Development of Environmental Durability Test Methods for Composite Bonded Joints

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FAA Sponsored Project Information

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  - **3M Corp: Maha DeSilva**

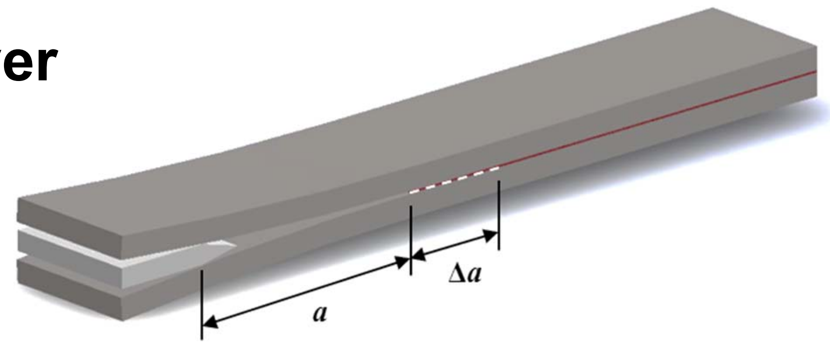
Outline

- **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**

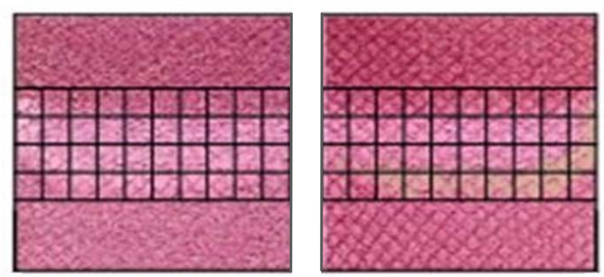
Revision of ASTM D3762:

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**

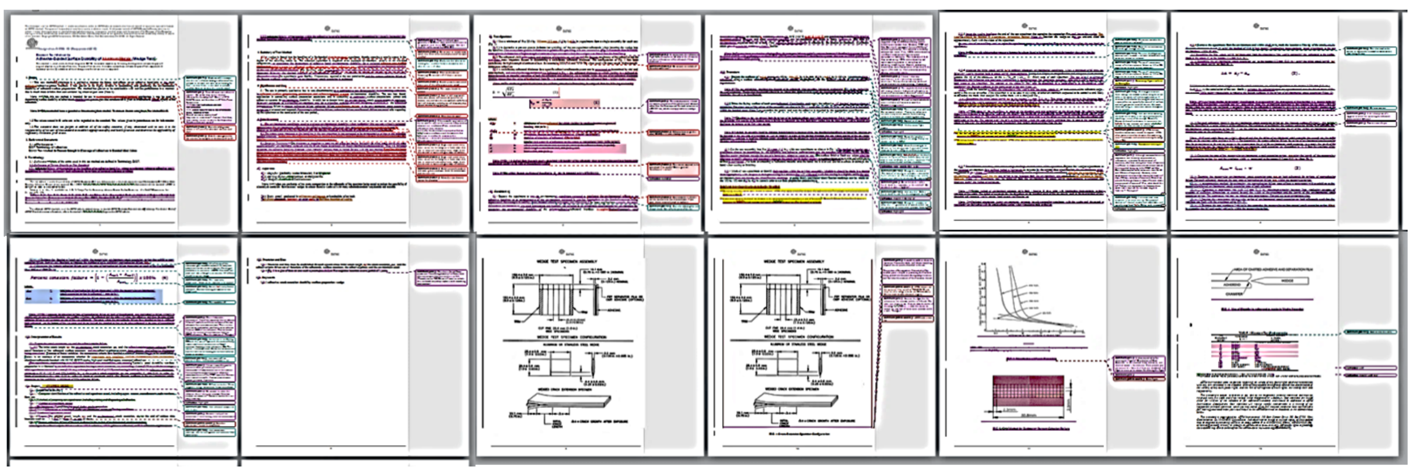
$\boldsymbol{Percent\ cohesion\ failure}$:

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



Revision of ASTM D3762:
Current Status

- Completed extensive revision of standard
- Initial D14.80 subcommittee balloting
- Addressing remaining concerns from negative votes
- Reballot at concurrent subcommittee/main levels later this summer



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

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

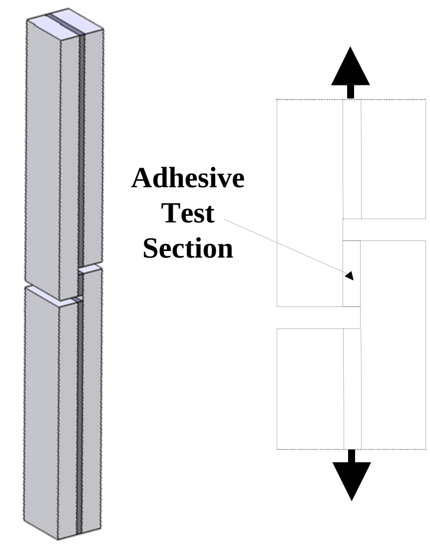
Current Activities

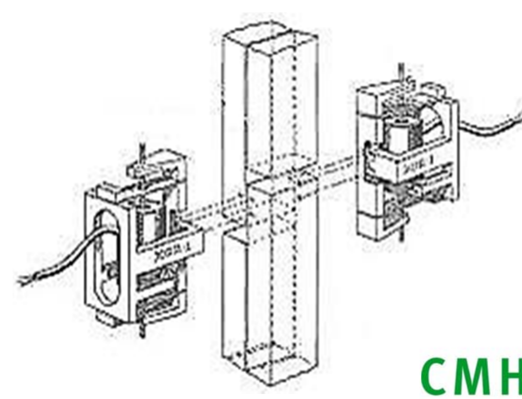
- ASTM D3762 Metal Wedge Test revision
- ASTM D5656 Thick Adherend Lap Shear Test revision
- Composite Wedge Test development/standardization

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
  - Determination of optimal attachment points for shear strain measurement
- Round-robin investigation initiated
  - Two paste adhesives
  - Four adhesive thicknesses
  - Three labs/measurement methods
- In conjunction with CMH-17 Testing Working Group





