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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
November 7, 2018

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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

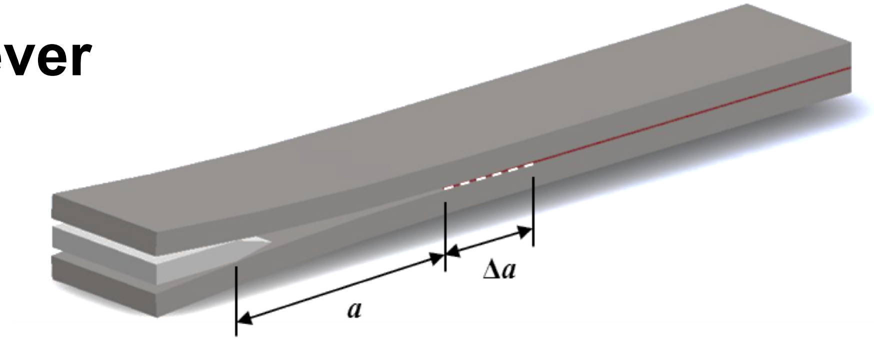
Outline

- **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)"



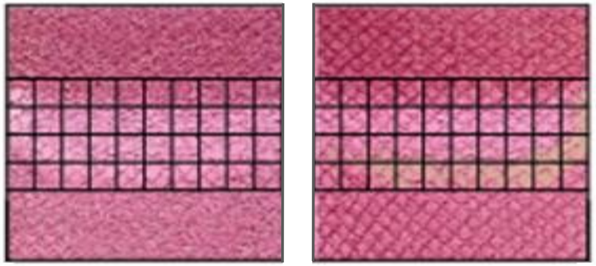
- **Bonded aluminum double cantilever beam loaded by forcing a wedge between adherends**
- **Assembly placed into test environment (ex: 50⁰ C, 95% RH)**
- **Crack growth *Δa* due to environmental exposure measured following prescribed time**
- **Able to asses bond quality quickly by causing rapid hydration 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

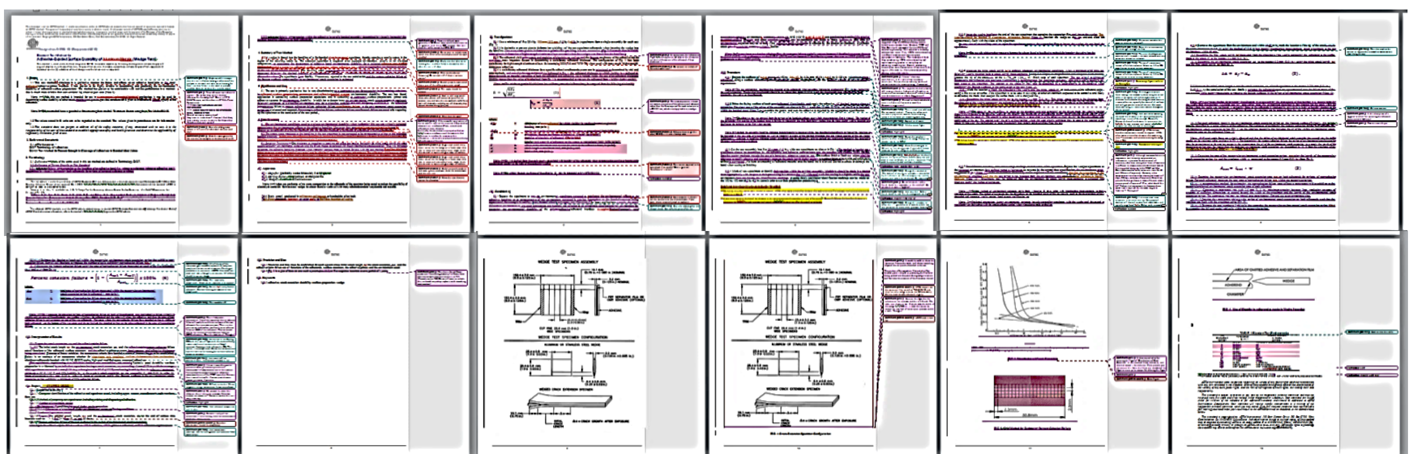
$$\boldsymbol{Percent\ cohesion\ failure}:$$

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



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 D30 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

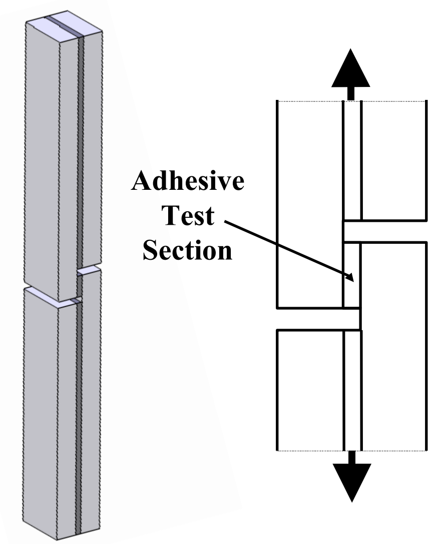
Current Activities

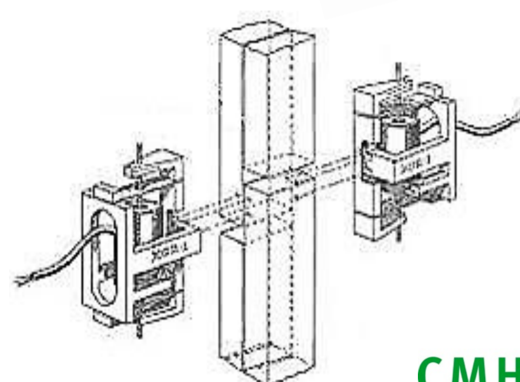
- ASTM D3762 Metal Wedge Test revision
- ASTM D5656 Thick Adherend Lap Shear Test revision
- Bonded composite fracture mechanics test evaluation
- Composite Wedge Test development/standardization

