Environmental Durability Test Method Development for Composite Bonded Joints

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AMTAS Autumn 2019 Meeting
November 5, 2019

FAA Sponsored Project Information

- Principal Investigators:
  - **Dr. Dan Adams**
- Graduate Student Researchers:
  - **Zachary Sievert**
  - **Heather McCartin**
- FAA Technical Monitor:
  - **Ahmet Oztekin**
- Collaborators:
  - **Boeing, Hexcel, 3M Corp, AFRL**
  - **ASTM Committees D30 and D14**
  - **Composite Materials Handbook, CMH-17**

Outline

- **Updates:**
  - ASTM Adhesive Bonding Task Group D14.80.01
  - New adhesives testing content in CMH-17 Handbook
- **Primary focus: Environmental durability test methods for composite bonded joints**
  - Composite wedge test development
  - "Smart Wedge" traveling wedge test concept

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

Update of Composite Materials Handbook, CMH-17: Inclusion of Adhesive Test Methods

- Update of (limited) existing content
- Tests used in NIAR Adhesive Characterization Project
  - Thin Metal Adherend Lap Shear
  - Thick Metal Adherend Lap Shear
  - Composite Adherend Lap Shear
  - Floating Roller Peel
  - Mode I Fracture Toughness
  - Mode II Fracture Toughness
  - Metal Adherend Tension
  - Fluid Sensitivity
- Other adhesion characterization tests
- Bonded joint characterization tests

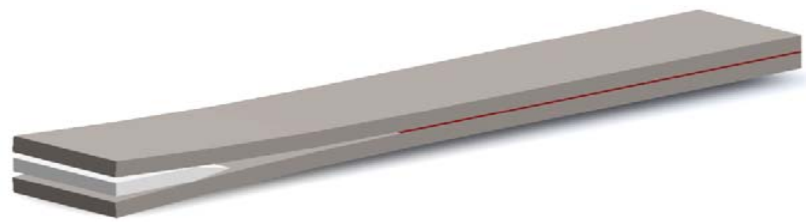
Overview:
Development of a Composite Wedge Test:

<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**



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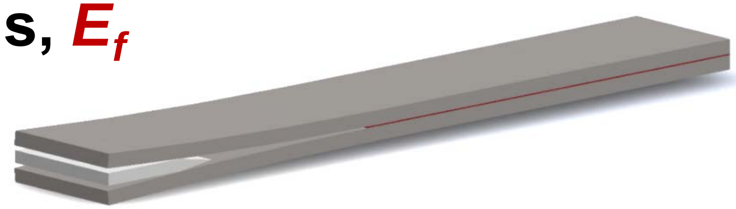
Use of Fracture Toughness
To Assess Environmental Durability

