_f = flexural modulus
I = area moment of inertia
t = wedge thickness
b = specimen width
a = crack length

G_C written in terms of flexural rigidity, $E_f I$

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

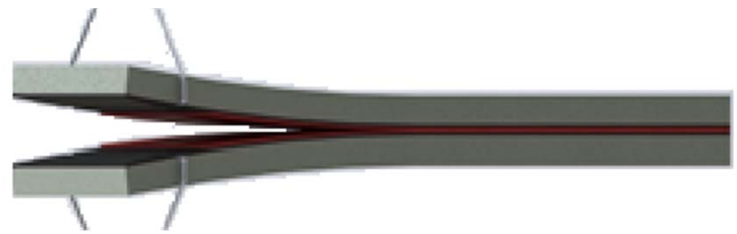
Measuring flexural rigidity $E_f I$…

- **Allows for direct slope measurement from load/displacement curve *(P/δ)***
- **Eliminates need for adherend thickness measurement**
- **Possible elimination of correction factor**

Use of In-Situ Flexural Rigidity From Composite Wedge Test Specimen

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

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



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

- **Express fracture toughness in terms of $E_f I$:**

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

G_c = fracture toughness
E_f = flexural modulus
I = area moment of inertia
t = wedge thickness
b = specimen width
a = crack length

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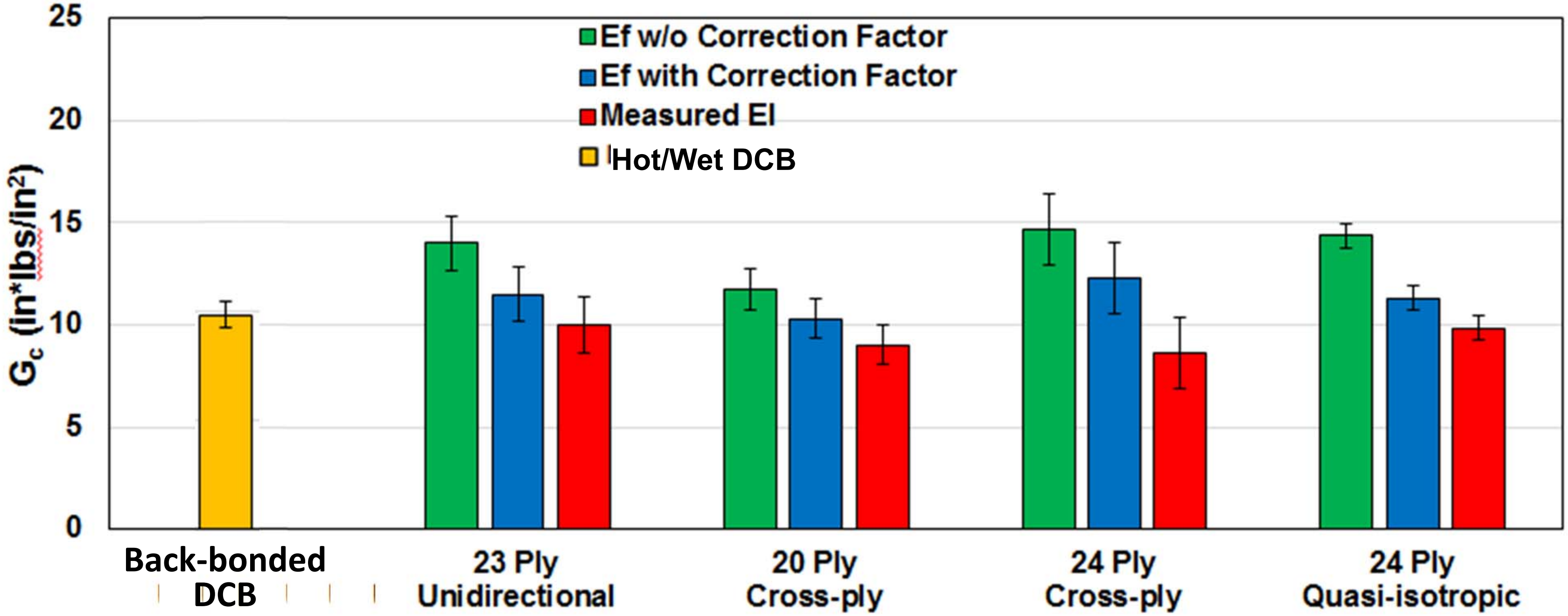
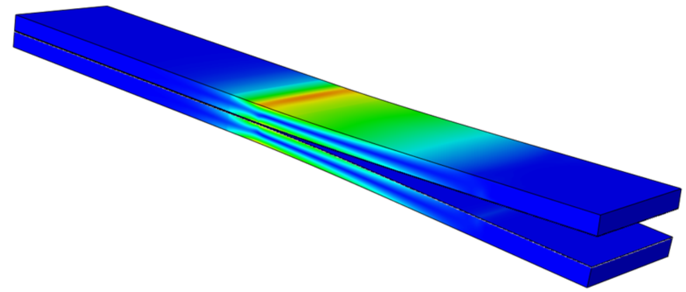
Comparison of Wedge Test and DCB Test Results: 50ºC, 95% RH, 5 days

