Environmental Durability Test Method Development for Composite Bonded Joints

Zachary Sievert
Heather McCartin
Dan Adams
University of Utah

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FAA Sponsored Project Information

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

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Outline

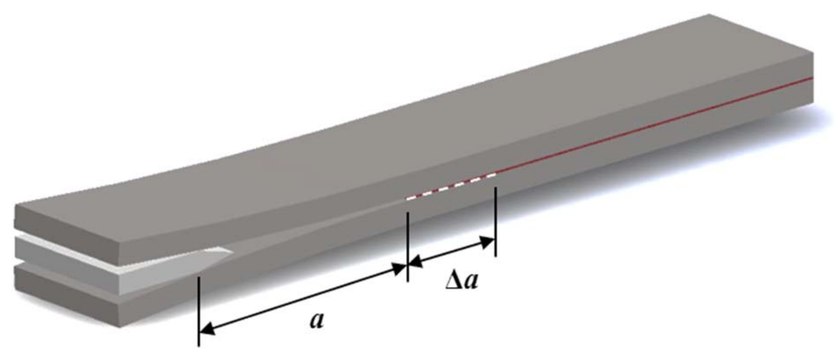
- **Updates:**
  - Revision of metal wedge test method (ASTM D3762)
  - ASTM Adhesive Bonding Task Group D14.80.01
  - New adhesives testing content in CMH-17 Handbook

- **Primary focus: Environmental durability test methods for composite bonded joints**
  - Composite wedge test development
  - "Smart Wedge" traveling wedge test concept

Background:
Revision of the Metal Wedge Test

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

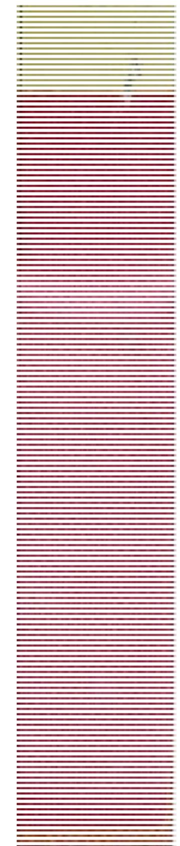
- **Bonded aluminum double cantilever beam loaded by forcing a wedge between adherends**
- **Assembly placed into test environment (ex: 50º C, 95% RH)**
- **Crack growth *Δa* due to environmental exposure measured following prescribed time**
- **Able to assess bond quality quickly by causing rapid hydration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



Revision of ASTM D3762:

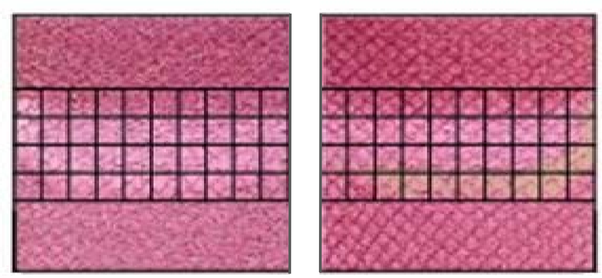
Summary of Revised Test Method

- **Completed extensive revision of standard**
- **Two ASTM balloting cycles completed to date; addressing remaining concerns**
- **Broadening of scope to include metals other than aluminum as adherends**
- **Provided additional guidance in specimen manufacturing, additional details in test procedure**
- **Addition of requirement to estimate % cohesion failure in region of environmental crack growth**



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

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



Collaborations with ASTM D14 (Adhesives):