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

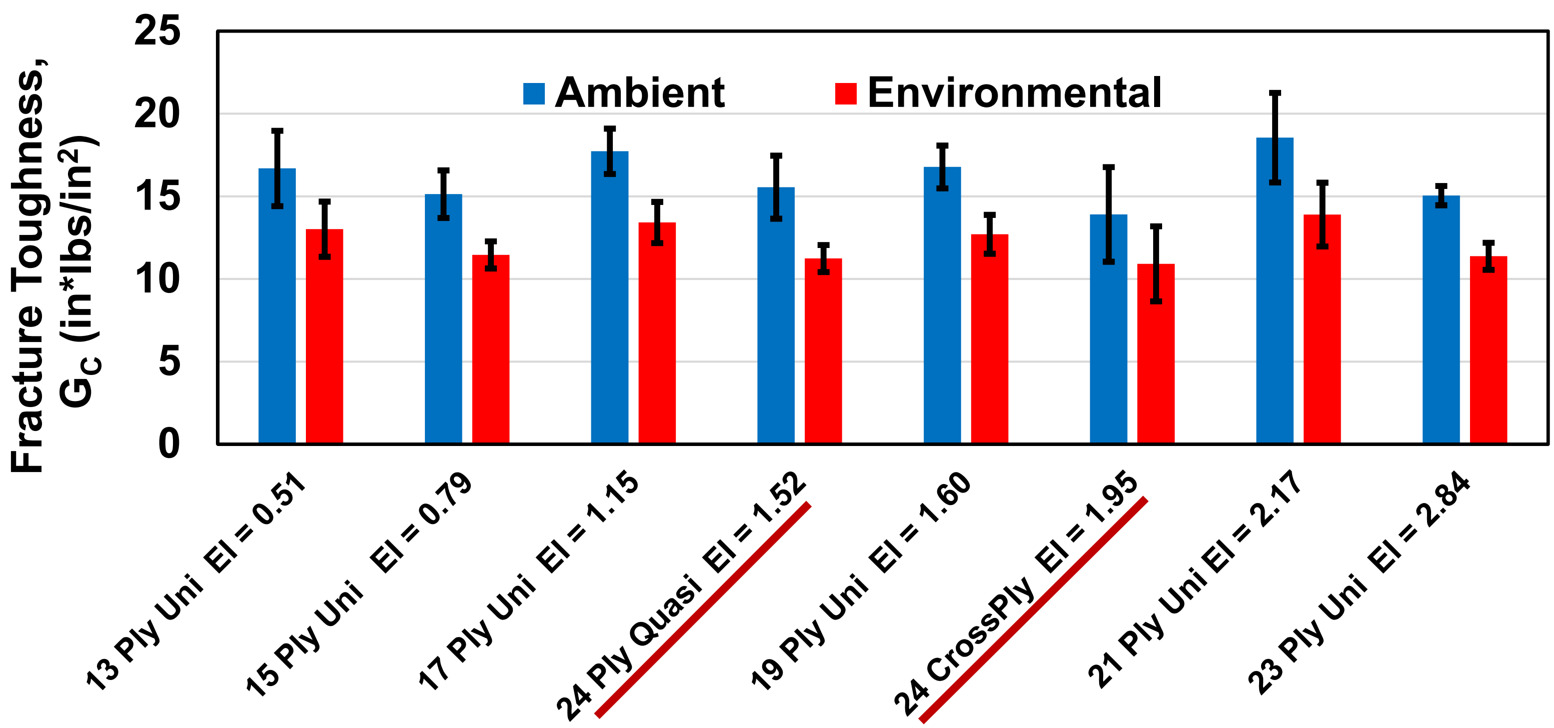
a = crack length

- **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

Wedge Testing of Multidirectional Laminates: Fracture Toughness Values

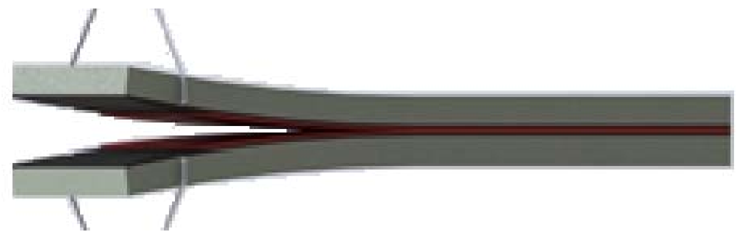


- **Apparent facture toughness values remain relatively constant**
- **Provides estimate of fracture toughness at ambient conditions**
- **G_c values from quasi-isotropic and crossply laminates consistent with previous unidrectional laminates**