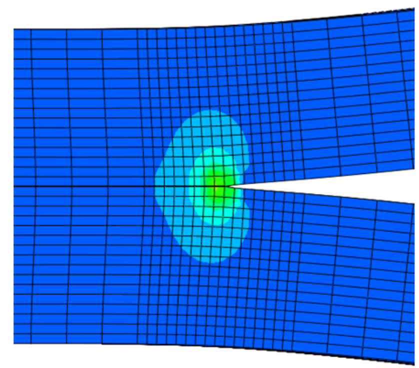


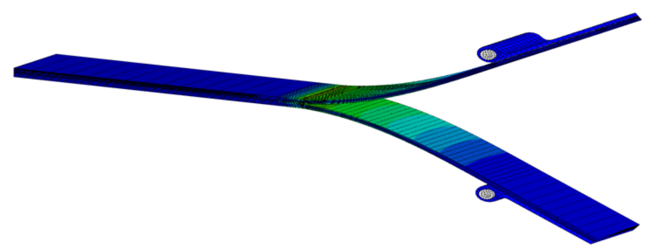
General agreement with both closed-form correction factor and measured E_f I approaches

Evaluation of G_c Calculation Methods: Numerical Simulations

- **3D finite element modeling of composite wedge test specimen**
- **Comparison with results for bonded composite DCB test methodology**
- **Evaluation of candidate G_c calculation methods for composite wedge test**
- **Determination of suitable range of adherend flexural rigidities (E_f * I)**

