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Development of Environmental Durability Test Methods for Composite Bonded Joints

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FAA Sponsored Project Information

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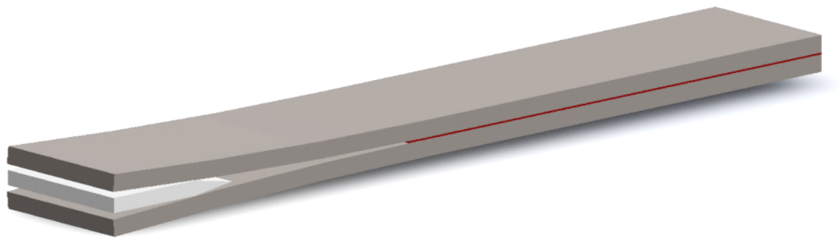
  Air Force Research Laboratory: Jim Mazza

Overview:
Development of a Composite Wedge Test

- 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



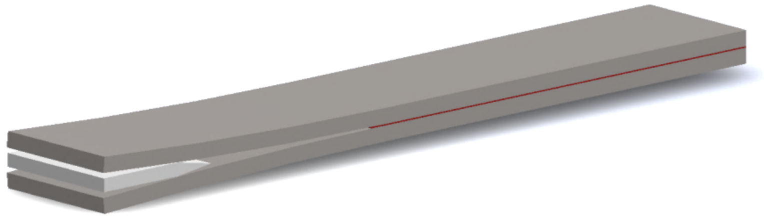
- Restrictions in fiber orientation adjacent to bonded interface
- Failure in the composite laminate prior to failure in the adhesive or at the bondline

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:

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

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

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

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

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

Correction factor for crack tip rotation

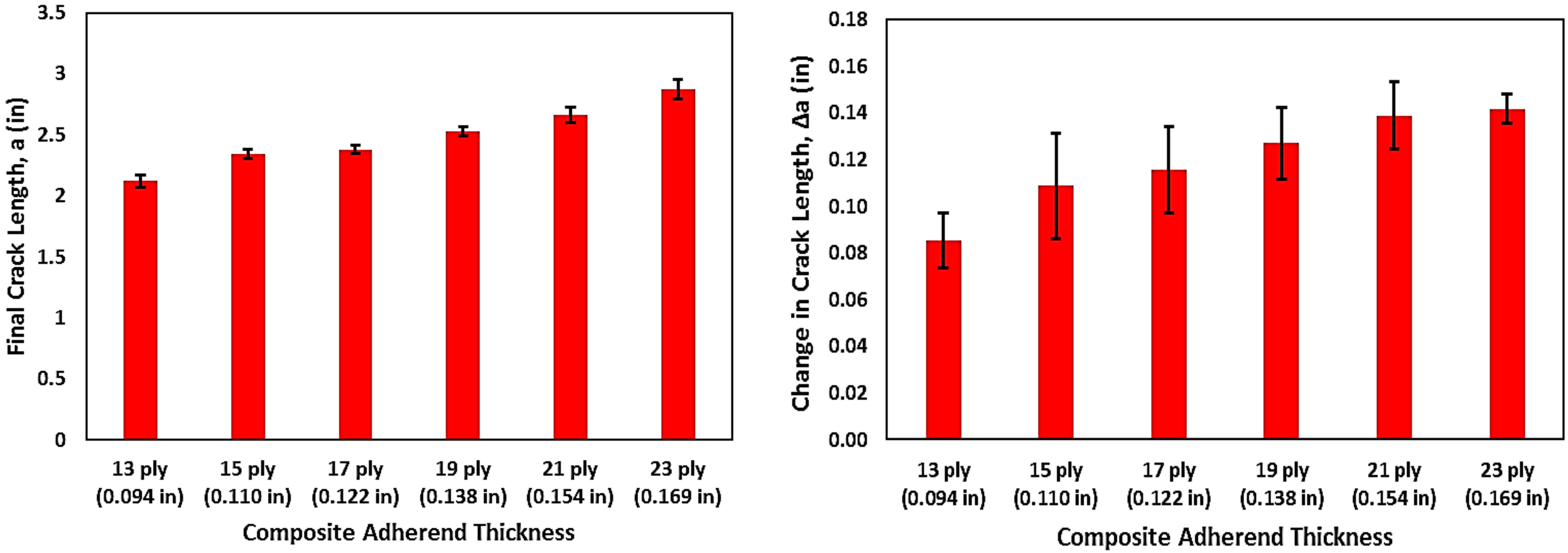
a = crack length
t = wedge thickness
h = adherend thickness
b = specimen width
T = load to deflect tip of beam
E_f = flexural modulus
G_c = fracture toughness