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 $E_f\,I$:**

$$G_c = \frac{3\,E_f\,t^2\,h^3}{16\,a^4} = \frac{9(E_f\,I)\,t^2}{4b\,a^4}$$

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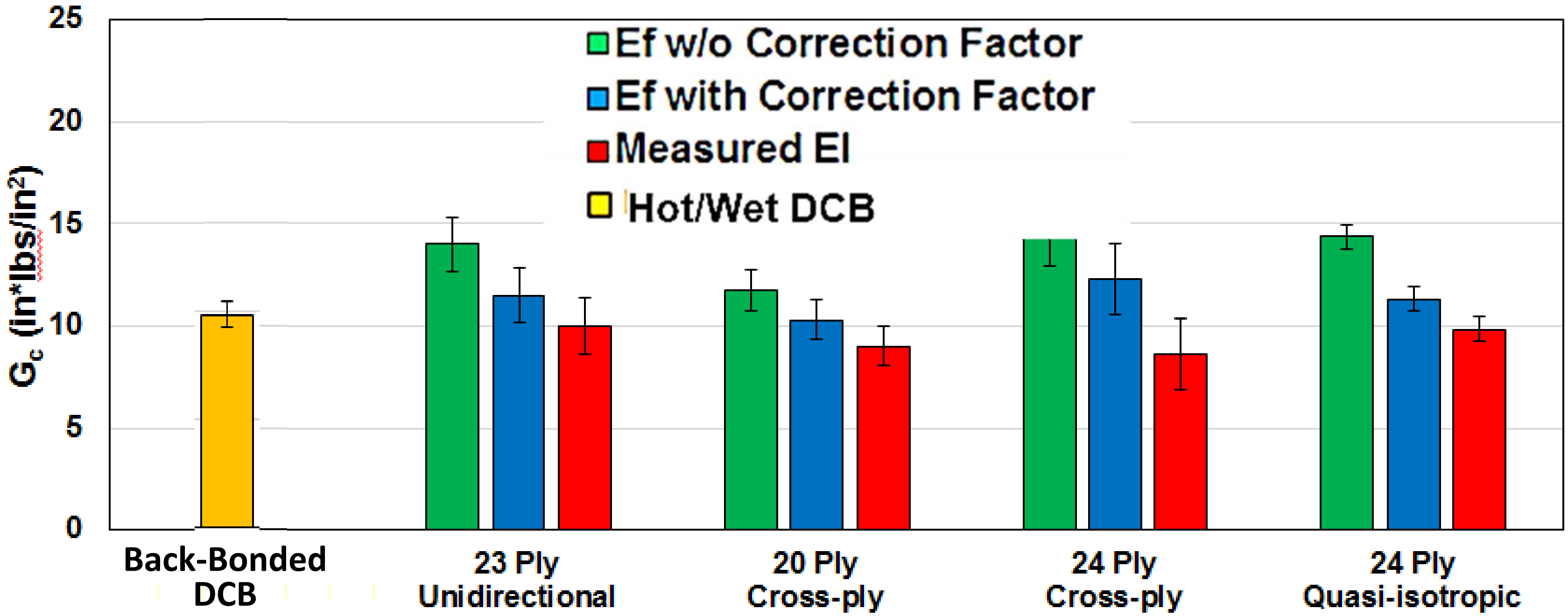
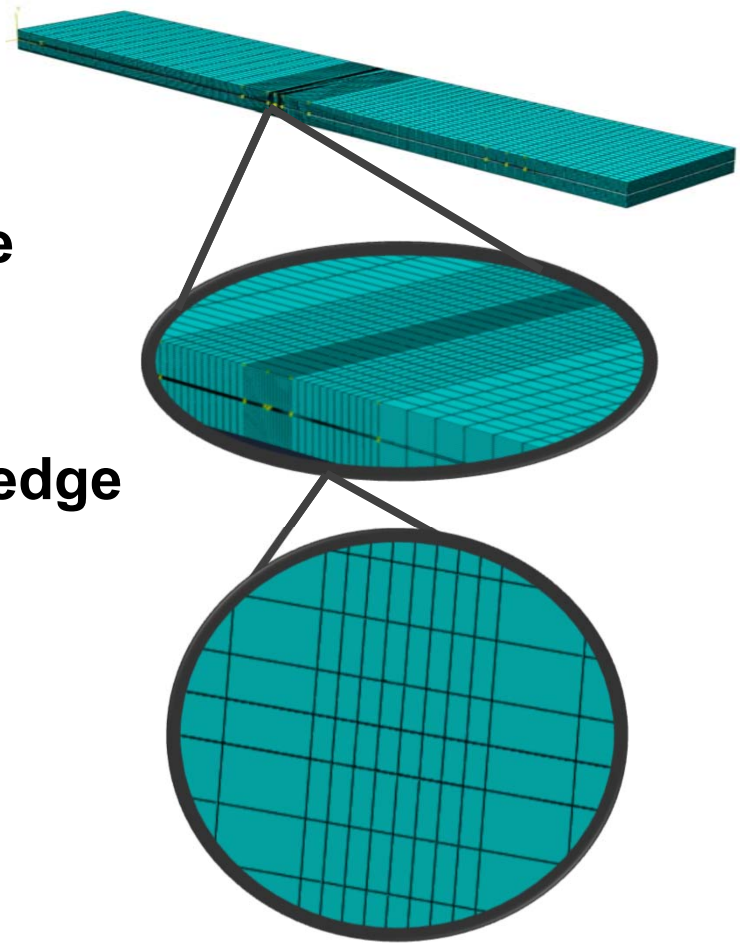
Comparison of Wedge Test and DCB Test Results: 50ºC, 95% RH, 5 days



Best agreement with DCB testing using measured $E_f I$ approach

Evaluation of G_{Ic} Calculation Methods Using Finite Element Analysis

- ABAQUS 3D finite element analysis
- Crack at center of adhesive bondline
- Highly refined mesh near crack tip
- Displacement loading to simulate wedge
- Investigation of candidate methods for G_c calculation
- Reference G_c value using VCCT