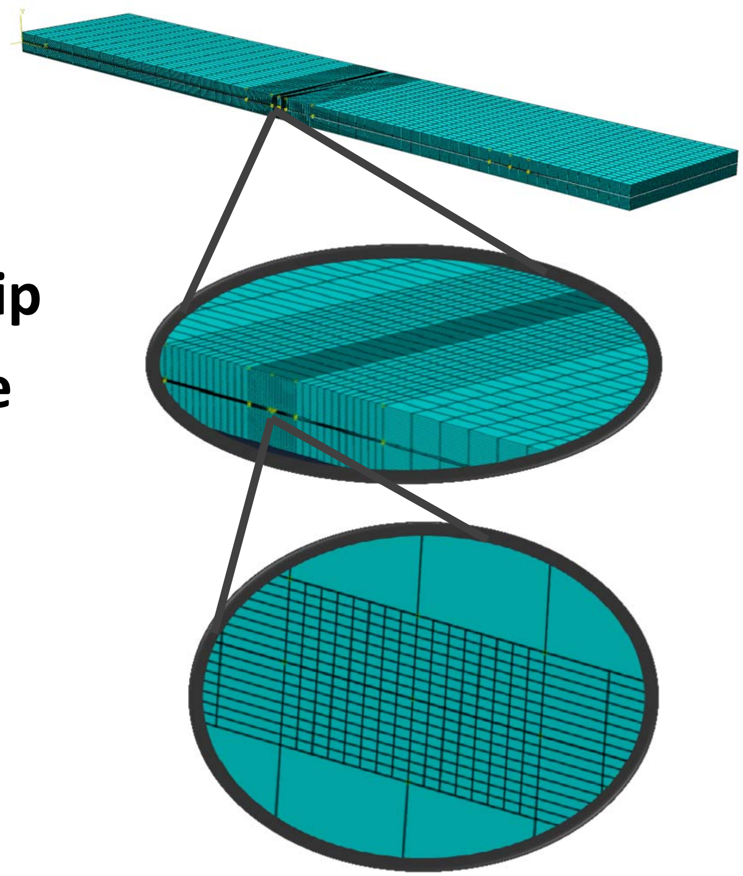




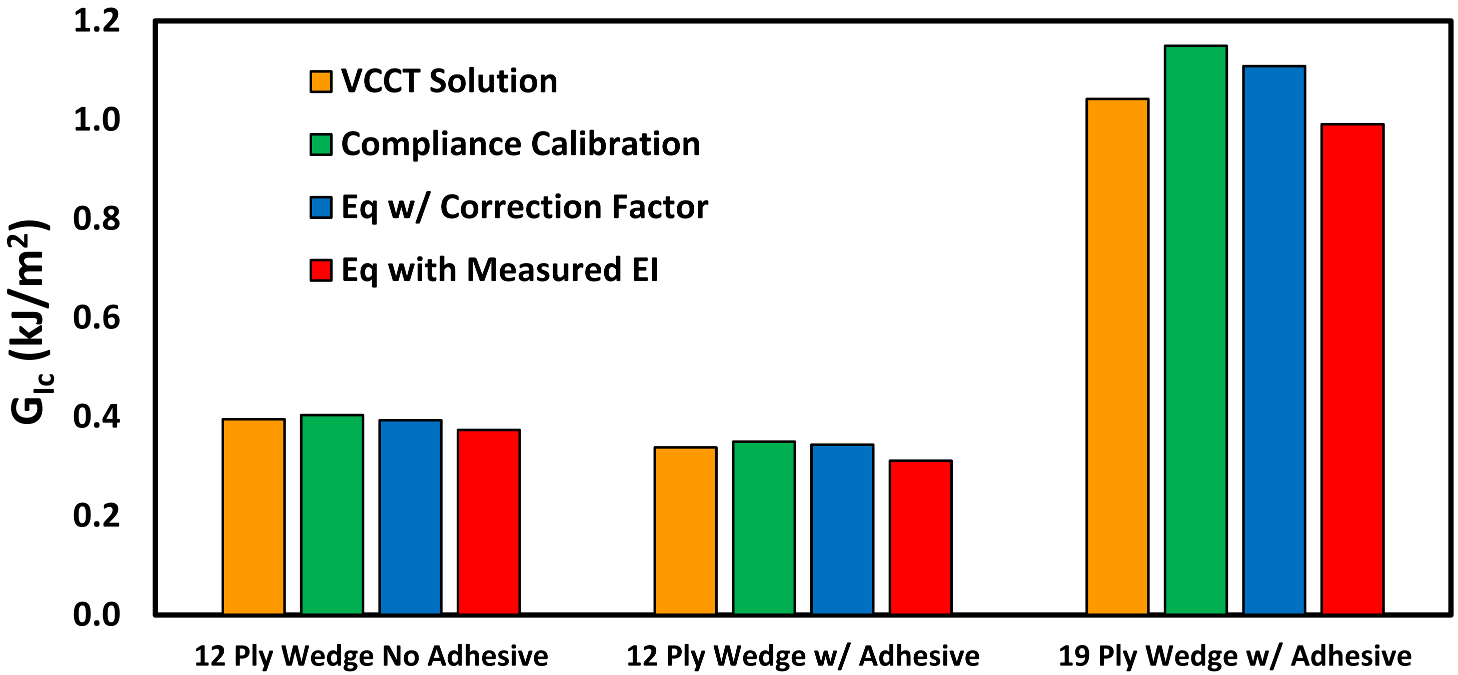


Finite Element Modeling Methodology

- ABAQUS 3D finite element analysis
- Crack modeled at center of adhesive bondline (cohesion failure)
- Highly refined mesh in vicinity of crack tip
- Displacement loading to simulate wedge inserted in bondline
- Use of VCCT to calculate reference G_c values
- Parametric study to evaluate effects of adherend flexural rigidity and adhesive thickness



Preliminary Results:
Comparison of Methods for G_c Determination:



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

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

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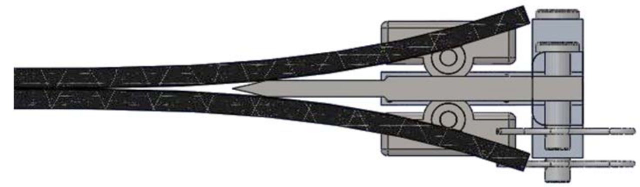
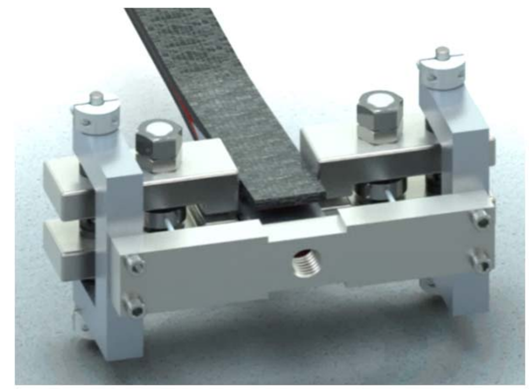
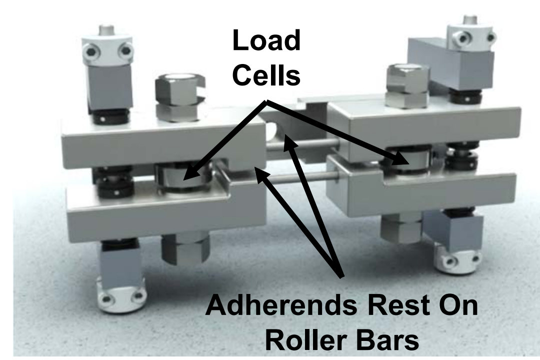
What if the Wedge Could Measure Opening Force During Wedge Testing?