Formation of 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

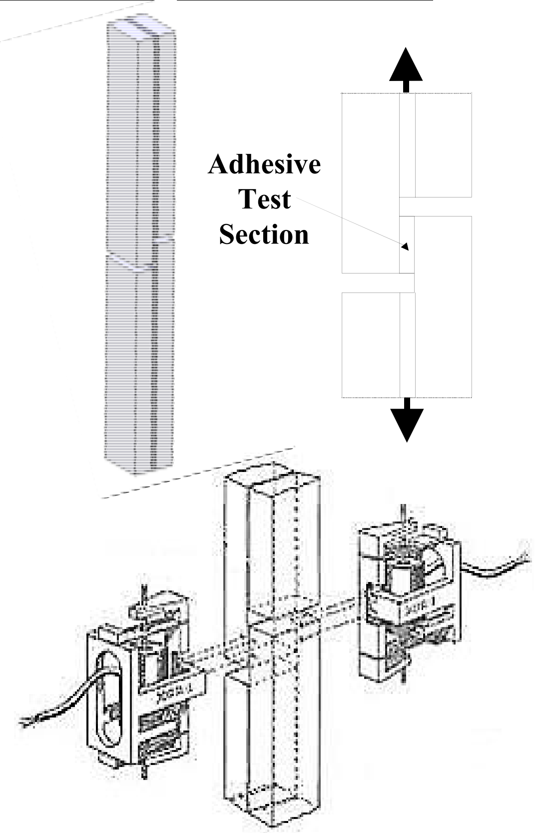
Current Activities

- 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
- Follow-on round-robin investigation planned
  - AFRL specimens, single film adhesive
  - Evaluation of candidate shear strain measurement methods
- Update ASTM D5656 Standard
- In conjunction with CMH-17



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

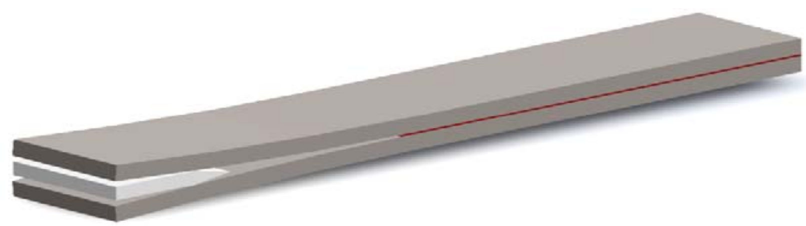
Overview:
Development of a Composite Wedge Test:

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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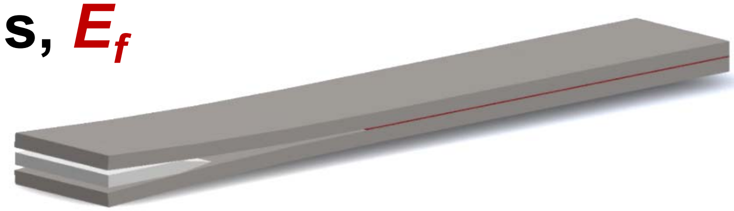
Use of Fracture Toughness, G_c To Assess Environmental Durability

G_C written in terms of flexural modulus, E_f

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



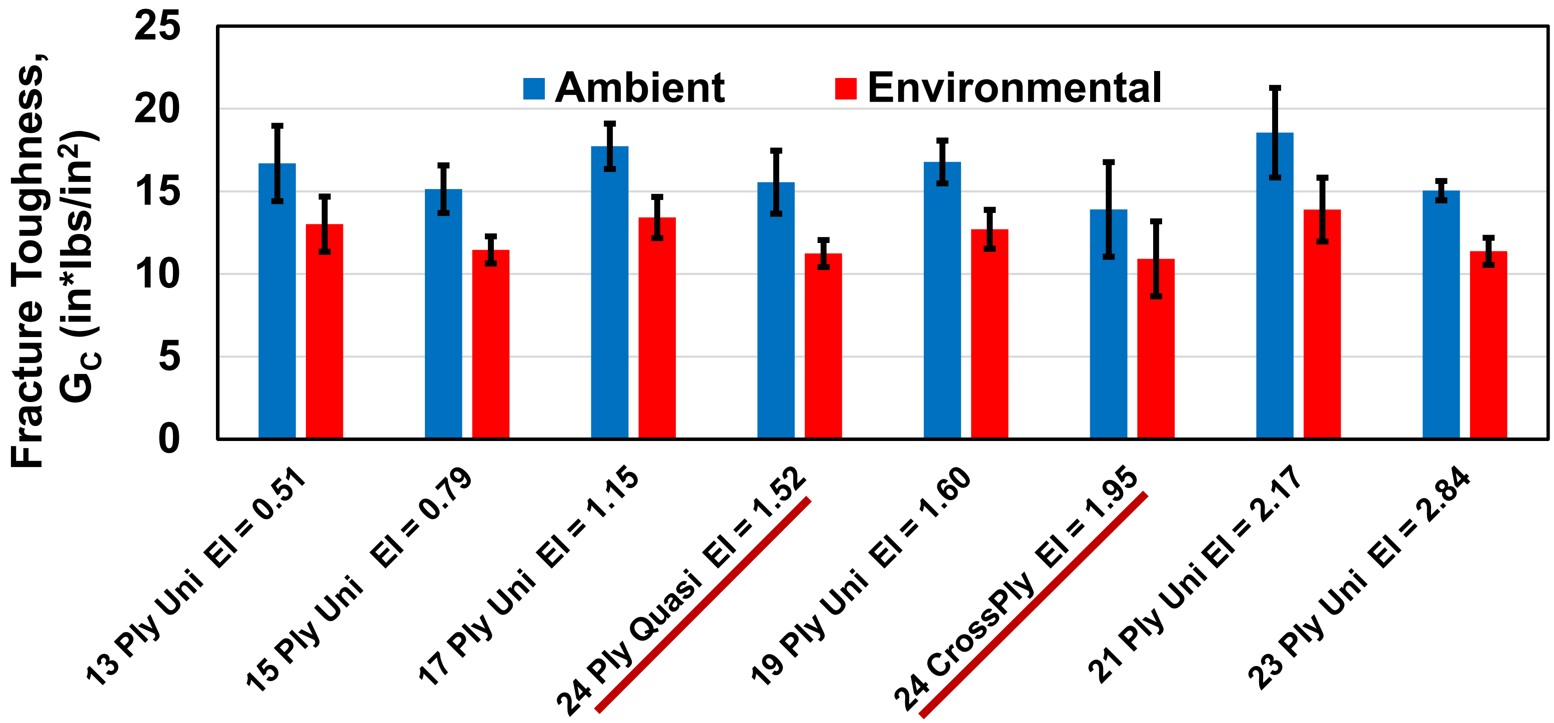
G_c = fracture toughness
E_f = flexural modulus
t = wedge thickness
h = adherend thickness
a = crack length