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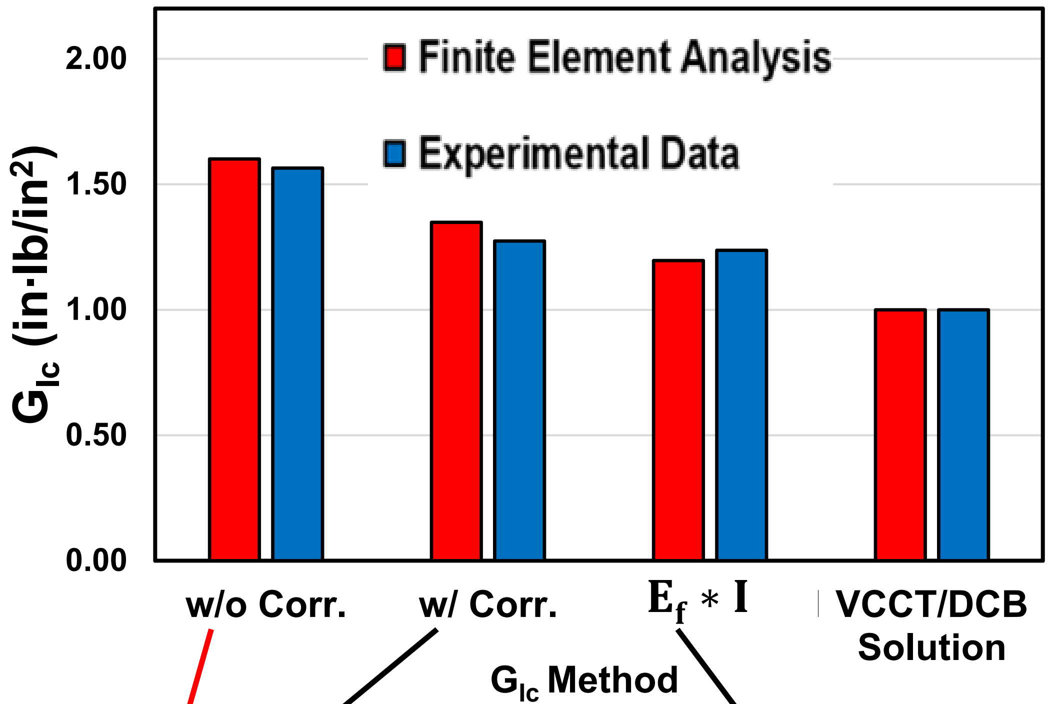
Numerical Analysis of Composite Wedge Test:

Comparison with Test Results

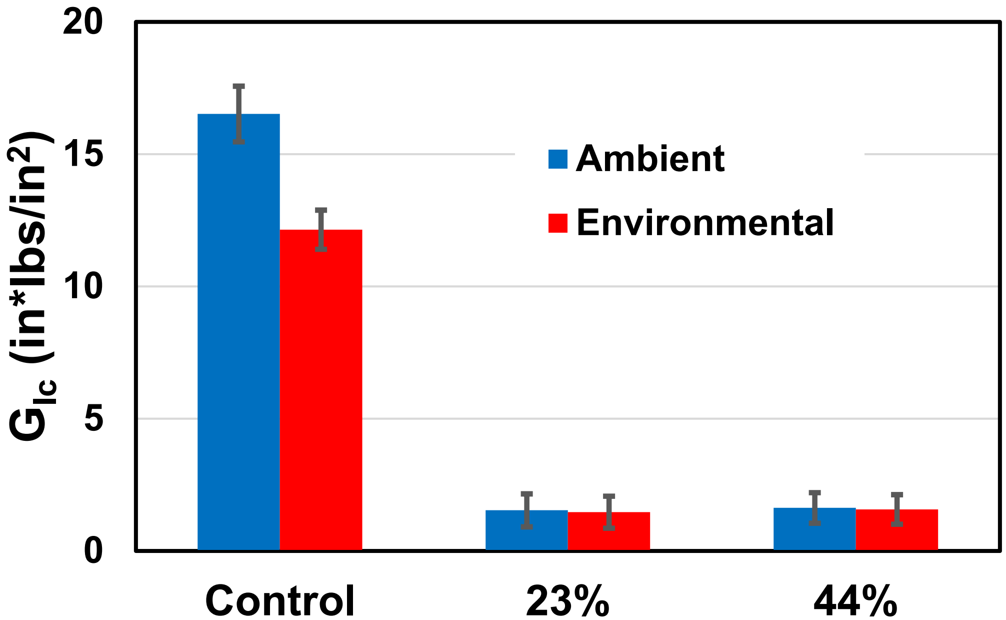


$$G_{Ic} = \frac{3}{16}\frac{t^2 E_f h^3}{a^4}\frac{1}{\left(1+0.64\frac{h}{a}\right)^4}$$

$$G_{Ic} = \frac{9}{4}\frac{E_f I}{ba^4}$$

- 19 ply IM7/8552 adherends, AF-163 2K adhesive
- Non-dimensionalized using VCCT & DCB results
- Similar trends from both analysis and testing
- Use of measured E_f*I method appears best suited

Evaluation of Composite Wedge Test: Identification of Contaminated Bond Surfaces



Specimens with 23% and 44% contamination treated at Florida International University

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Evaluation of Composite Wedge Test:
Identification of Porosity in Bondline

Creation of Bondline Porosity

- Frozen film adhesive exposed to ambient conditions prior to thawing
- Termination of vacuum during adhesive cure