Outline

- **Updates:**
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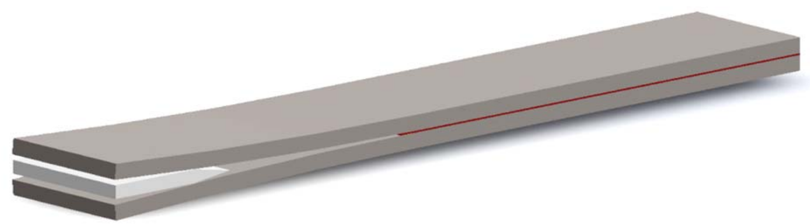
➡ **Primary focus: Environmental durability test methods for composite bonded joints**
  - Composite wedge test development
  - Comparison of results with other test methods
  - "Smart Wedge" traveling wedge test concept

Overview:
Development of a Composite Wedge Test:

<u>Additional Complexities</u>:

- **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**

Why Environmental Durability Tests of Composite Bonded Joints?

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

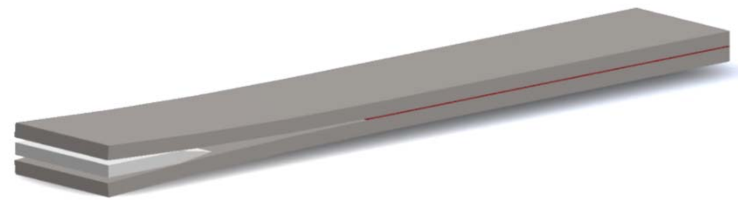
- **Ensure longer-term environmental durability of composite bonds**
- **Investigate effects of environmental exposure on performance of bonded composite joints**
  - **Failure mode: cohesion versus adhesion failure**
  - **Estimate fracture toughness reduction**
- **Evaluate effectiveness of surface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

  $\delta = t/2$ (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: $G_c = \frac{dU}{dA}$

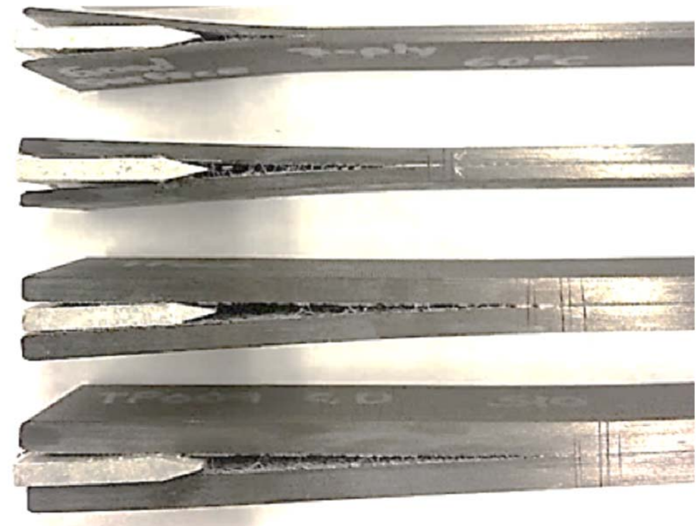
$$\Rightarrow G_c = \frac{3E_f\,t^2\,h^3}{16\,a^4}\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]$$

Correction factor for crack tip rotation

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

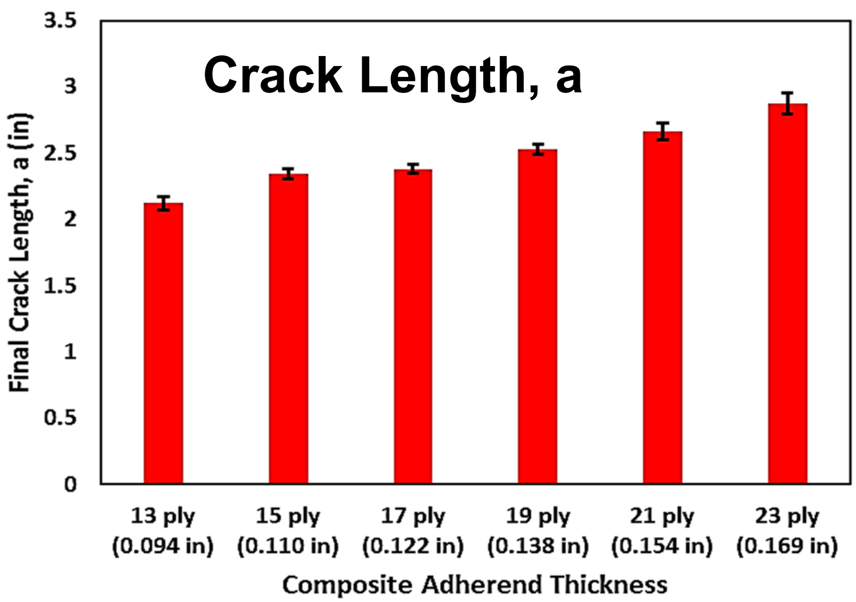
Experimental Investigation:
Composite Wedge Test Development

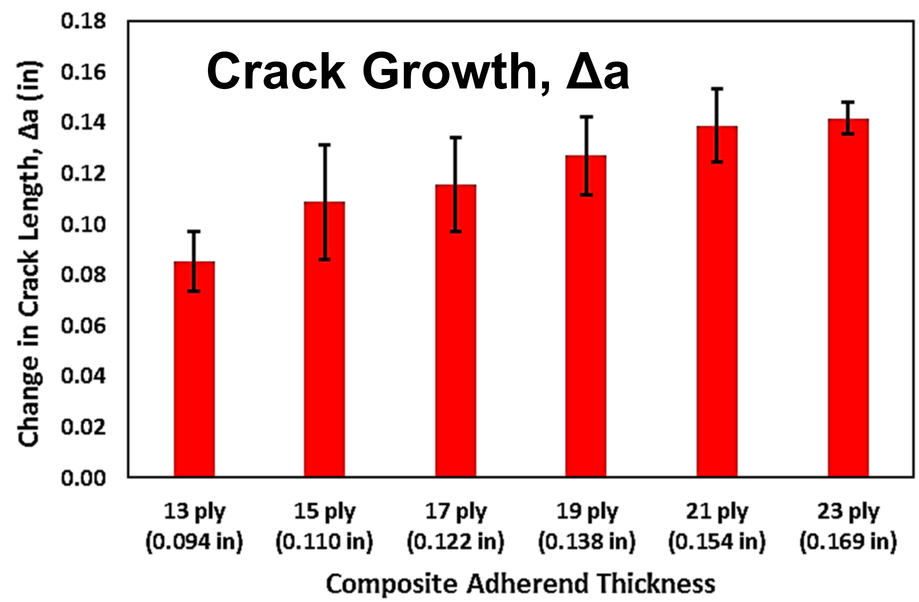
- **IM7/8552 carbon/epoxy adherends**
- **AF163-2K film adhesive**
- **“Ideal Bond”: Grit-blast & acetone wipe bond surfaces**
- **Multiple adherend thicknesses to produce different flexural rigidities (E_f * I)**
  - **13, 15, 17, 19, 21, 23 ply thicknesses**
  - **(0.10 to 0.17 in thick adherends)**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