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**

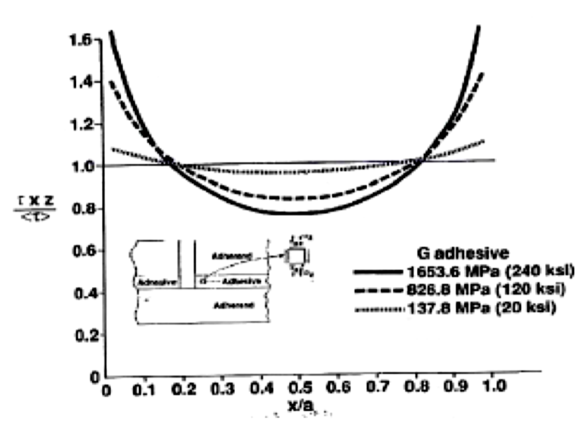




Current Activities:
ASTM D14.80.01 Task Group

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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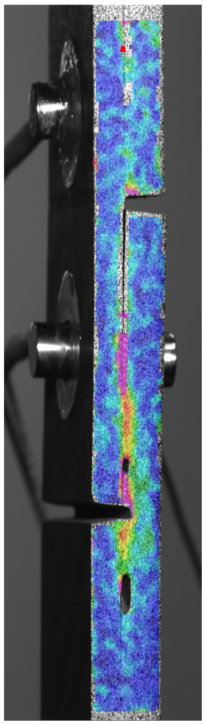

R. Cole, NRC Canada

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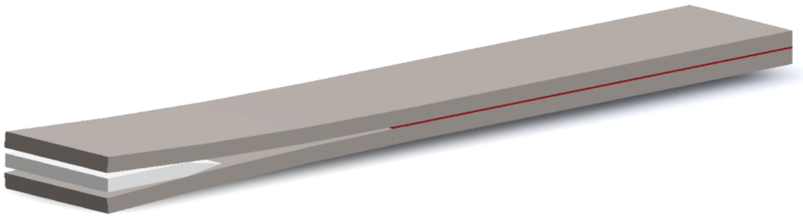
Overview:
Development of a Composite Wedge Test:

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

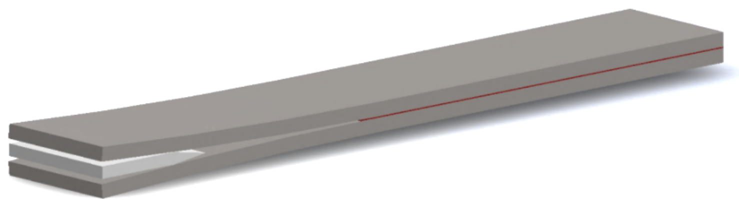
    or…
  - Must use another quantity to assess durability

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: $U = \frac{1}{2} T\,\delta$

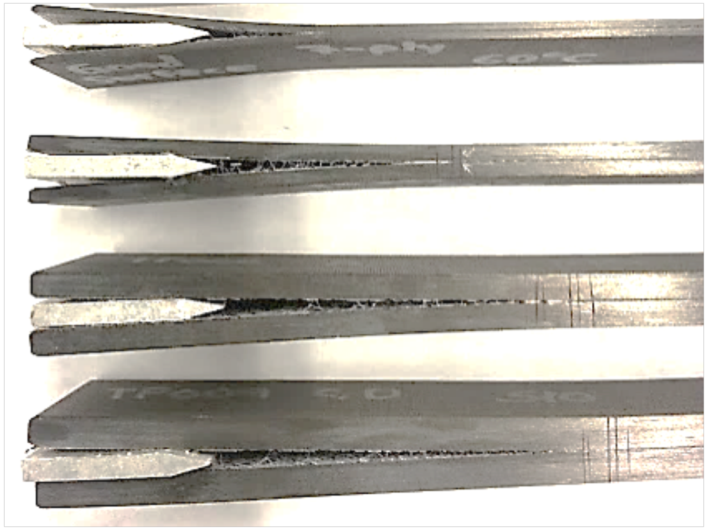
Strain energy release rate: $G_c = \frac{dU}{dA}$