Crack growth region during wedge testing

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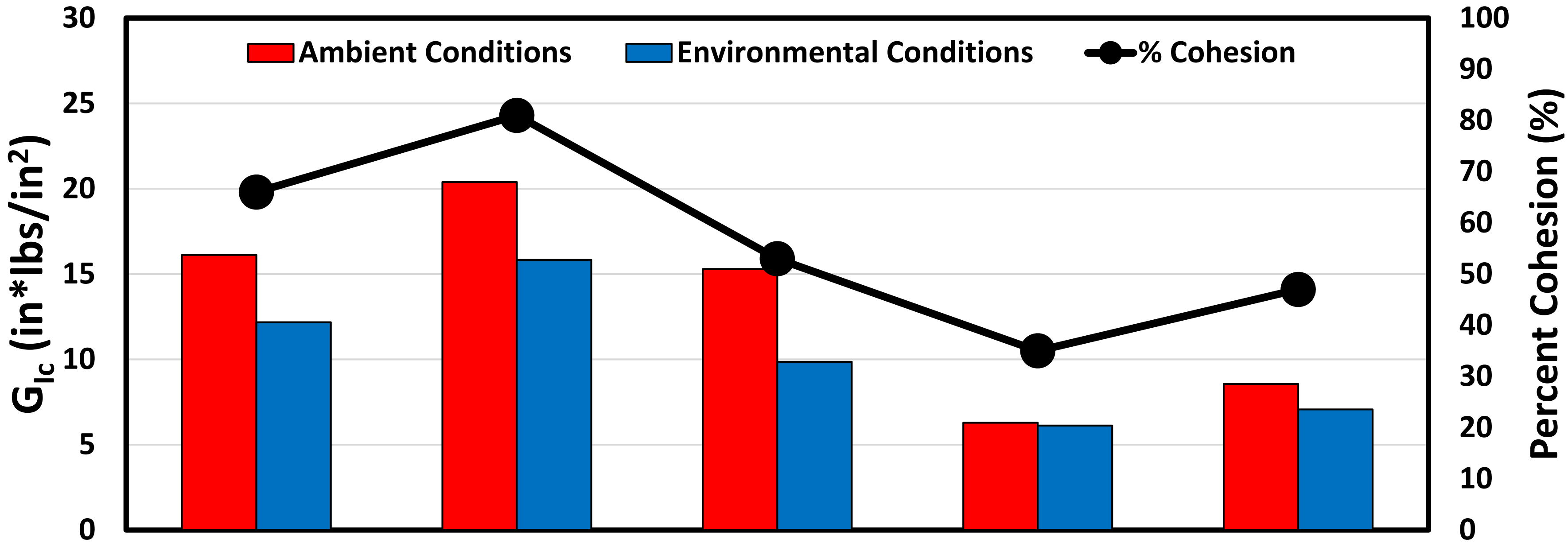
Evaluation of Composite Wedge Test: Identification of Porosity in Bondline



- **% cohesion failure estimated in crack growth area**
- **General agreement between percent cohesion failure and measured G_c values**

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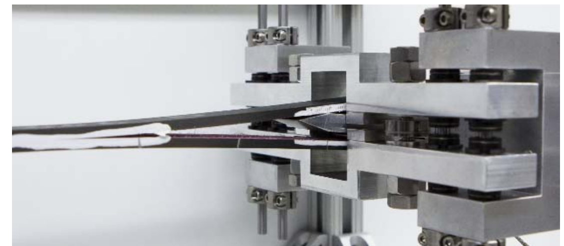
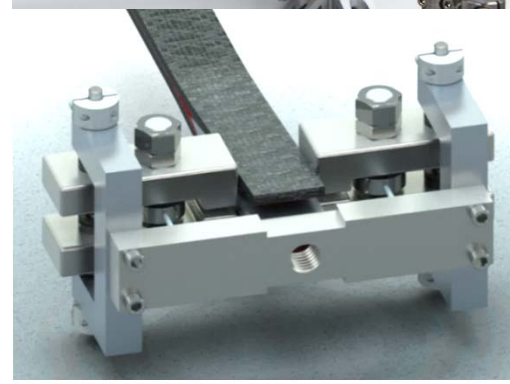
Summary:
Status of Composite Wedge Test

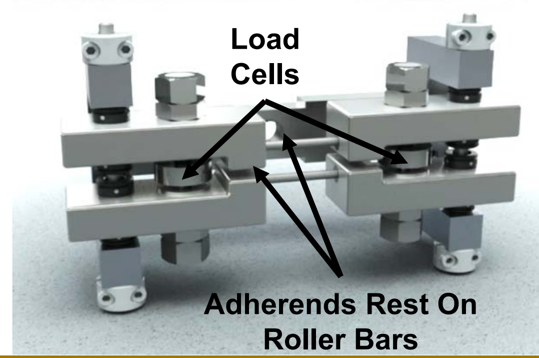
- Appears to be well suited for evaluating environmental durability of composite bonds
- Can be used for wide variety of composite laminates and a range of flexural rigidities (E_f*I)
- Provides an estimate of the fracture toughness G_{1C} at both ambient and other environmental conditions (hot, hot/wet, cold, fluid exposure, etc)
- To be proposed for ASTM standardization
  - Draft standard under development (Heather McCartin)
  - To be presented discussed at upcoming ASTM D14.80 Task Group
- FAA report and journal paper underway