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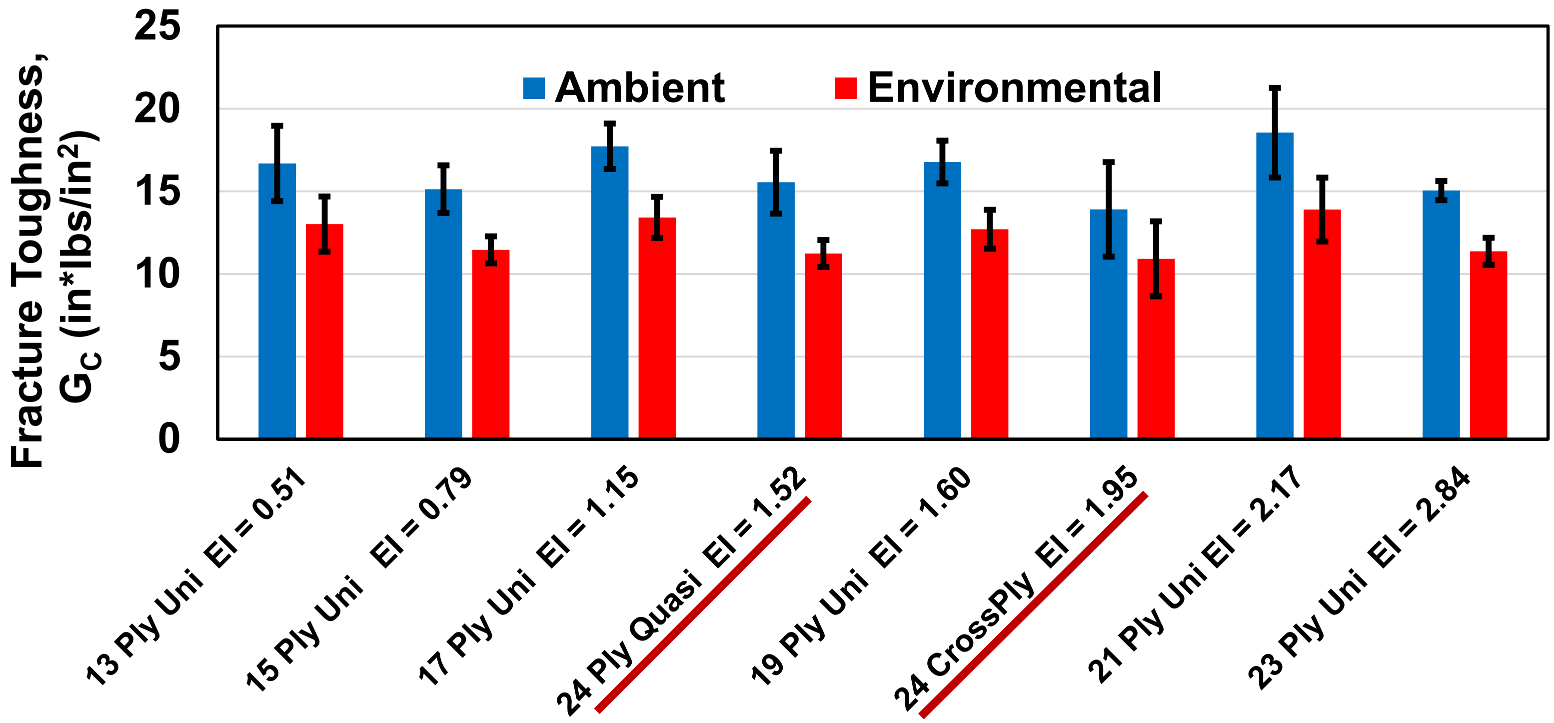
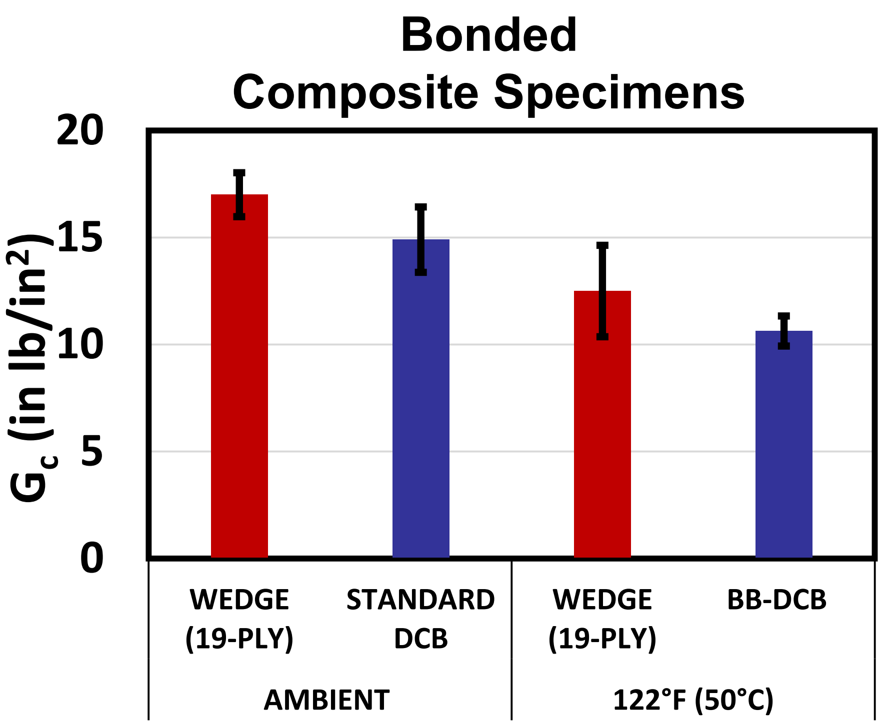
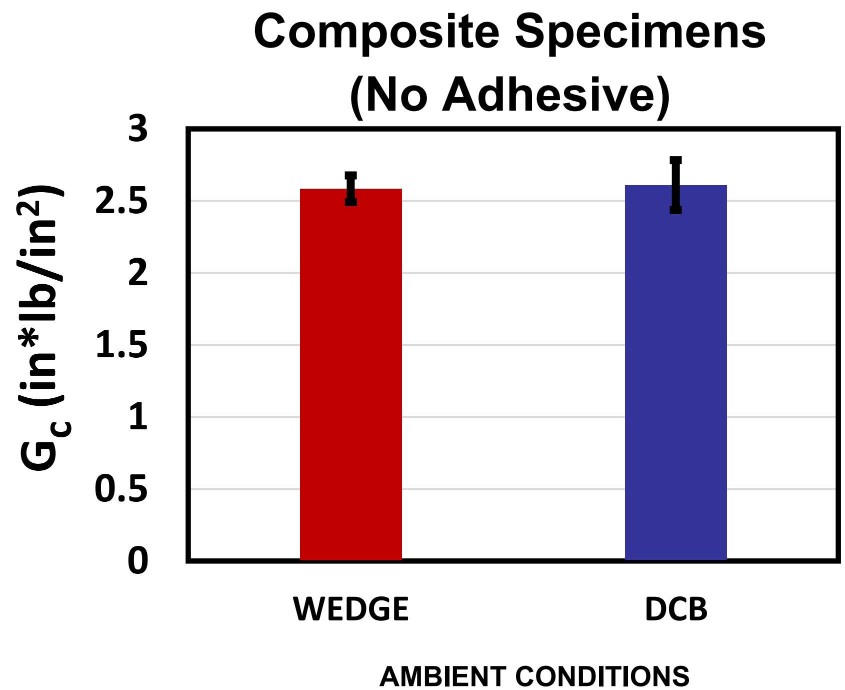
Wedge Testing of Multidirectional Laminates: Fracture Toughness Values