Experimental Investigation:
Composite Wedge Test Development

- **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

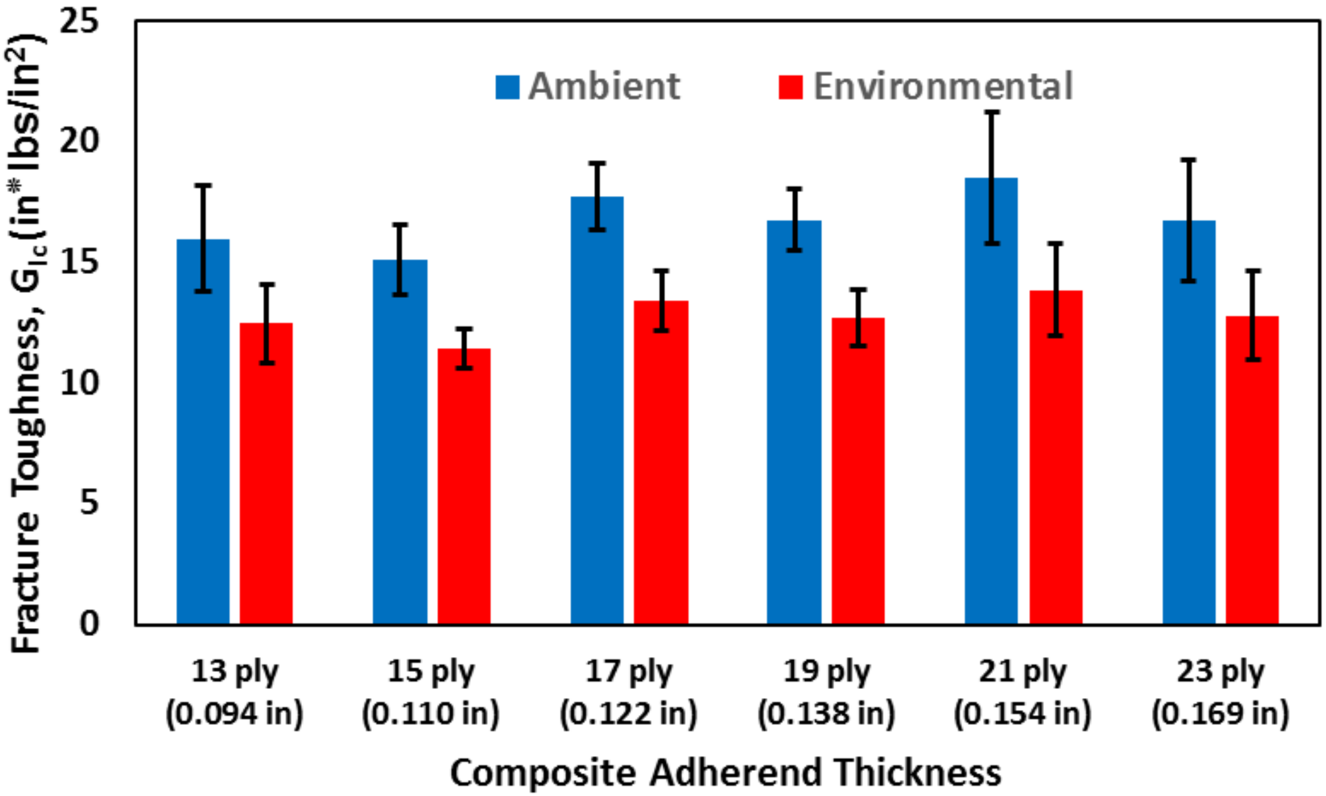
122°F (50°C) and 95% humidity environment