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

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

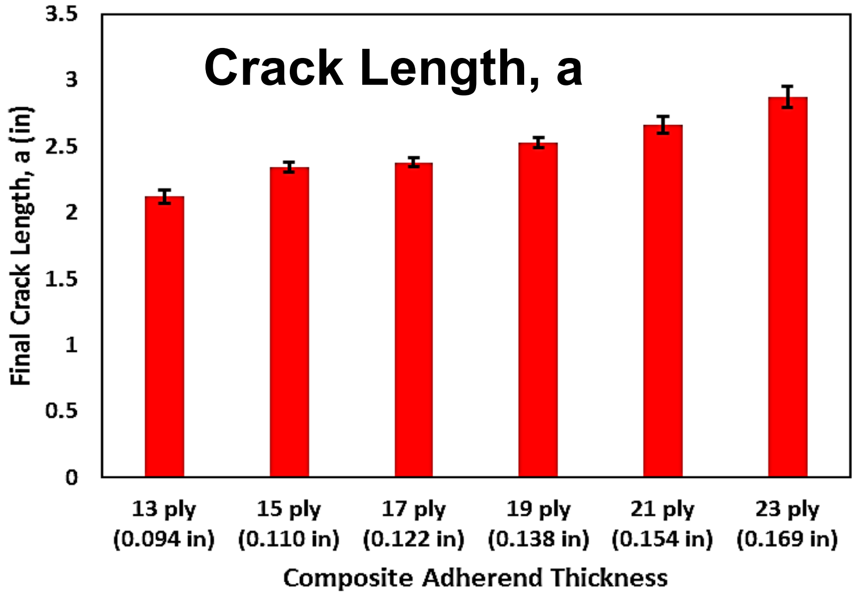
Experimental Investigation:
Composite Wedge Test Development

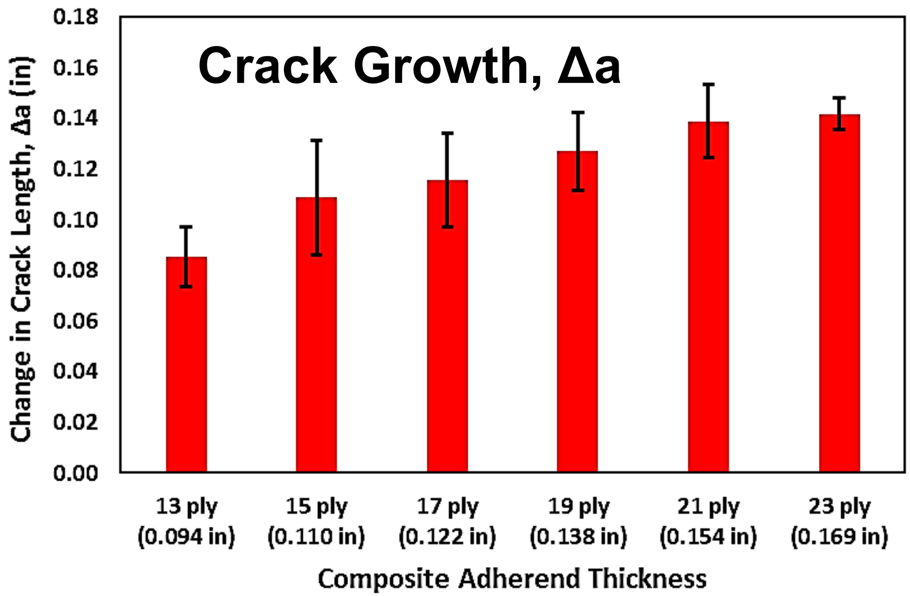
- **IM7/8552 carbon/epoxy adherends**
- **AF163-2K film adhesive**
- **"Ideal Bond": Grit-blast & acetone wipe bond surfaces**
- **Multiple adherend thicknesses to produce different flexural rigidities (E_f * I)**
  - **13, 15, 17, 19, 21, 23 ply thicknesses**
  - **(0.10 to 0.17 in thick adherends)**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