- 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

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Investigating Accuracy of G_c Values From Wedge Test:

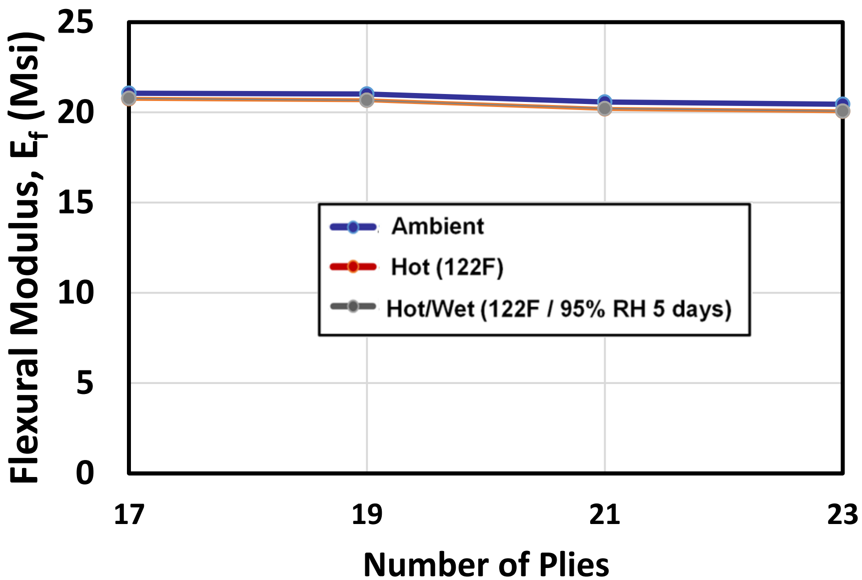
Determination of Flexural Modulus, E_f

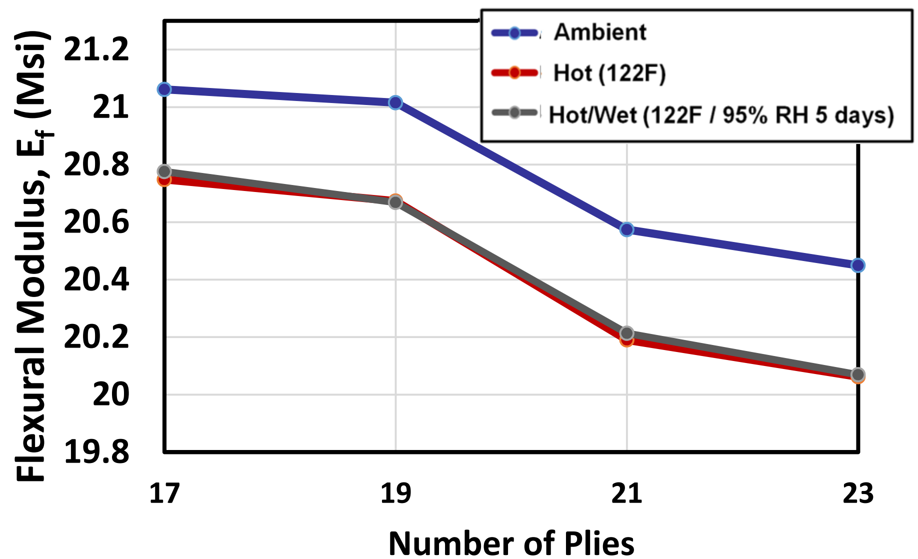
- Require value of flexural modulus, E_f, for calculating fracture toughness,

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

- E_f value should be representative of that experienced during wedge testing
- What type of test should be used to measure E_f?
- What environment should testing be performed at:
  - *How does environmental exposure affect E_f?*
  - *Can RT/ambient E_f measurement be used?*