- 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

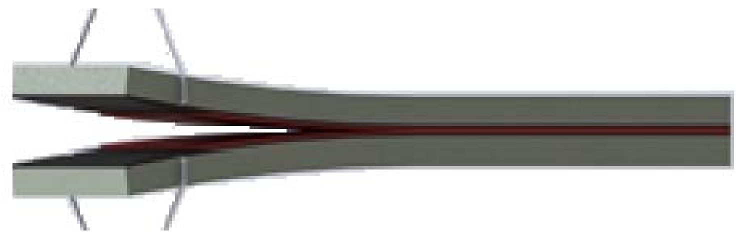


- Apparent facture toughness values remain relatively constant
- Provides estimate of fracture toughness at ambient conditions
- G_c values from quasi-isotropic and crossply laminates consistent with results from unidirectional laminates

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 $E_f\, I$:**

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

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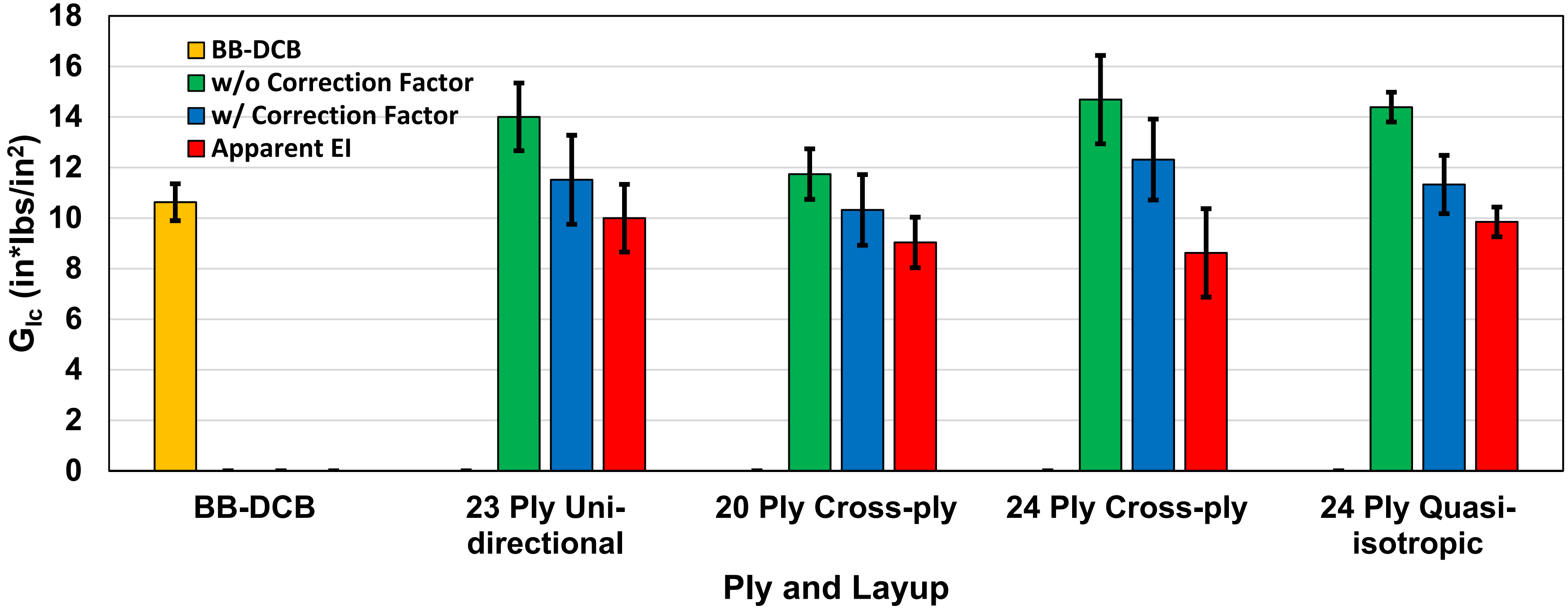
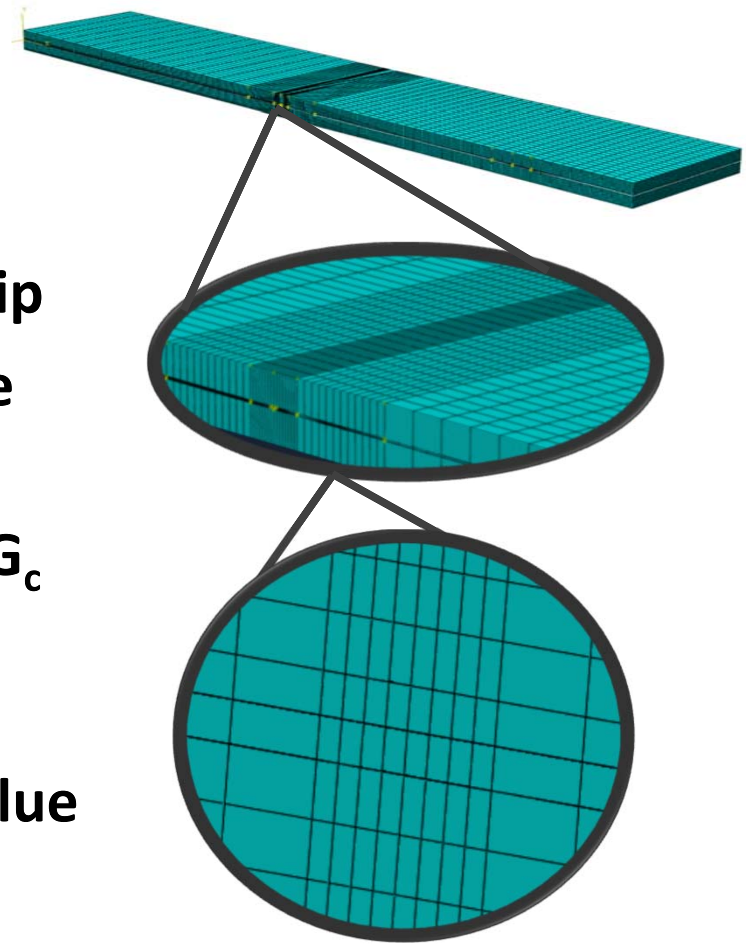
Comparison of Wedge Test and DCB Test Results: 50ºC, 95% RH, 5 days



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

Evaluation of G_c Calculation Methods: Numerical Simulations

- **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**
- **Investigation of candidate methods for G_c calculation using results from simulated composite wedge test**
- **Use of VCCT to calculate reference G_c value**