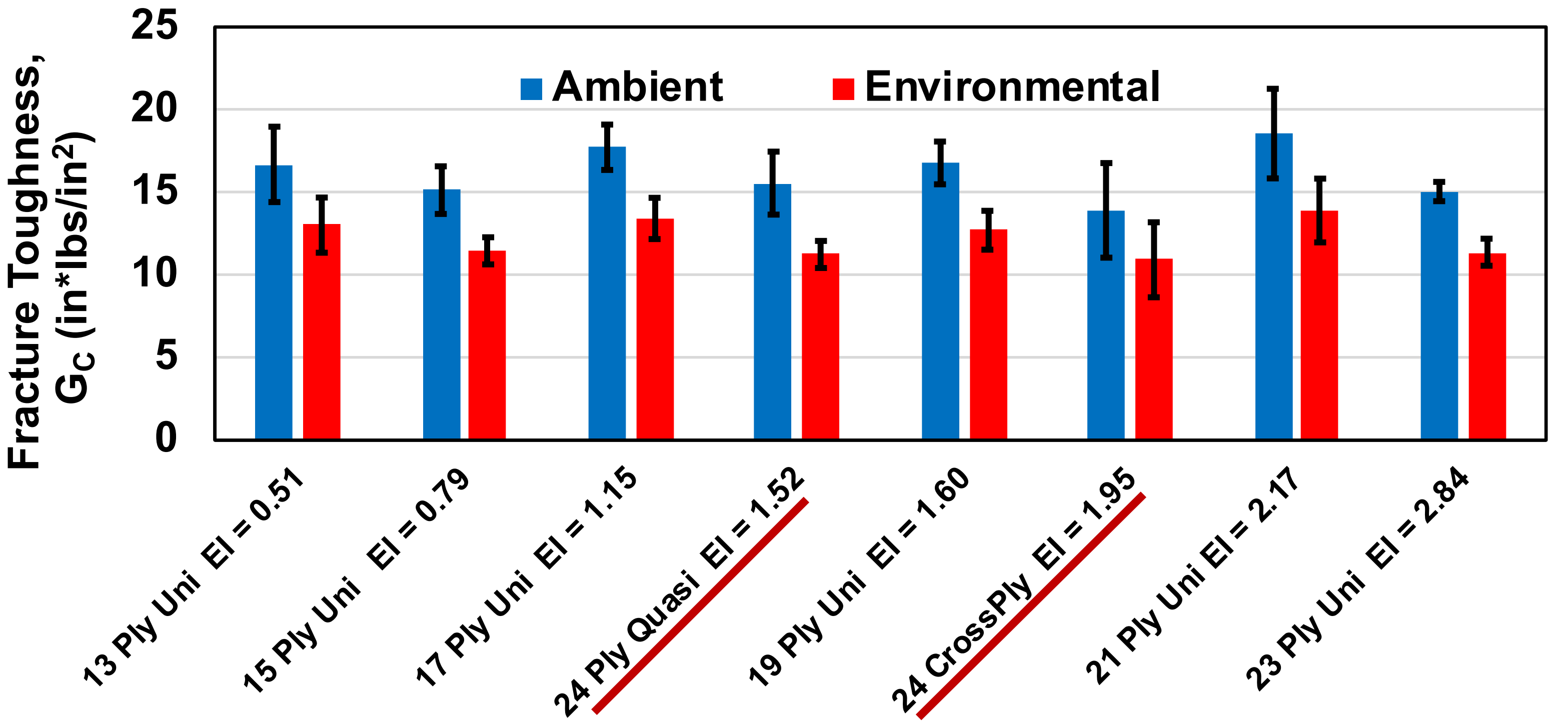




Increasing adherend thickness (and flexural stiffness)…

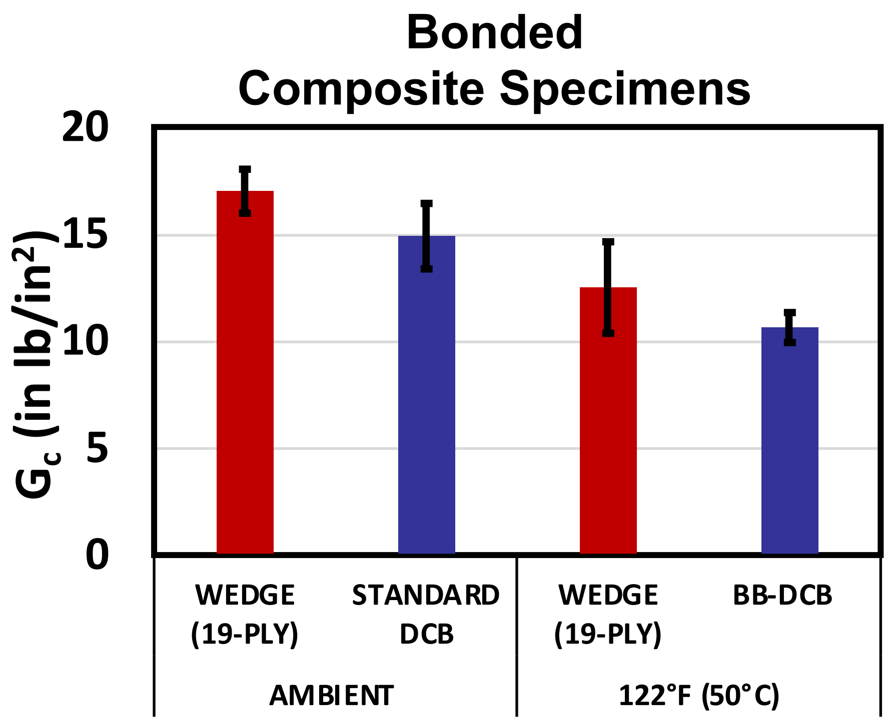
- **Increases crack length, a**
- **Increases crack growth, Δa**

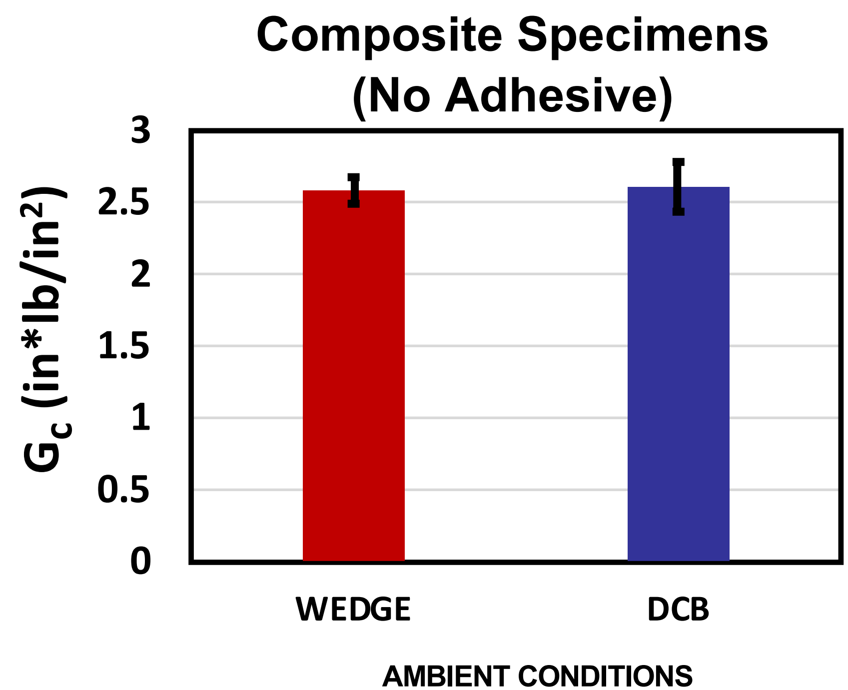
Wedge Testing of Multidirectional Laminates: Fracture Toughness Values