Three-Point Flexural Modulus (E_f) Testing of Composite Adherends:
Effects of Environmental Conditioning





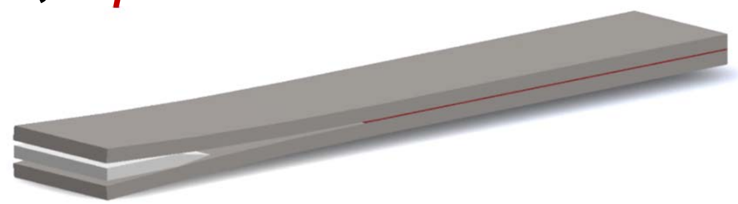
- **Three-point flexure testing**
- **Less than 2% reduction in E_f due to conditioning environment (122 ^{0}F, 95% RH for 5 days)**
- ***Flexure testing of adherends at RT/Ambient conditions appears suitable for E_f determination***

Since We're Testing Adherends to Measure E_f…

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

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

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

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

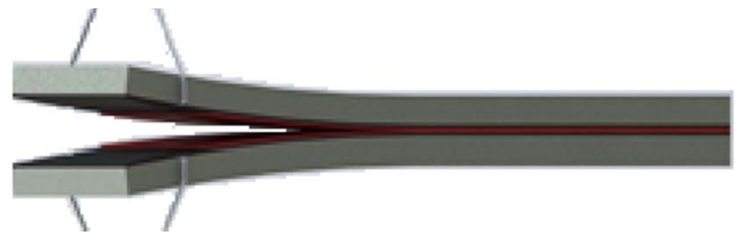
Use of Effective Flexural Rigidity For Fracture Toughness Determination

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

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

- **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 effective $E_f\, I$ measurement**

a = beam span (crack length)
P = applied force
δ = crosshead displacement
t = wedge thickness
E_f = flexural modulus
I = moment of inertia

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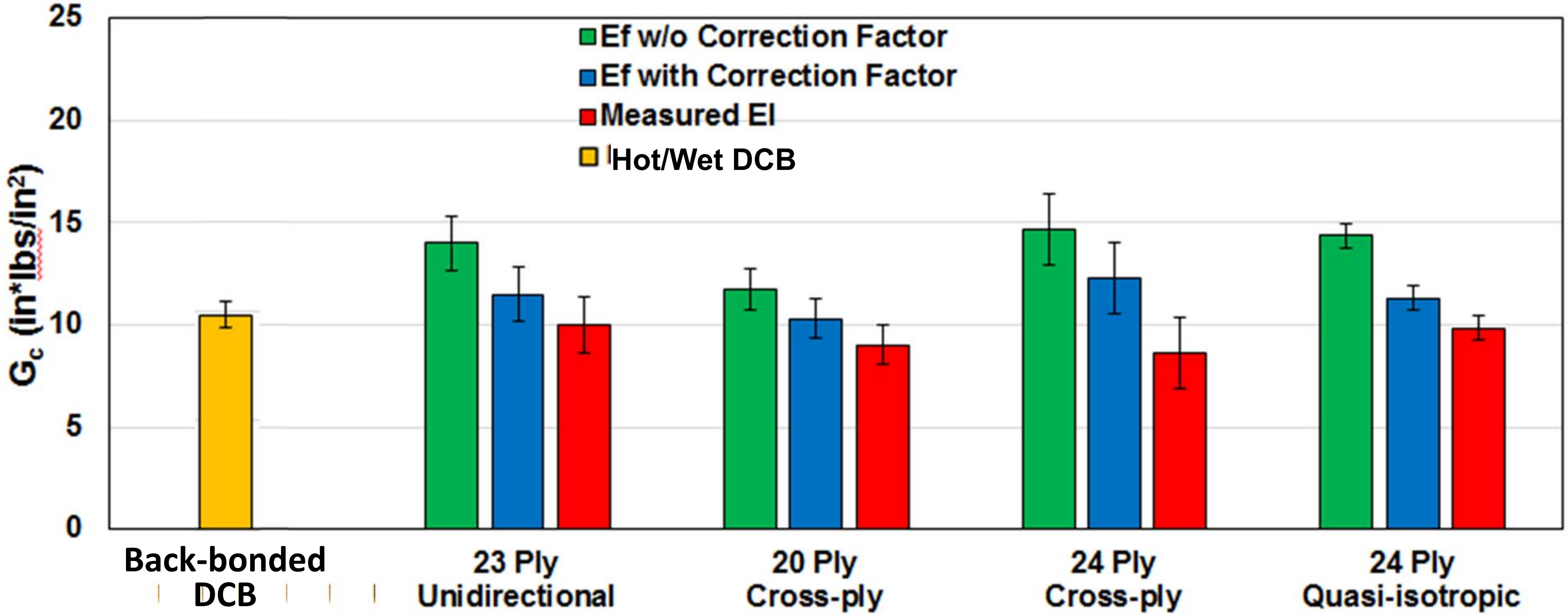
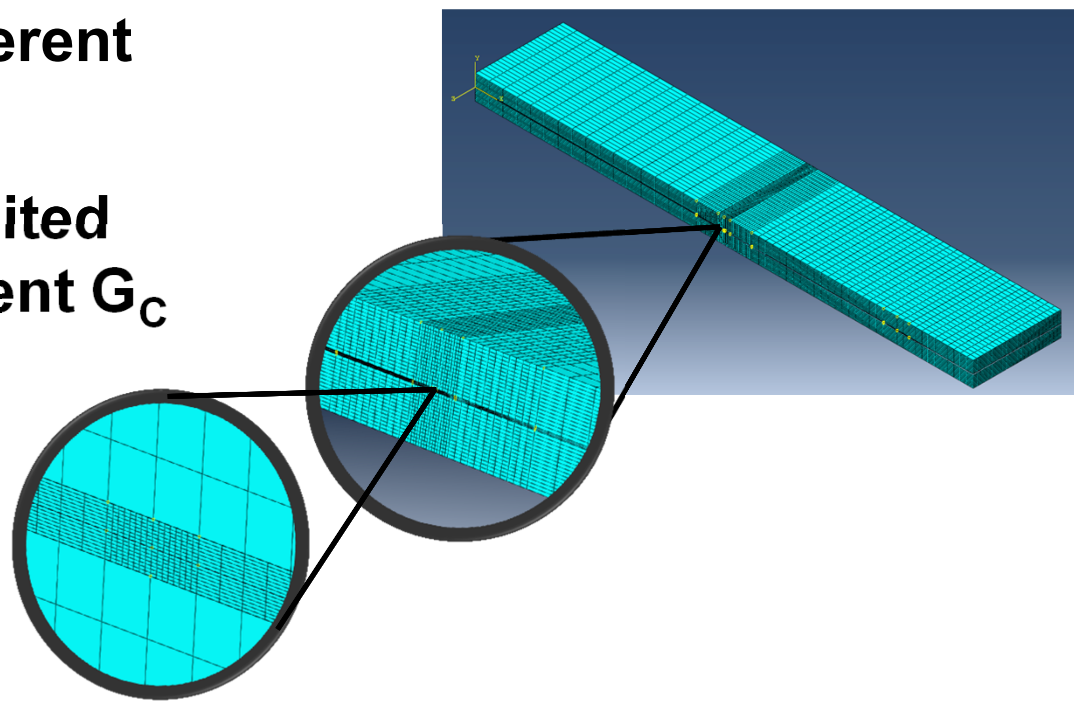
Comparison of Wedge Test and DCB Test Results: 50ºC, 95% RH, 5 days