Increasing adherend thickness (and flexural stiffness)…

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

Effects of Composite Adherend Thickness: Fracture Toughness Values

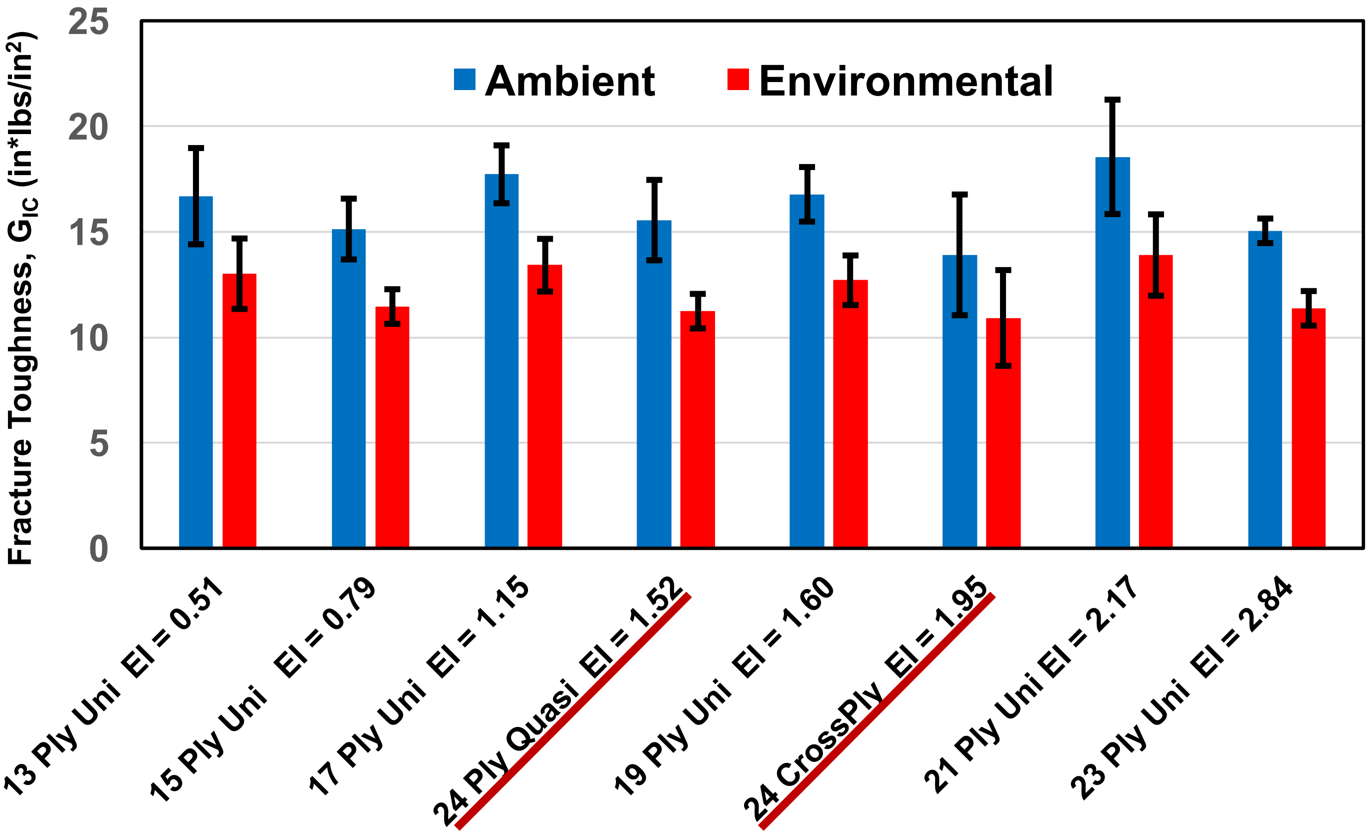


- Apparent facture toughness values remain relatively constant
- Provides estimate of fracture toughness at ambient conditions

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**

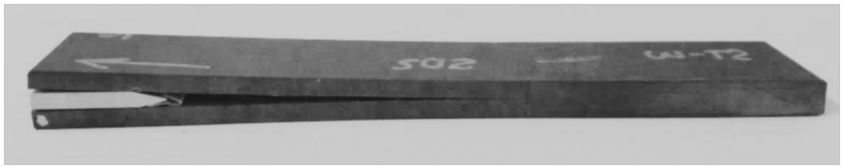
Wedge Testing of Multidirectional Laminates: Fracture Toughness Values



G_c values from quasi-isotropic and crossply laminates consistent with previous unidrectional laminates

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)