- 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



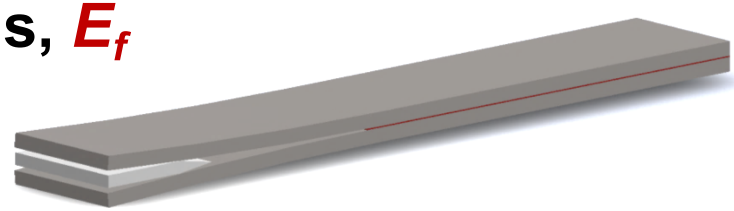


General agreement to date between double cantilever beam (DCB) and composite wedge test results

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**

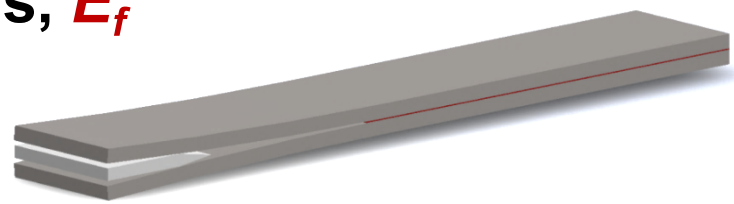
$$G_c = \frac{3E_f\, t^2\, h^3}{16\, a^4}\left[\;\frac{1}{(1+0.64\,\frac{h}{a})^4}\;\right]$$

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, ***$E_f I$***

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

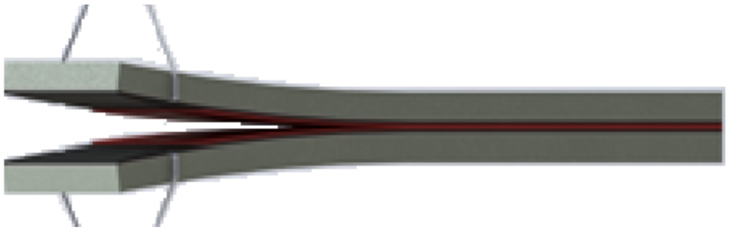
Measuring flexural rigidity *$E_f I$*…

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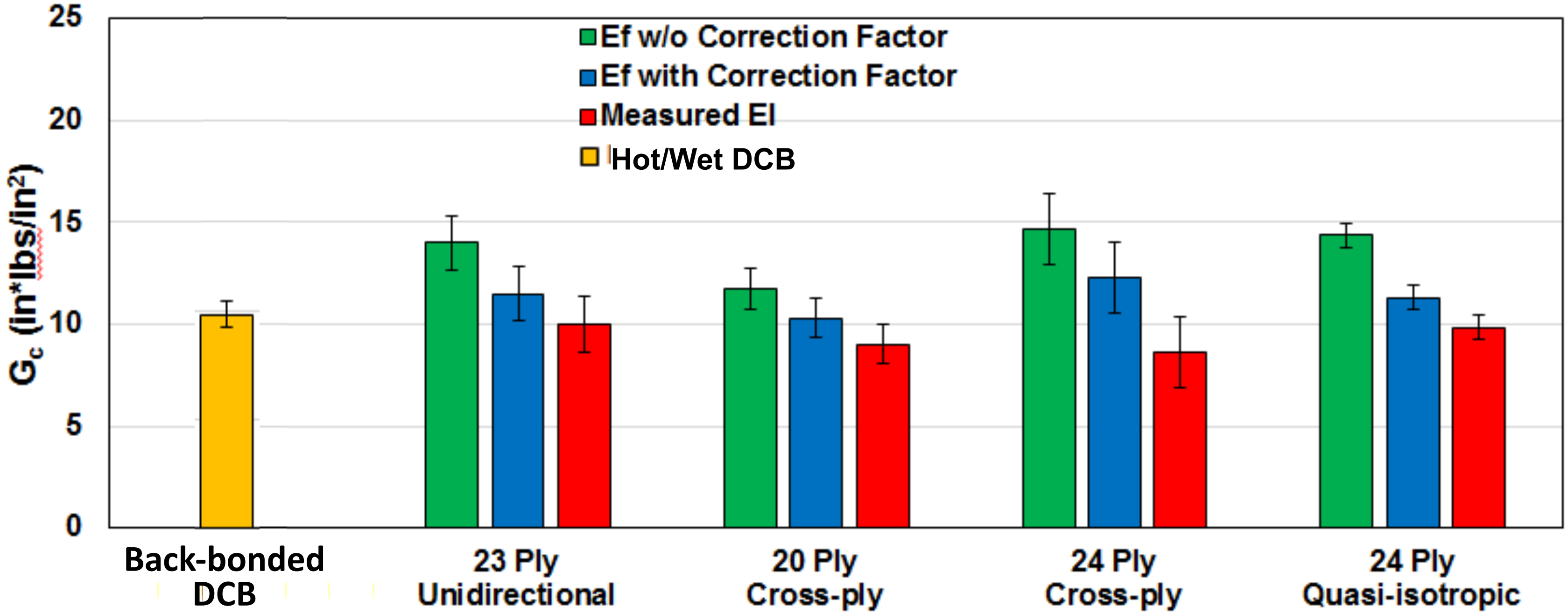
Comparison of Wedge Test and DCB Test Results: 50ºC, 95% RH, 5 days