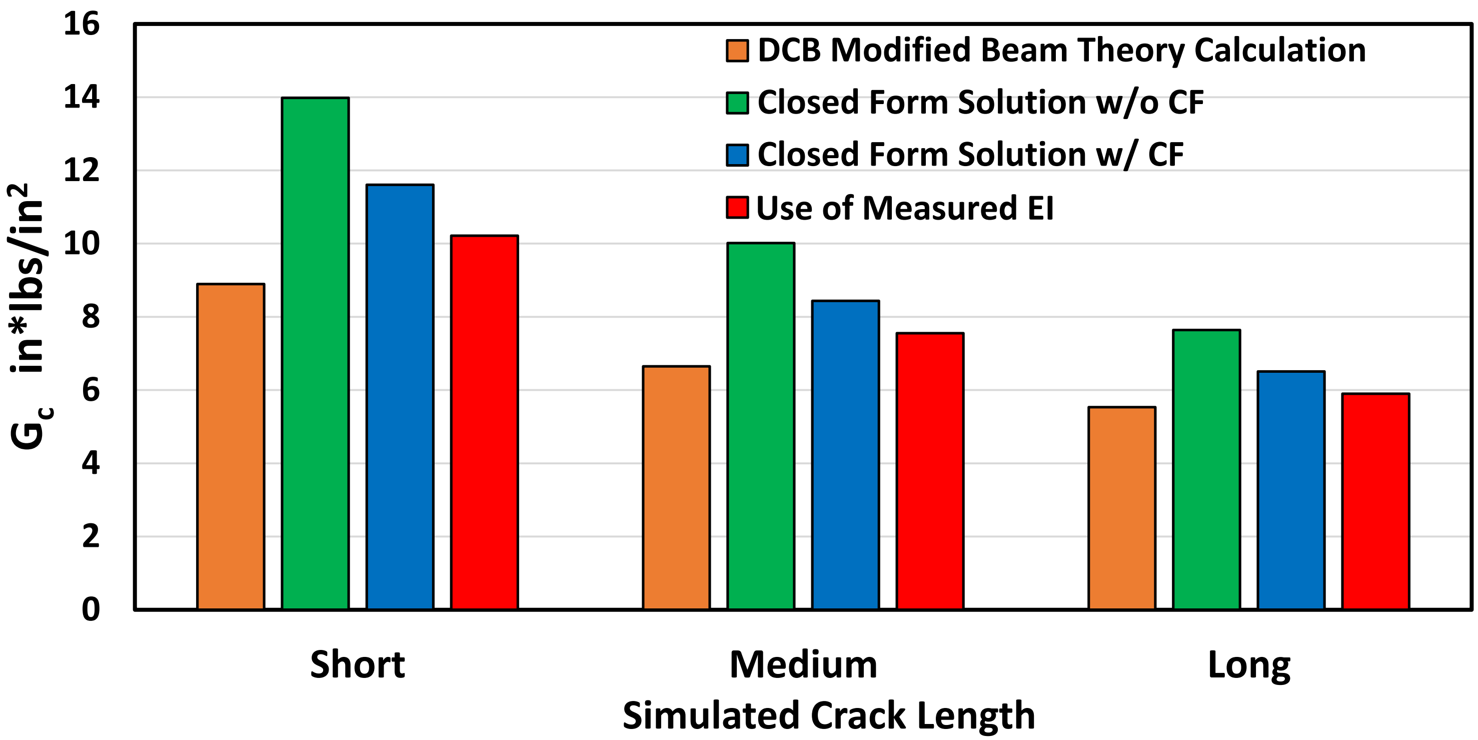
General agreement with both closed-form correction factor and measured $E_f I$ **approaches**

Current Focus:
Numerical Simulation To Investigate Correction Factor

- 3D finite element analysis of composite adherends with adhesive layer
- Prescribed displacement loading simulating wedge
- Simulation of three different crack lengths
- Simulation of three different adhesive thicknesses
- Identification of best suited methodology for apparent G_C determination



Comparison of Methods for G_c Determination: Preliminary Results From Numerical Simulation