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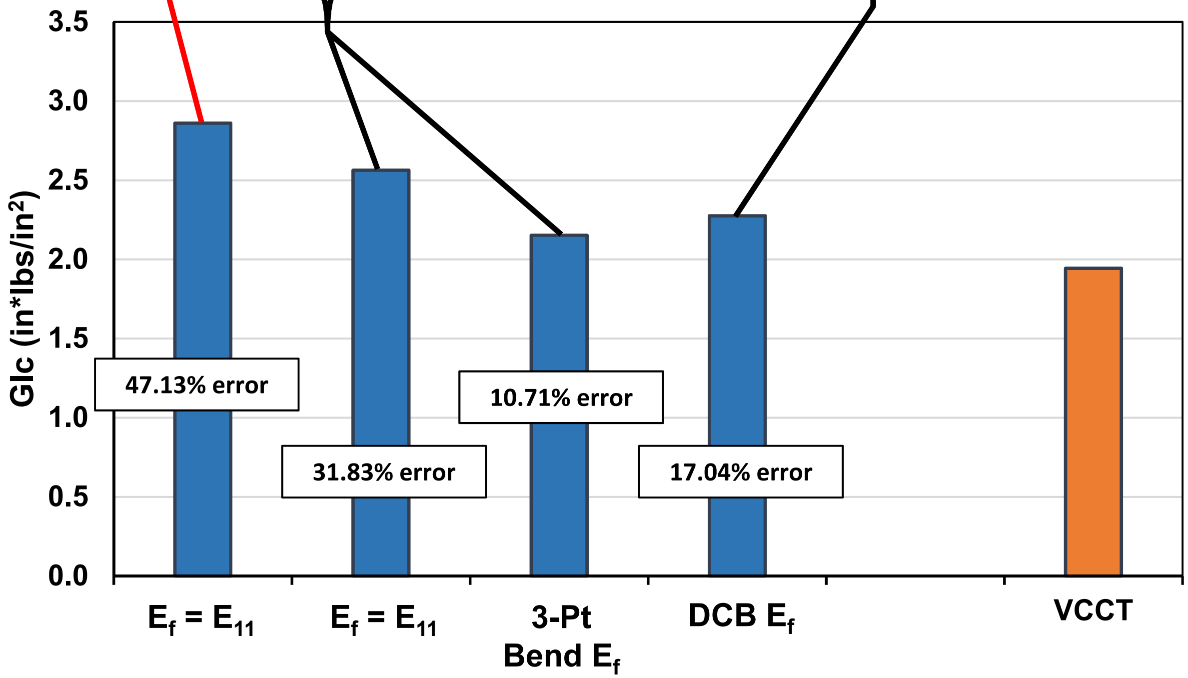
Evaluation of G_c Calculation Methods: Finite Element Results

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

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



Flexural modulus values:

- Tensile modulus
- FE simulated flexure test
- FE simulated DCB

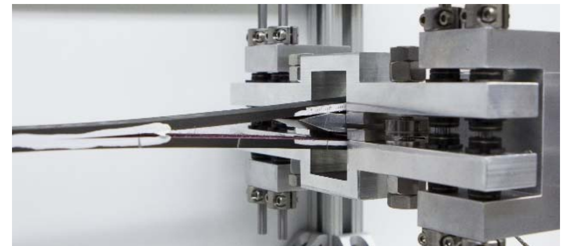
G_{Ic} calculated from beam theory:

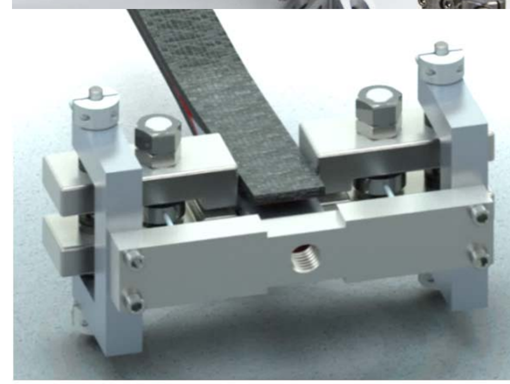
- w/o correction factor
- w/ correction factor
- Apparent $E_f I$

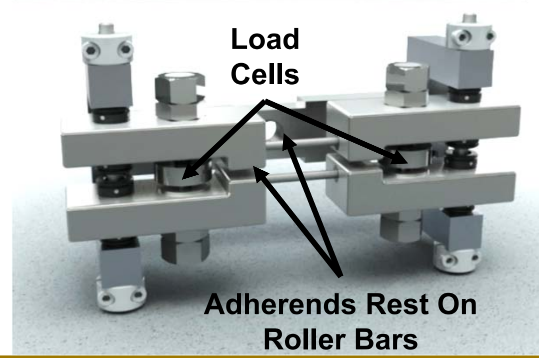
Compared to energy release rate at crack tip as analyzed by finite element analysis of wedge test