- **Continuous opening-force measurement as wedge driven through specimen**
  - **Two compression load cells to measure opening force**
  - **Adherends supported by roller bars**
- **Monitor for drop in measured force**
  - **Increased crack length ahead of wedge**
  - **Reduced fracture toughness**
- **Similar to traveling wedge test, but with force-sensing "smart" wedge**
- **Retain wedge in specimen for environmental durability test**







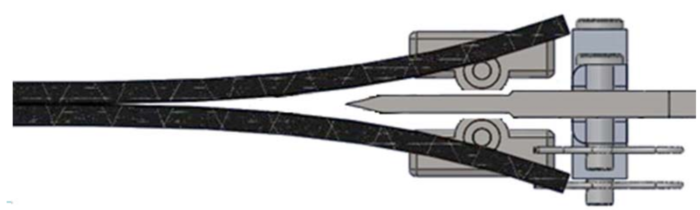
"Smart Wedge" Concept:

Fracture Toughness Measurement

- G_c written in terms of E_f I: $$G_c = \frac{9(E_f I)\, t^2}{4\, b\, a^4}$$
- From beam theory, solving for crack length, $a = \sqrt[3]{\frac{3\,(E_f\, I)\, t}{P}}$

$$G_c = \left[\frac{9\, P^4\, t^2}{4\, b^3 (E_f\, I)}\right]^{1/3}$$

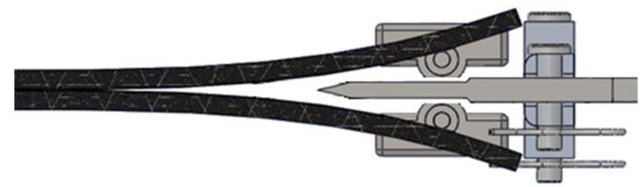
- Can calculate G_c knowing:
  - P (measured force)
  - t (wedge thickness)
  - Flexural rigidity, E_f I (measured)

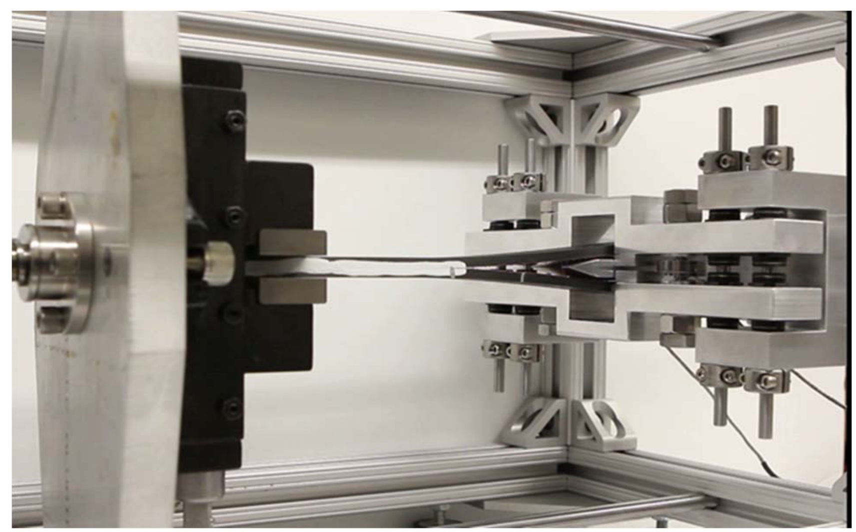


Do not need crack length measurement!