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

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

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

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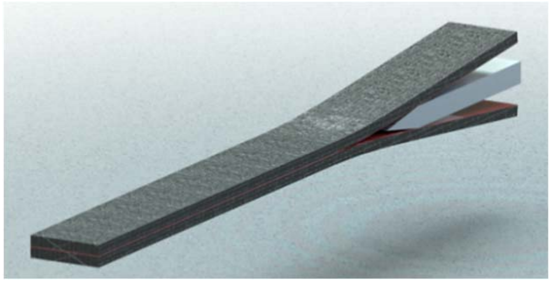
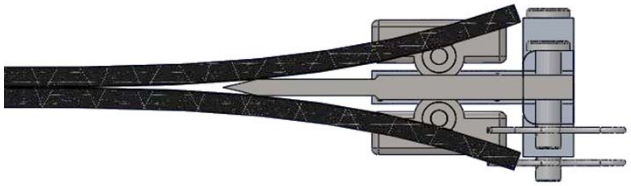
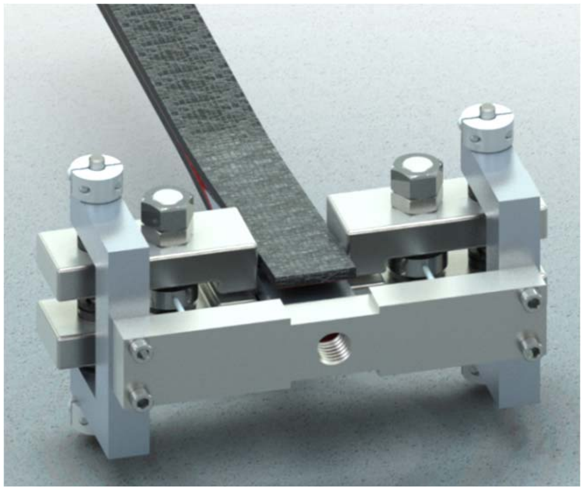
What if the Wedge Could Measure Opening Force During Wedge Testing?



- **Continuous opening-force measurement as wedge driven through specimen**



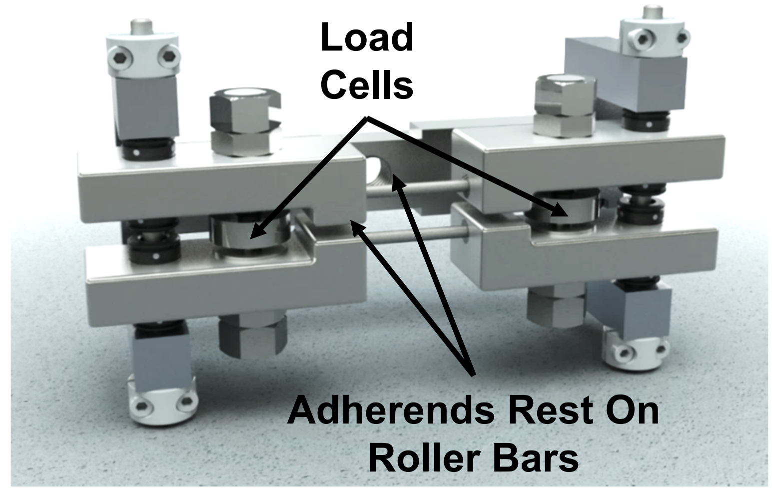
- **Monitor for drop in measured force**
  - **Increased crack length ahead of wedge**
  - **Reduced fracture toughness**

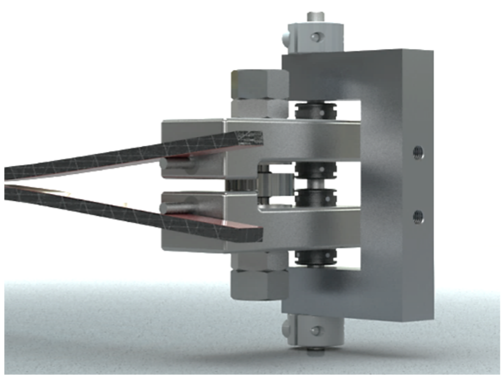


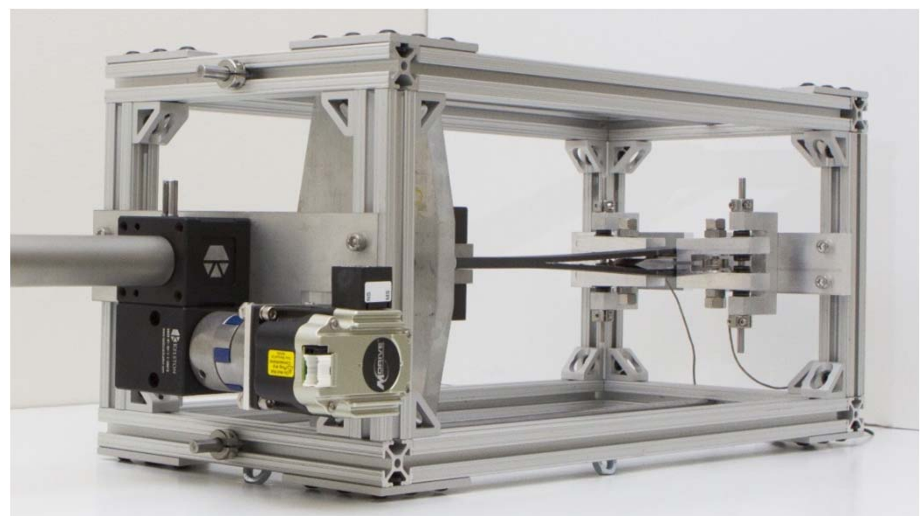
- **Retain wedge in specimen for environmental durability test**
- **Similar to traveling wedge test, but with force-sensing “smart” wedge**

"Smart Wedge" Concept

- Two compression load cells to measure opening force
- Adherends supported by roller bars
- Linear bearings allow for vertical displacement
- Wedge driven through bondline or held in place







“Smart Wedge” Concept:

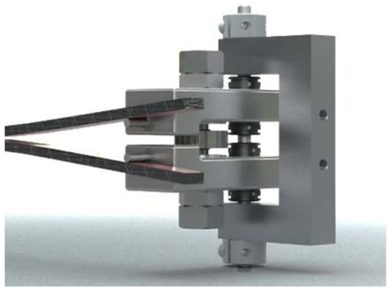
Fracture Toughness Measurement

- 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, $a = \sqrt[3]{\frac{3\,(E_f\, I)\, t}{P}}$