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

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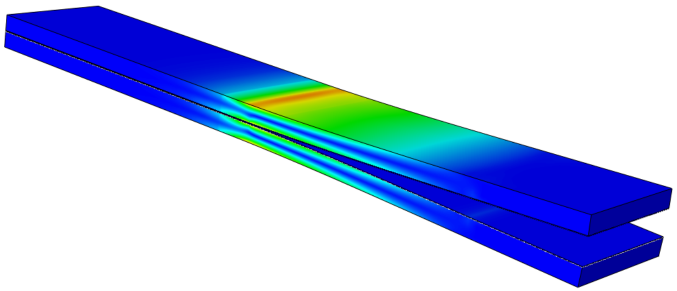
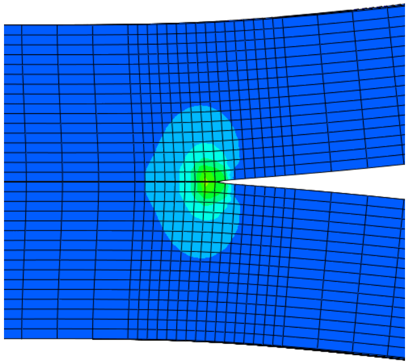
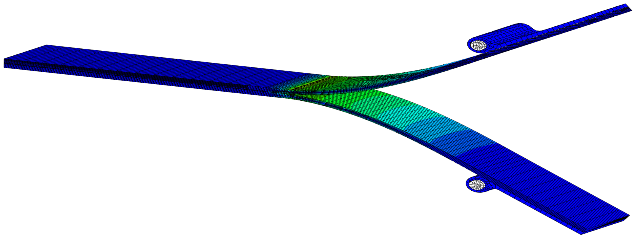
Evaluation of G_c Calculation Methods: Numerical Simulations