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

- **Opening force measured continuously as wedge driven through specimen**
  - **Adherends supported by roller bars**
  - **Use of dual compression load cells**
- **Monitor for drop in measured force**
  - **Longer crack lengths**
  - **Reduced fracture toughness**
- **Similar to traveling wedge test, but measures the opening force rather than driving force**
  - **Allows for determination of fracture toughness, G_c**
- **Can retain wedge in specimen for environmental durability test**







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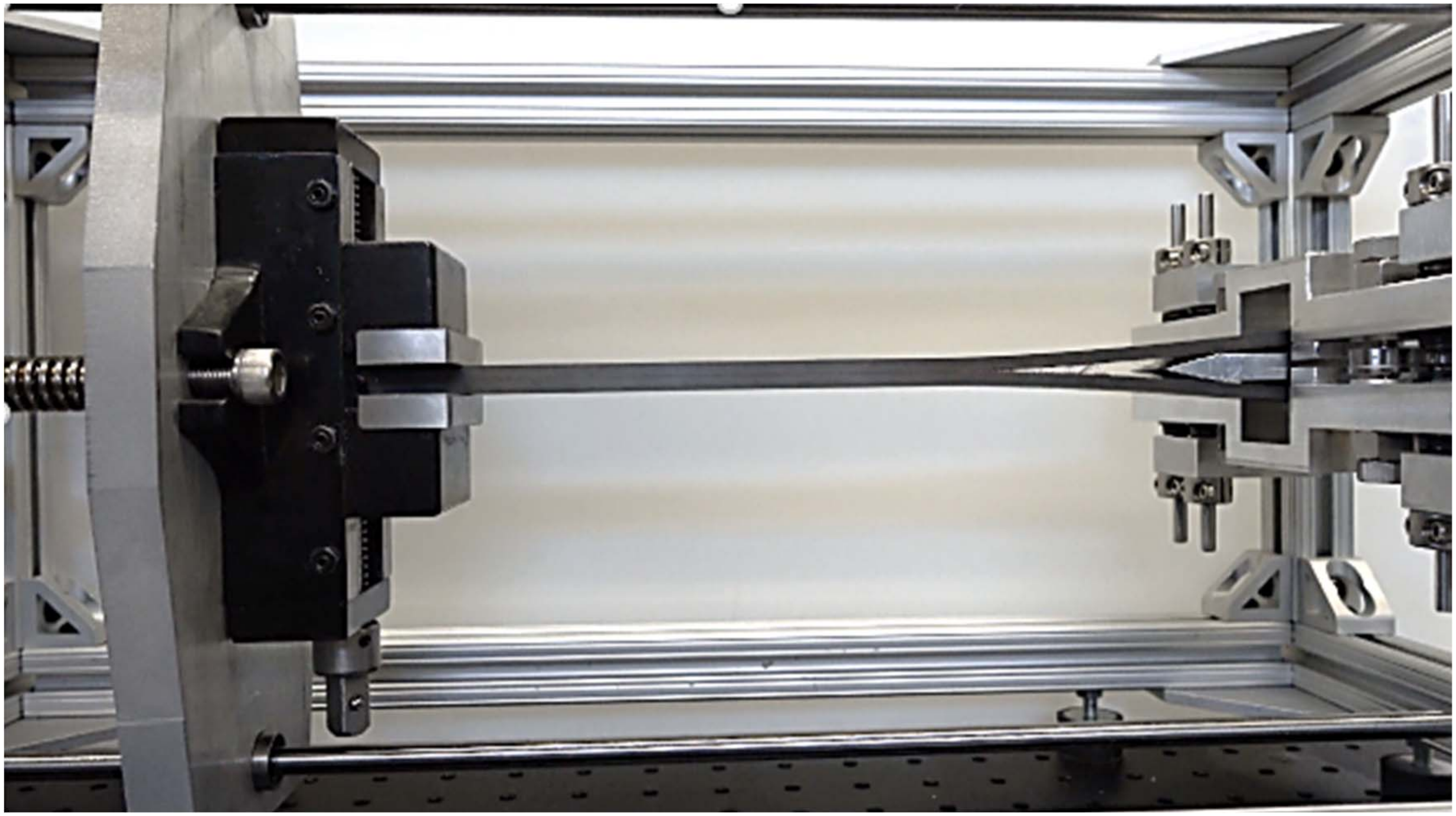
Smart Wedge Testing: Envisioned "Hybrid" Procedure