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

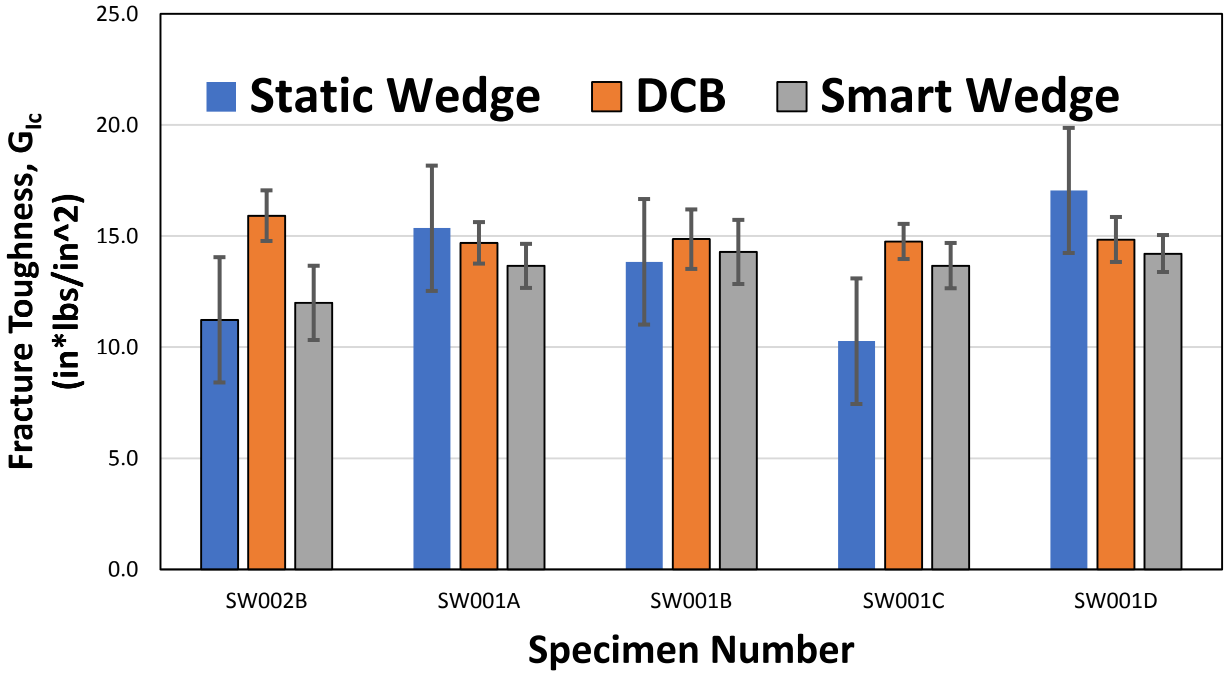
a = beam span (crack length)
P = applied force
t = wedge thickness
E_f = flexural modulus
I = moment of inertia

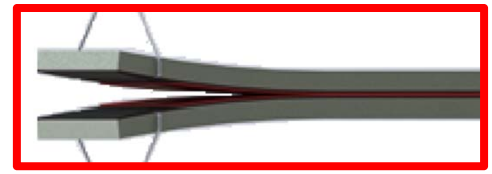
- Can calculate G_c knowing:
  - P (measured force)
  - t (wedge thickness)
  - Flexural rigidity, E_f I (measured)



Do not need crack length measurement!

Preliminary Results: "Smart Wedge" Testing

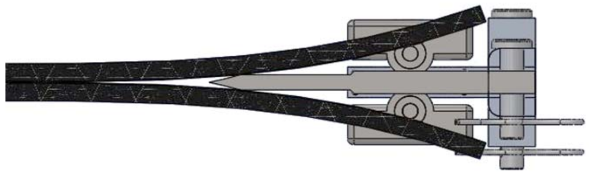


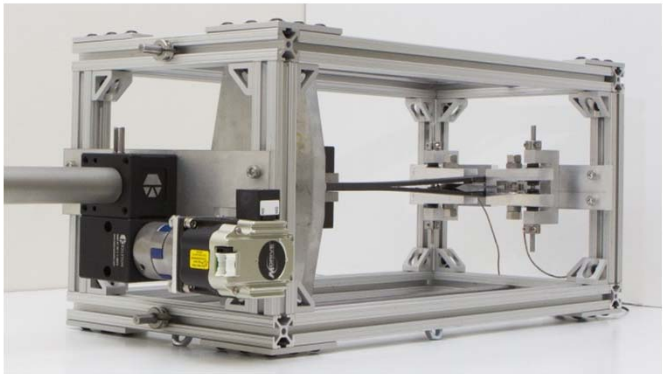


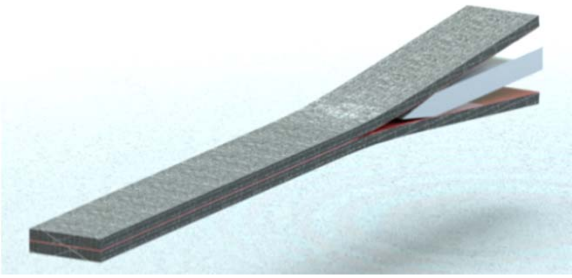
- **3 tests (DCB, static wedge and Smart Wedge) performed on each bonded composite specimen**
- **Initial results appear promising**

Smart Wedge Testing:
Envisioned "Hybrid" Procedure

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



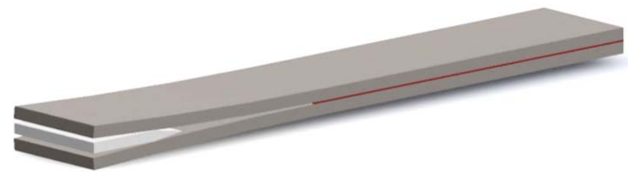




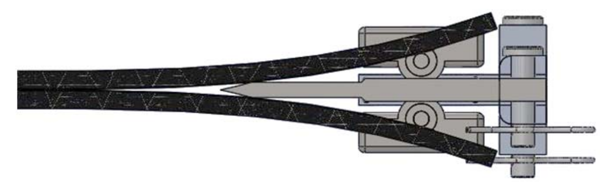
Plans for Upcoming Research:

Development of Environmental Durability Test Methods for Composite Bonded Joints

- **Establish limits of applicability and recommended procedures for the composite wedge test**
  - **Acceptable range of flexural rigidities $E_f I$**
  - **Method of G_C determination**



- **Assessment of "Smart Wedge concept for hybrid assessment of bond quality over larger bond areas**
  - **Continuous fracture toughness measurements**
  - **Environmental durability assessment when desired**



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 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?

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