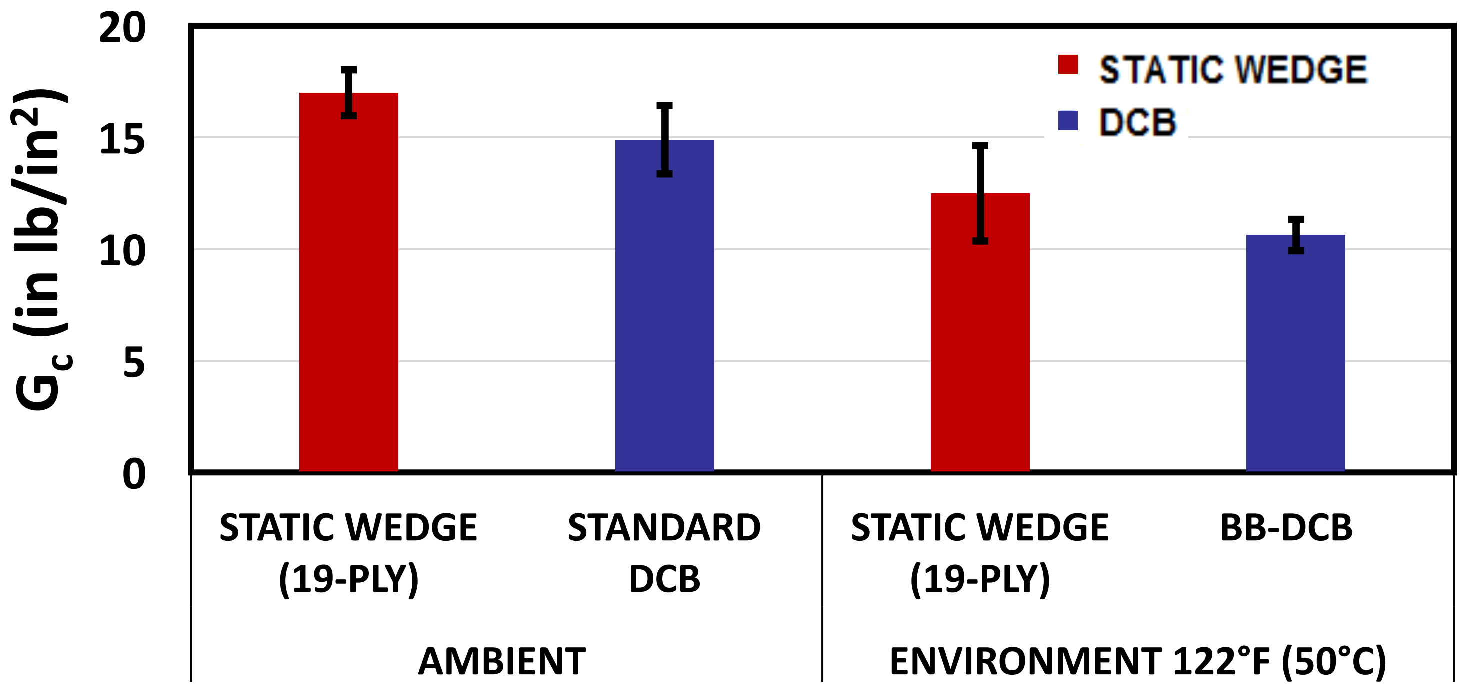


Composite Wedge Test

Double Cantilever Beam (DCB) Test

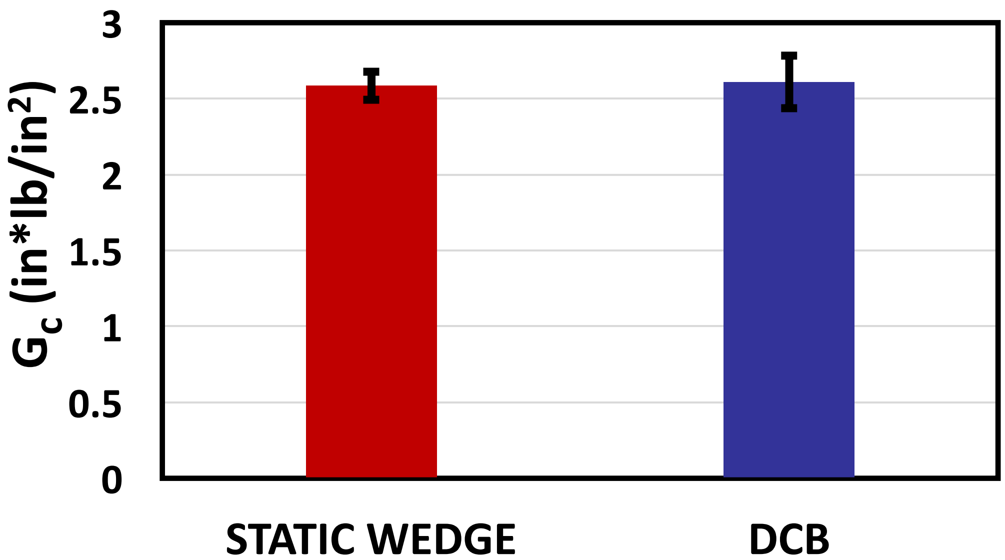
Wedge Test vs. DCB Test:
Bonded Composite Specimens

- General agreement in testing to date between DCB and static wedge tests
- Further testing to be performed

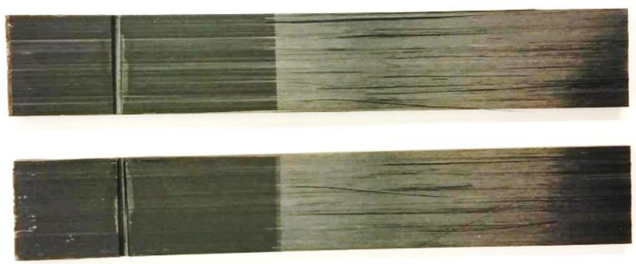


Wedge Test vs. DCB Test:
Composite Specimens – No Adhesive

- **Results at RT/Ambient conditions**
- **Similar appearance on fracture surfaces**