Operation of Current Prototype

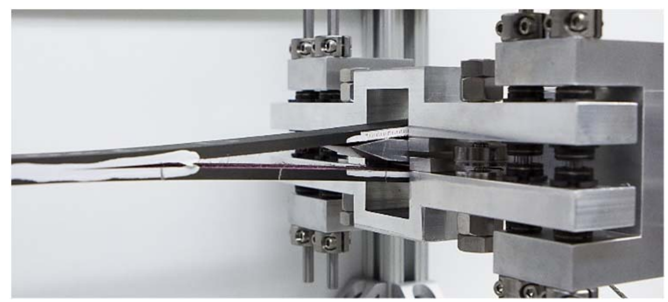
"Smart Wedge" Concept:

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

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

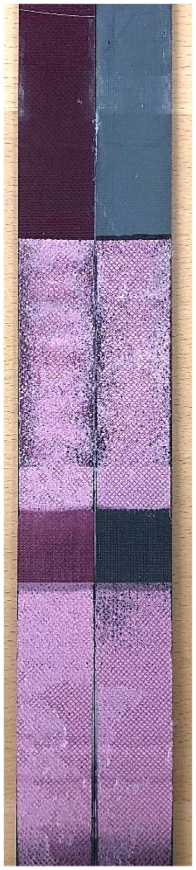
- Can calculate G_c knowing:
  - P (measured force)
  - b (measured specimen width)
  - t (opening displacement)
  - Flexural rigidity, E_f I (measured/calculated)

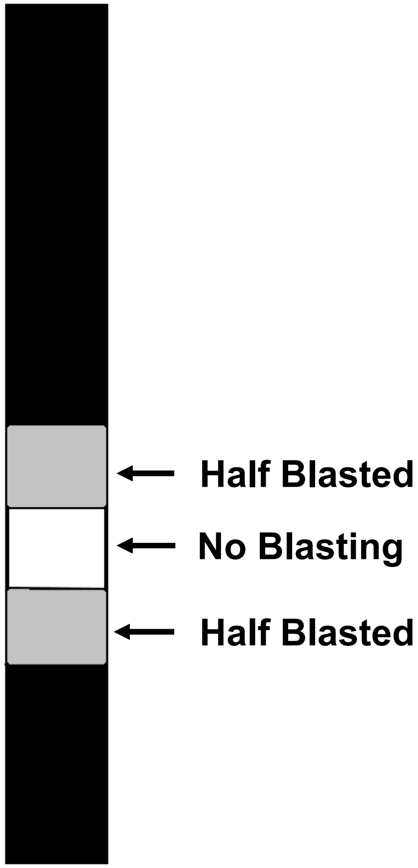


Do not need crack length measurement!

Smart Wedge Testing:
Identification of Contaminated Bond Regions

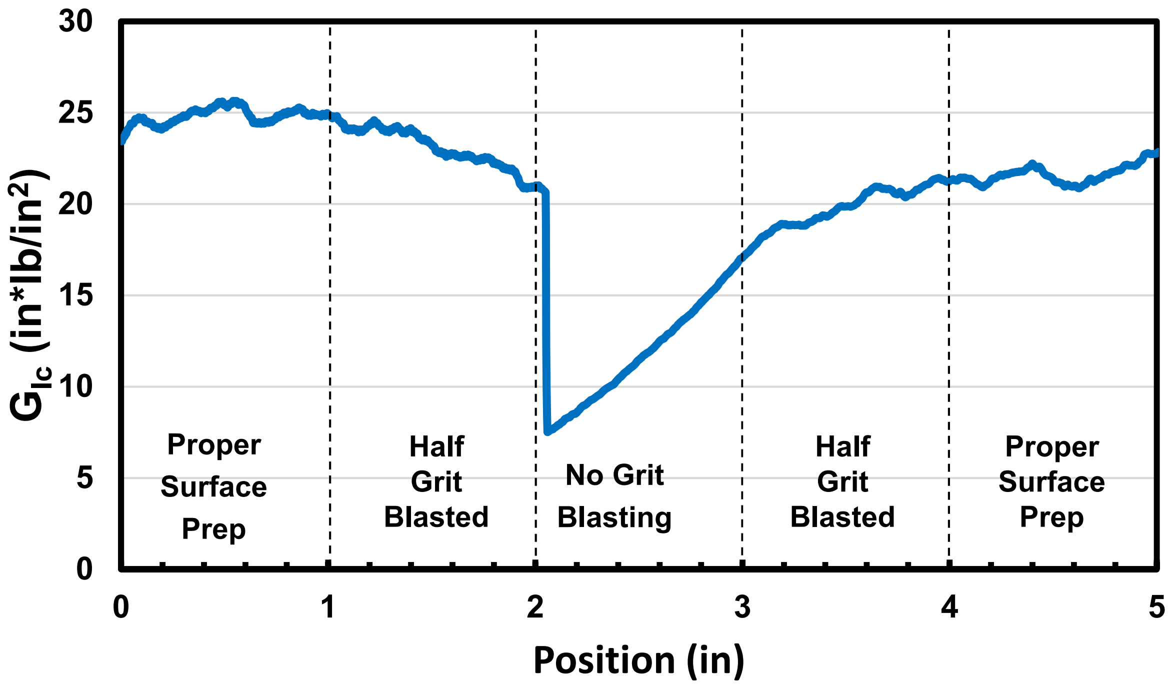
- **Different levels of grit blasting performed on strips across one adherend**
  - **Full grit blast duration**
  - **Half grit blast duration**
  - **No grit blasting**
- **Other adherend prepared in standard manner**