Smart Wedge Testing: Envisioned "Hybrid" Procedure

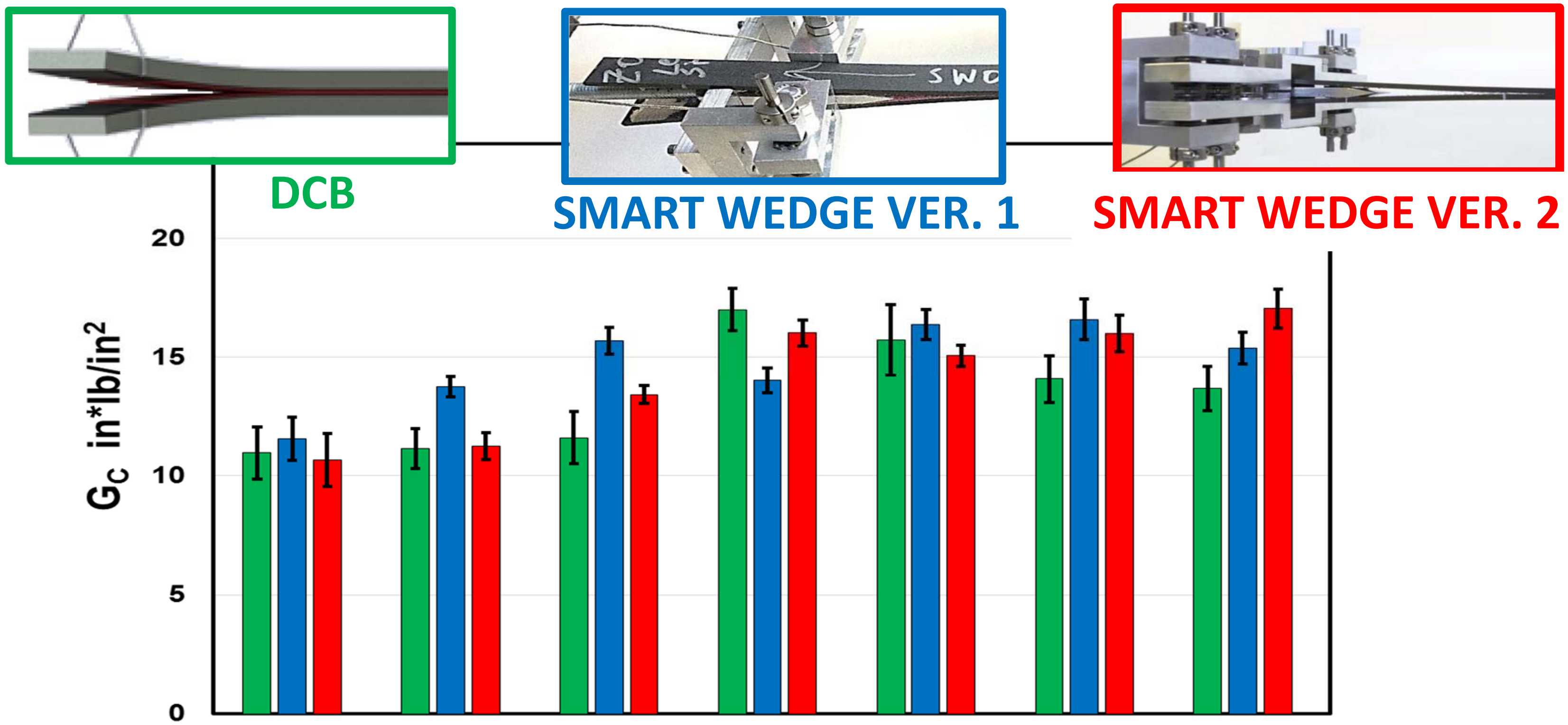
- Install specimen into smart wedge, retract installation wedge
- Obtain initial force and crack length measurements, calculate flexural rigidity, $E_f I$
- Perform "traveling wedge" type testing, obtain real-time fracture toughness G_C estimates
- When desired, halt traveling wedge, reinsert wedge, and subject specimen to environmental exposure for durability assessment





Operation of Updated Prototype (6X Speed)

Preliminary Results:
"Smart Wedge" Testing



- **3 tests performed on each bonded composite specimen**
- **Initial results appear promising**

BENEFITS TO AVIATION

- Improved environmental durability test method for metal bonds (metal wedge test, ASTM D3762)
- Improved shear test method for adhesives (ASTM D5656)
- Composite wedge test for assessing the environmental durability of composite bonds and assessing surface preparations
- Hybrid traveling wedge/static wedge test for evaluation of larger bond areas
- Dissemination of research results through FAA technical reports and conference/journal publications

Thank you for your attention!

Questions?