- **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)**

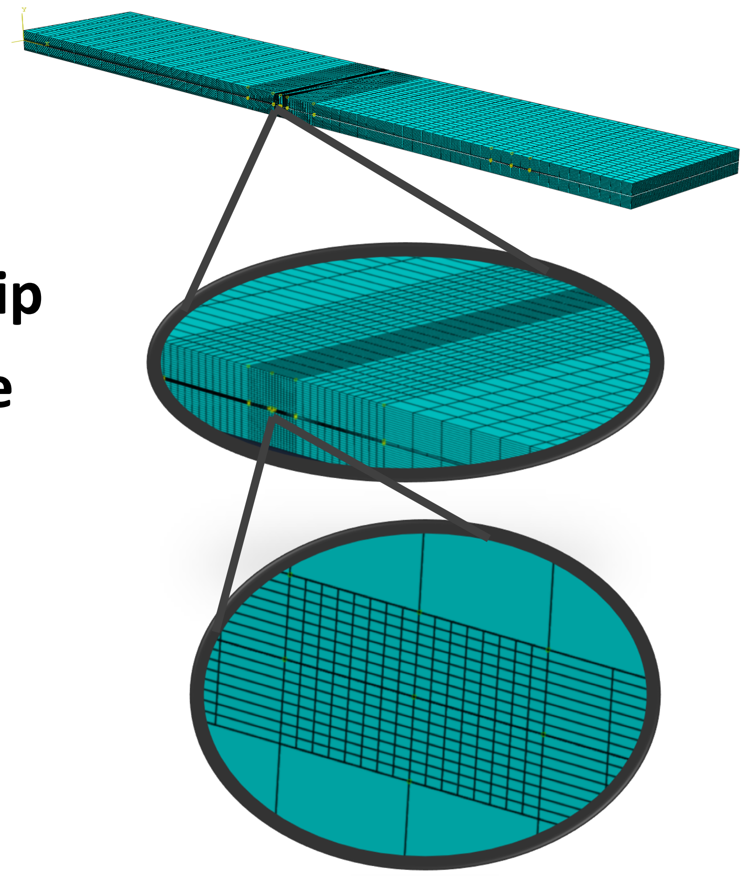




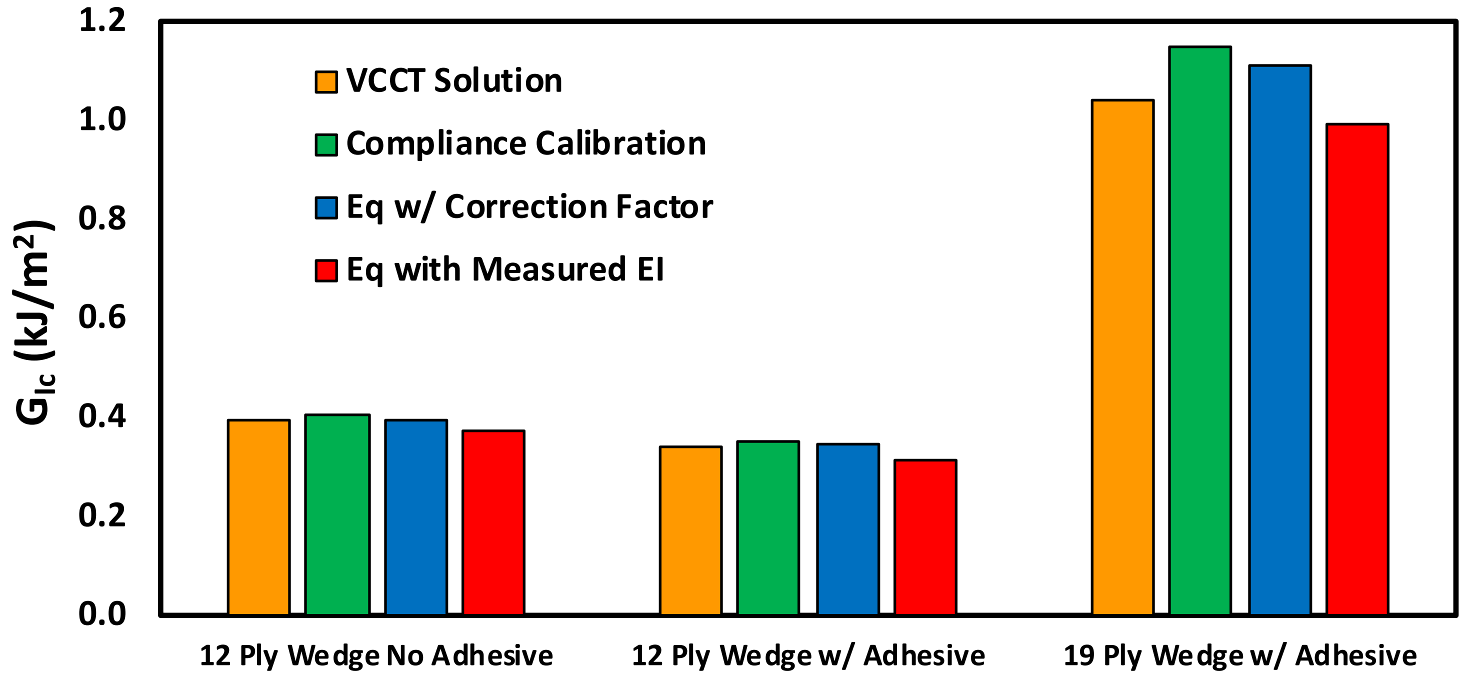


Finite Element Modeling Methodology

- 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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  - Comparison of results with other test methods
  - ➡ "Smart Wedge" traveling wedge test concept

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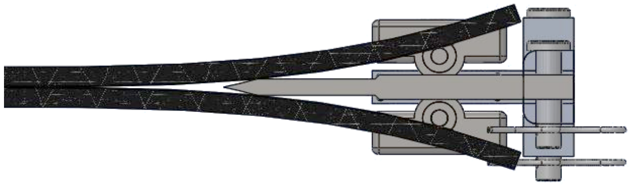
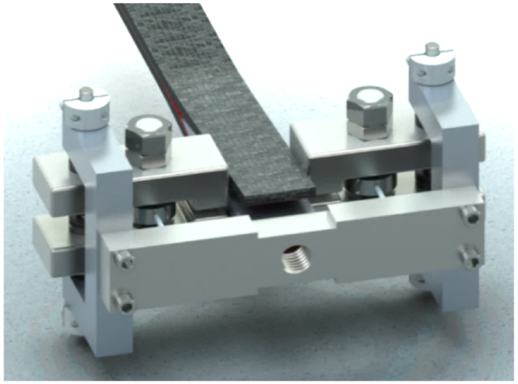
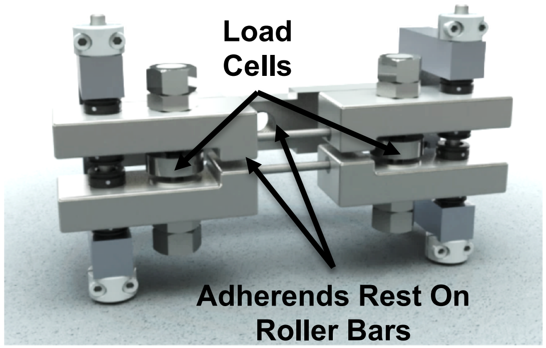
What if the Wedge Could Measure Opening Force During Wedge Testing?

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

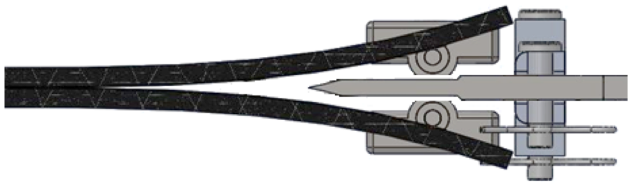
$$G_c = \left[\frac{9\, P^4\, t^2}{4\, b^3 (E_f\, I)}\right]^{1/3}$$