Composite Wedge Test Specimen



Double Cantilever Beam (DCB) Specimen

Rather Than Measuring E_f of the Composite Adherends…

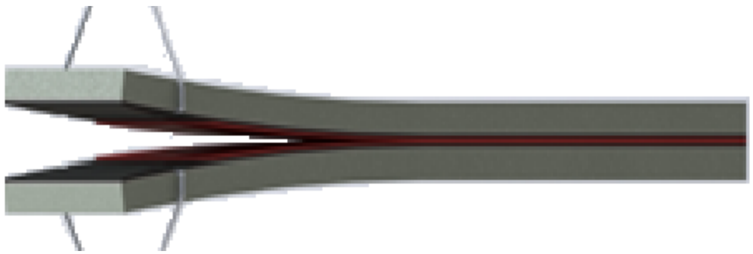
*Why Not Measure E_f * I ?*

- 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

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



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

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

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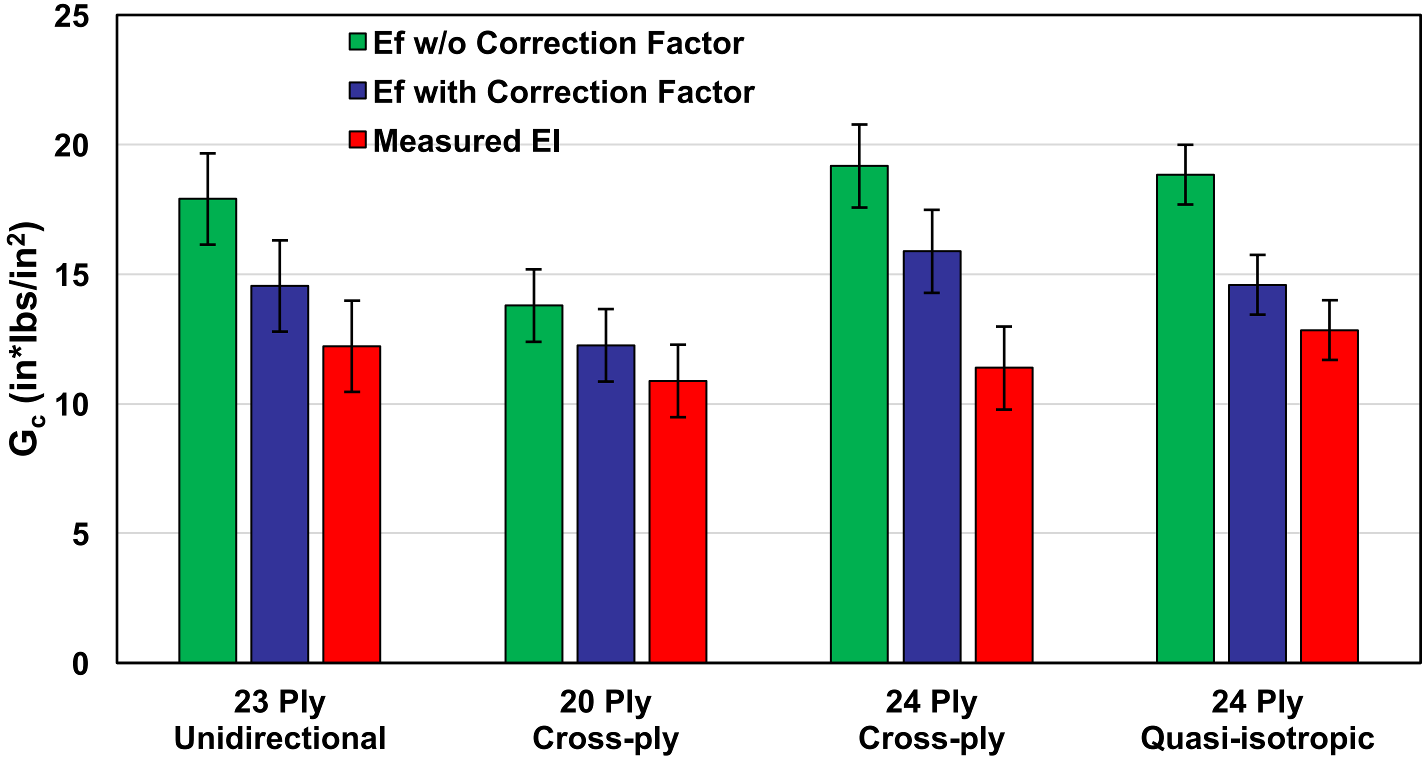
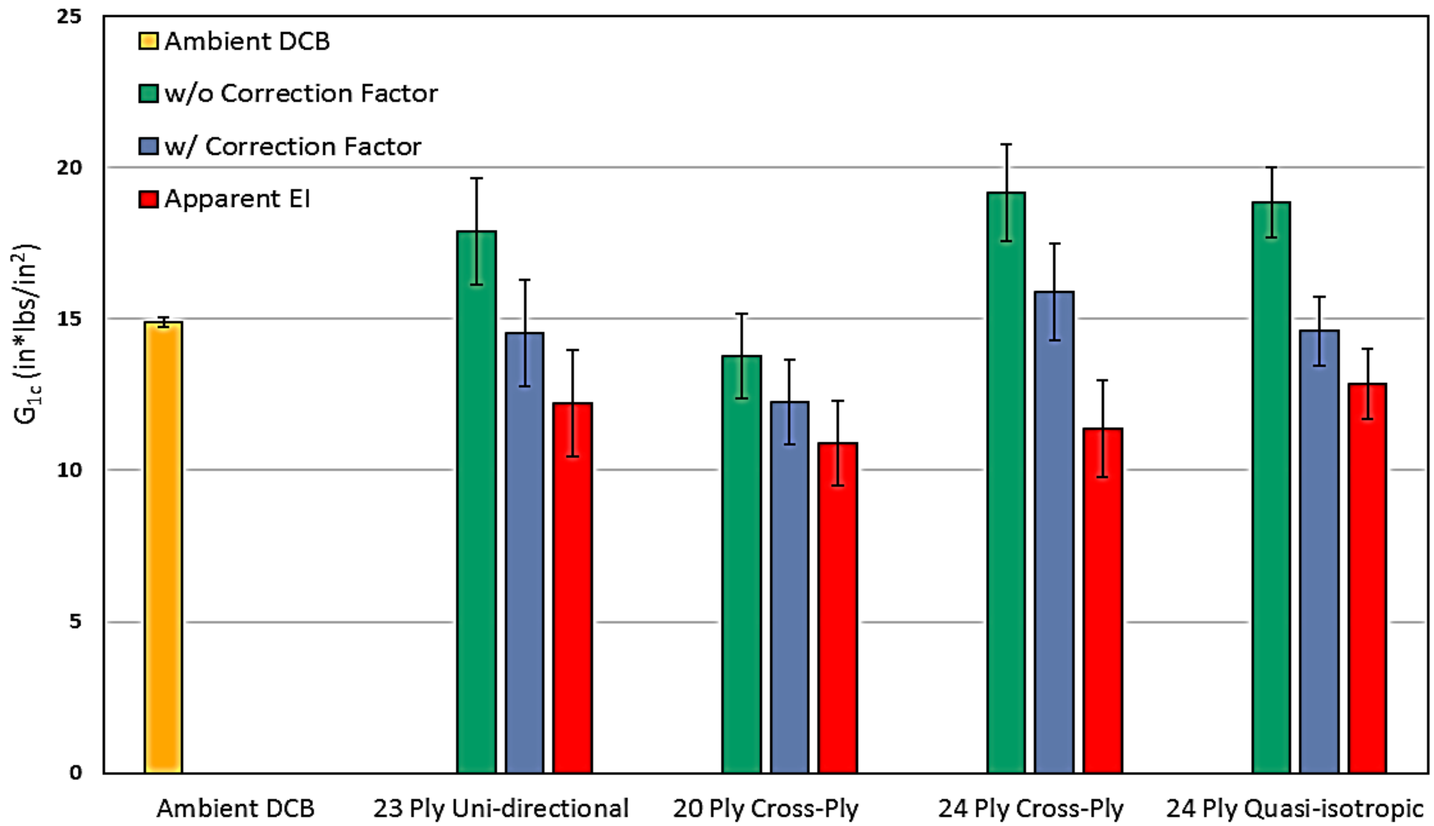
Comparison of Methods for G_c Determination: RT/Ambient Conditions