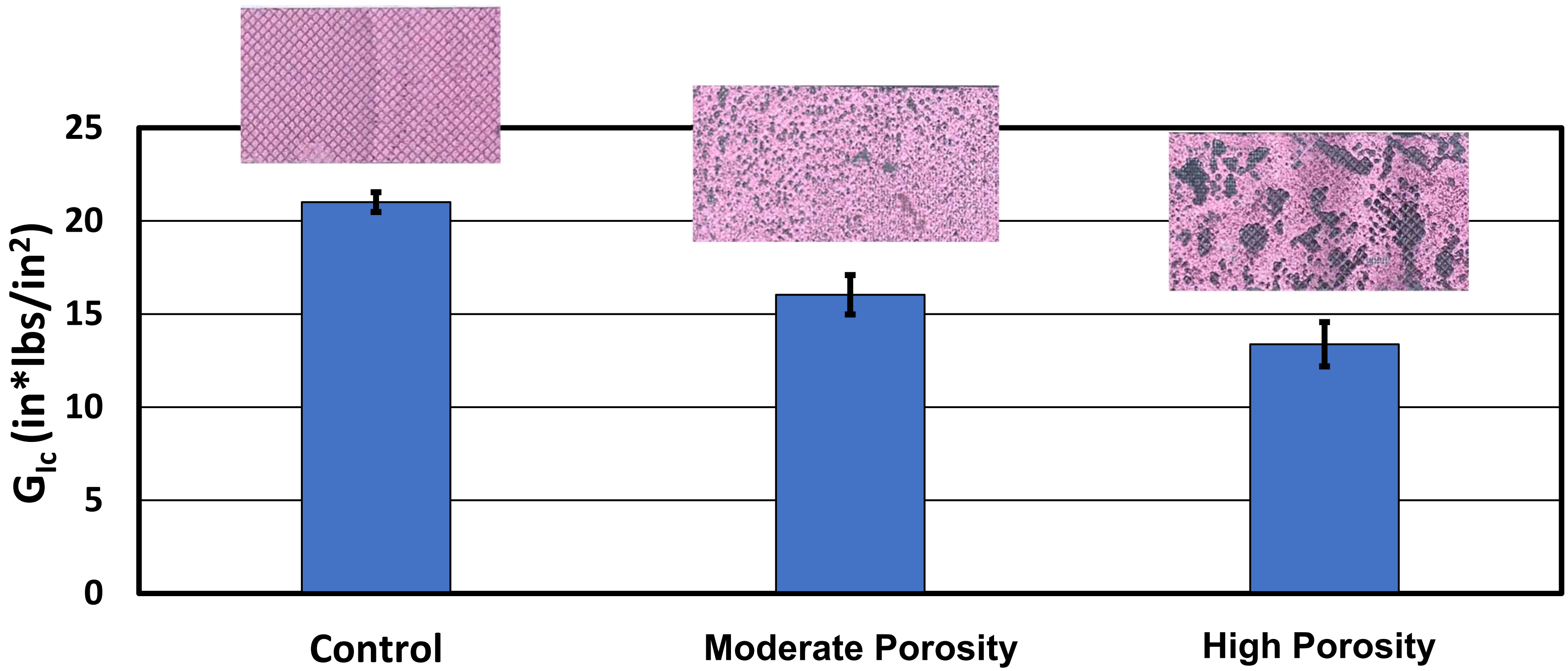
Smart Wedge Testing:
Identification of Contaminated Bond Regions

General agreement level of grit blasting, % cohesion failure and measured G_c values



Smart Wedge Testing:

Identification of Bonds with Porosity



Reductions in G_{1C} correspond to increasing porosity

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Summary:
Status of Composite "Smart Wedge" Test

- Useful for assessing larger bond areas
- Able to detect regions of high porosity and reduced-strength bonds
- May be used to estimate fracture toughness
- Follow-on composite wedge testing to investigate environmental durability

Thank you for your attention!

Questions?