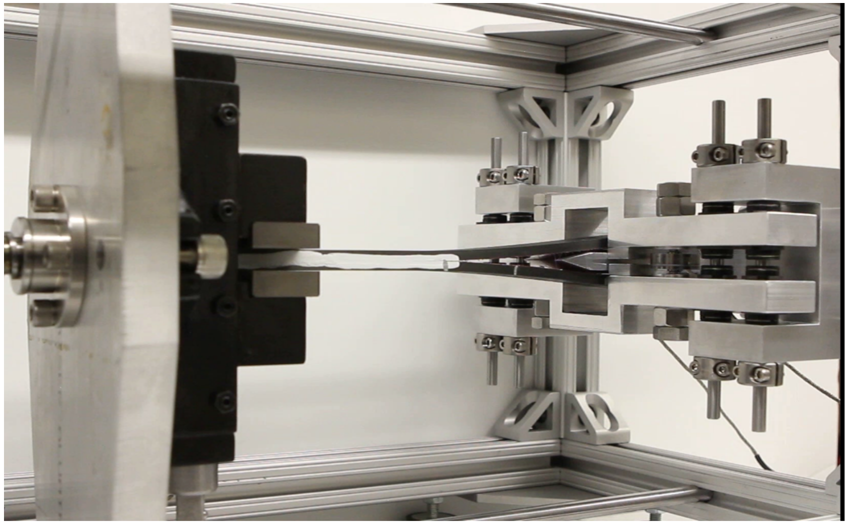
- Can calculate G_c knowing:
  - P (measured force)
  - t (wedge thickness)
  - Flexural rigidity, E_f I (measured)

Do not need crack length measurement!

Smart Wedge Testing:
Envisioned "Hybrid" Procedure

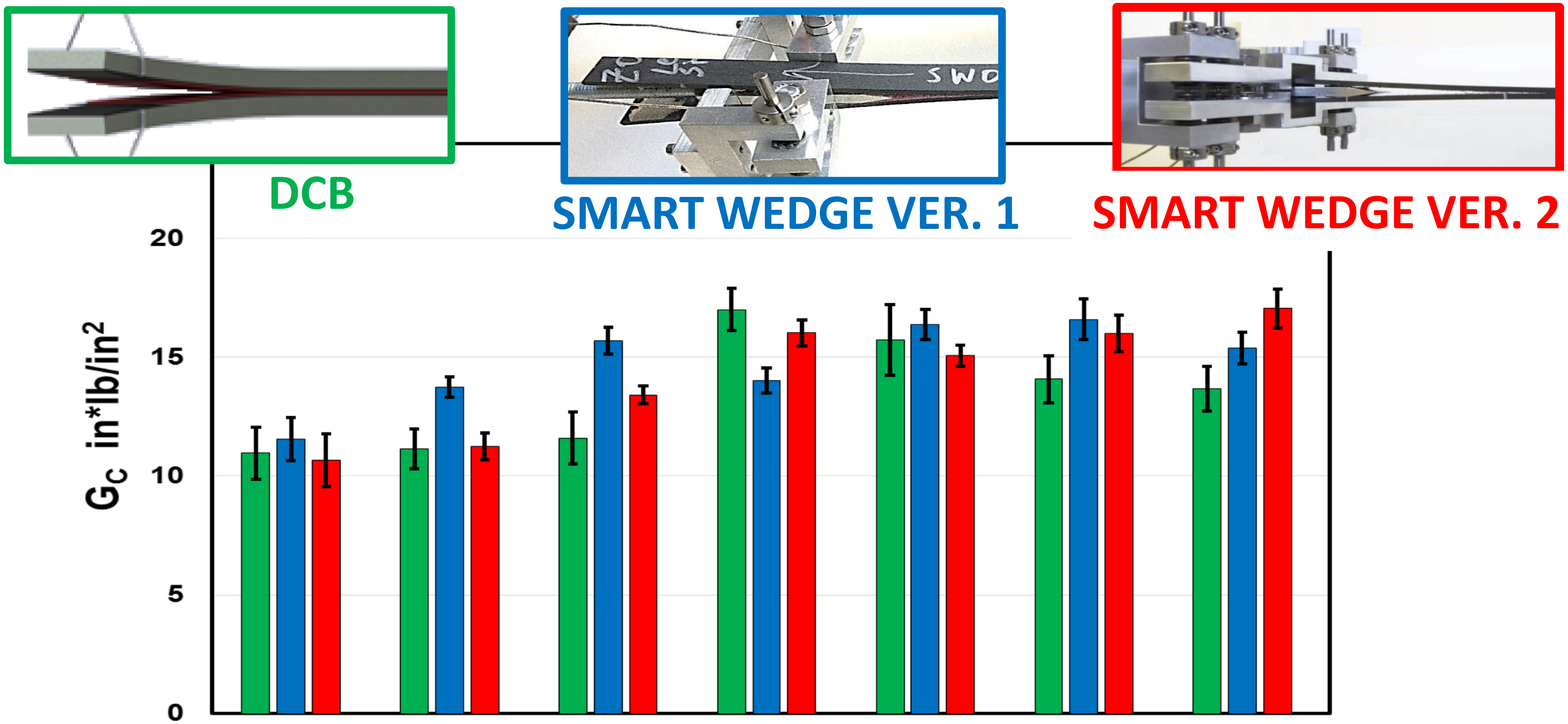
- **Install specimen into smart wedge, retract installation wedge**
- **Obtain initial force and crack length measurements, calculate flexural rigidity, $E_f I$**
- **Perform "traveling wedge" type testing, obtain real-time fracture toughness G_C estimates**
- **When desired, halt traveling wedge, reinsert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

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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?

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**