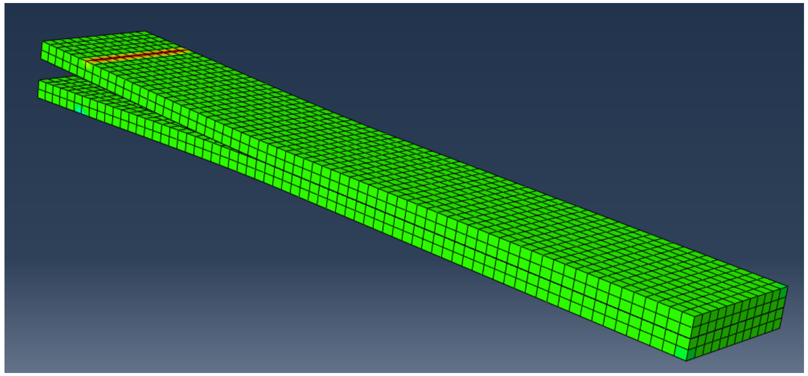
- **Reduced values of Gc using E_f*I from DCB loading**
- ***Which method is most accurate?***

Comparison of Wedge Test and DCB Test Results: RT/Ambient Conditions



Gc values using correction factor (blue) and with measured E_f*I (red) in general agreement with DCB data

Current Focus:
Numerical Simulation To Investigate Correction Factor



- Composite adherends with adhesive layer
- Prescribe displacement and crack length simulating wedge loading
- Determining the effective flexural rigidity using beam theory

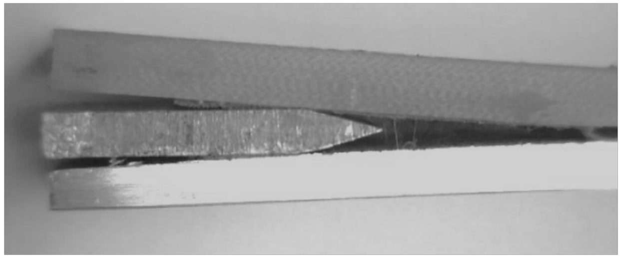
$$\delta = \frac{t_{wedge}}{2} = \frac{P\, l^3}{3\, (E_f\, I)_{effective}}$$

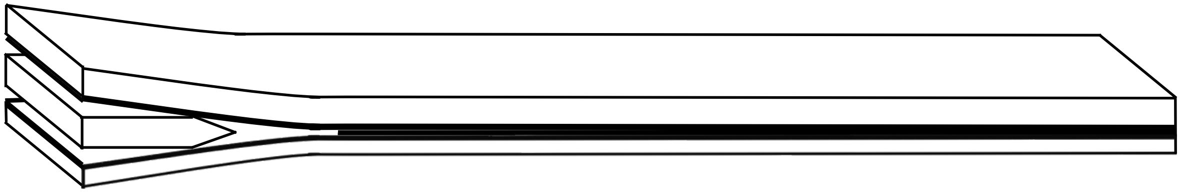
- Comparison of input value of $E_f\, I$ and calculated $(E_f\, I)_{effective}$ provides correction factor
- Comparison with closed-form correction factor:

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

Current Focus:
Investigating Wedge Testing of Hybrid Specimens

- Assessing environmental durability of bonded joints using dissimilar adherend materials, different adherend thicknesses





- Require that $E_f * I$ of two adherends be the same

- Currently investigating carbon/epoxy to glass/epoxy and carbon/epoxy to carbon/epoxy with dissimilar layup bonded specimens

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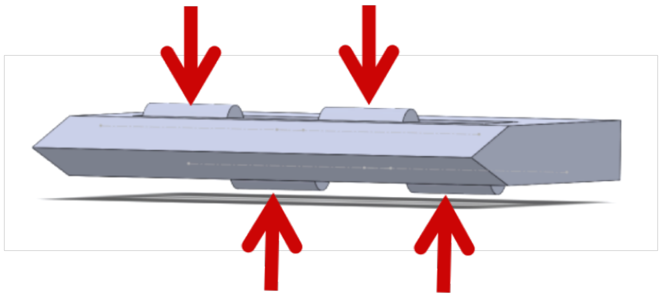
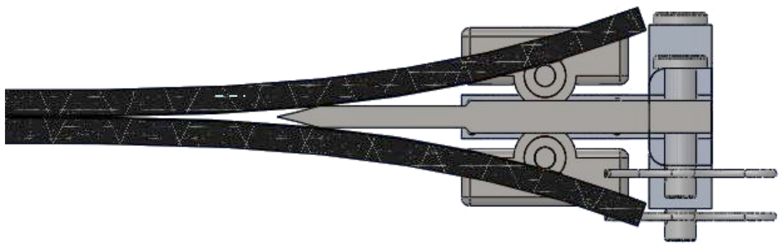
"Smart Wedge" Concept:

What if Wedge Measured Opening Force During Testing?

- 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, $a = \sqrt[3]{\frac{3\, E_f I\, \delta}{P}}$
- Can calculate G_c knowing:
  - P (measured force)
  - δ (wedge thickness)
  - Flexural rigidity, E_f I (measured)

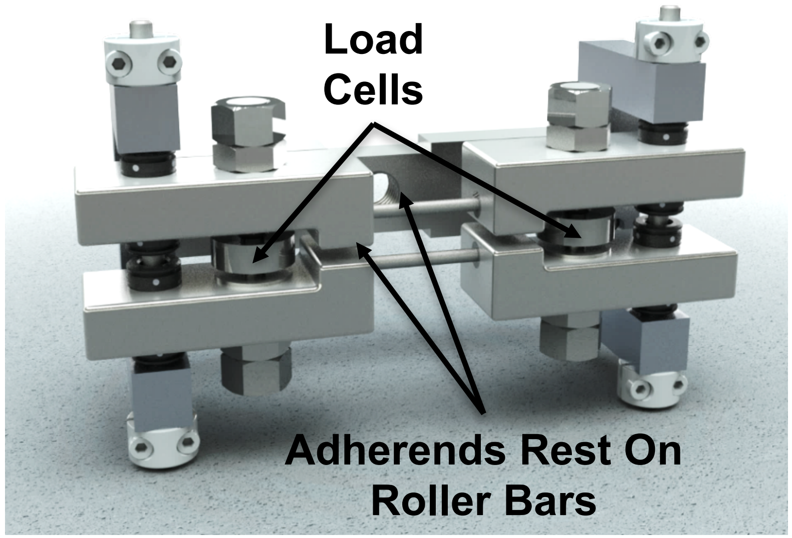
Do not need crack length measurement!

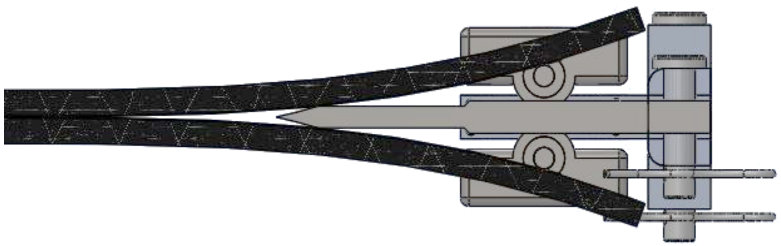


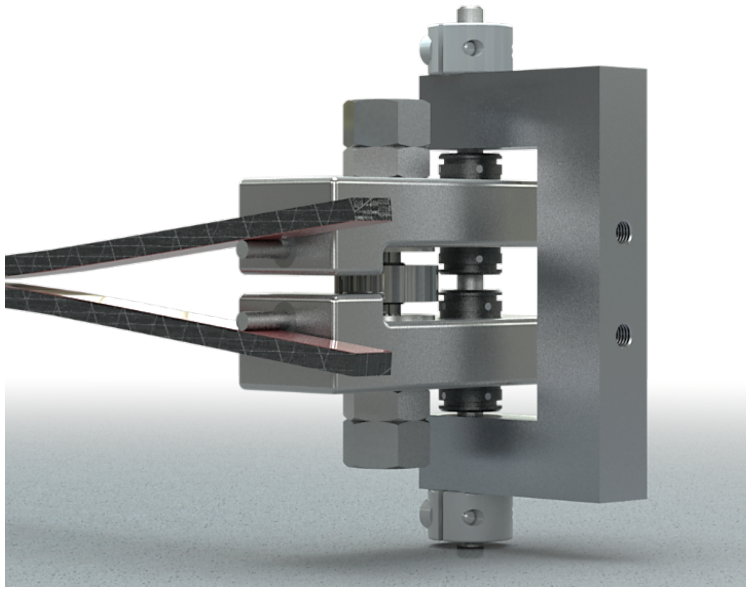


“Smart Wedge” Concept

- 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

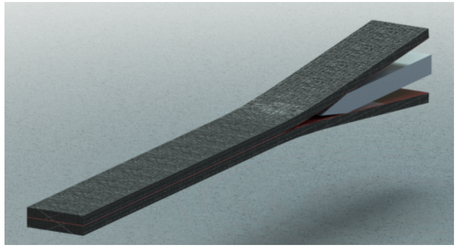


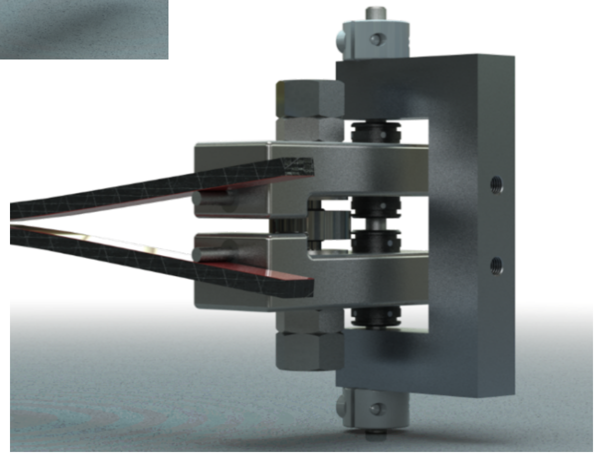


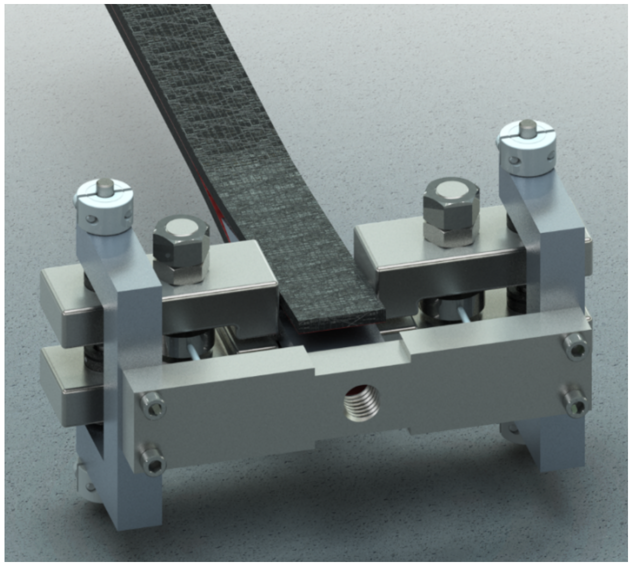


Smart Wedge Testing: Proposed Procedure

- Open specimen using oversized installation wedge
- Fit smart wedge onto specimen, remove installation wedge
- Take initial load reading and measure crack length (calculate $E_f I$)
- Calculate G_c while driving wedge through specimen
- Hold smart wedge in place during environmental exposure for durability assessment

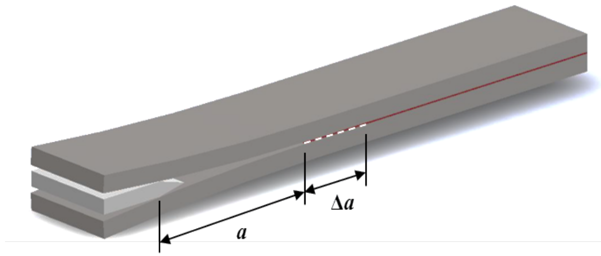






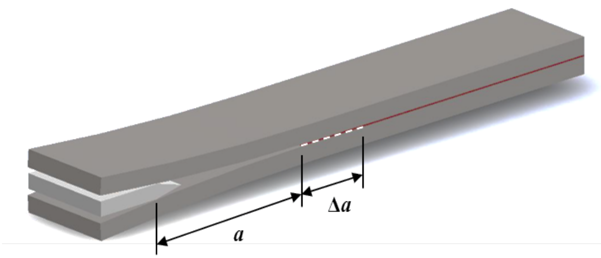
Update: ASTM D3762 Metal Wedge Test Revision

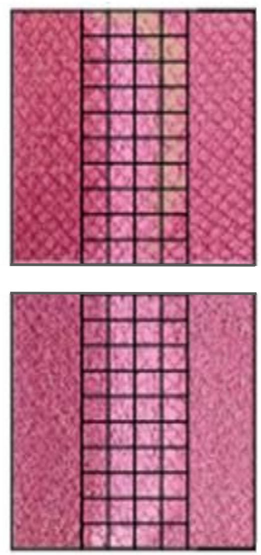
- Major revision of ASTM standard completed
- Distributed to Boeing and AFRL collaborators for comprehensive review
- To be submitted for ASTM subcommittee D14.80 balloting in January



ASTM D3762 Metal Wedge Test Revision:
Measurement of Percent Cohesion Failure

- Included as part of acceptance criteria
- Examine region (Δa) of crack extension under environmental exposure
- Estimate percent cohesion failure on adherends
- Recommended procedure: rectangular "grid method"
- Will require a round-robin investigation to evaluate written procedure





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Thank you for your attention!

Questions?

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