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

- **Continuous opening displacement reaction 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**
  - **Caused by unstable crack growth**
  - **Reduced fracture toughness**
- **Similar to traveling wedge test, but with reduced damage to new surface area**
- **Retain wedge in specimen for environmental durability test**







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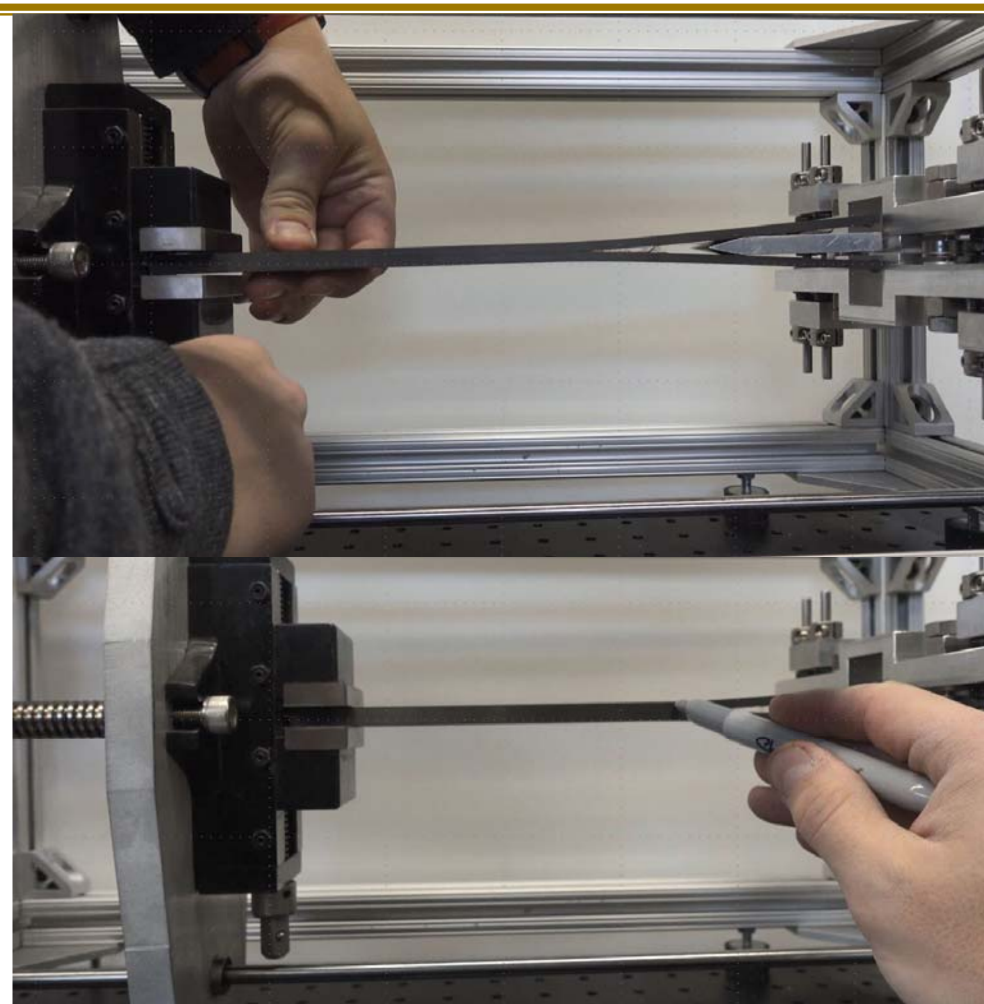
Smart Wedge Testing: Operation & Procedure



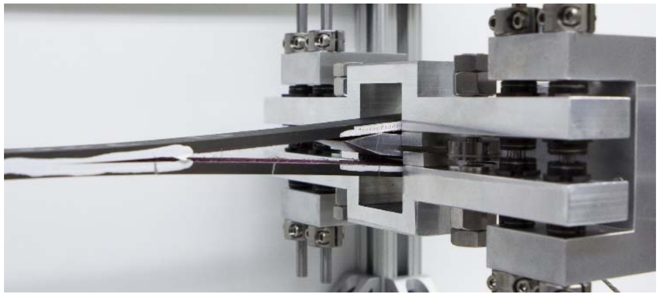
"Smart Wedge" Concept:

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 (opening displacement)
  - Flexural rigidity, E_f I (measured)

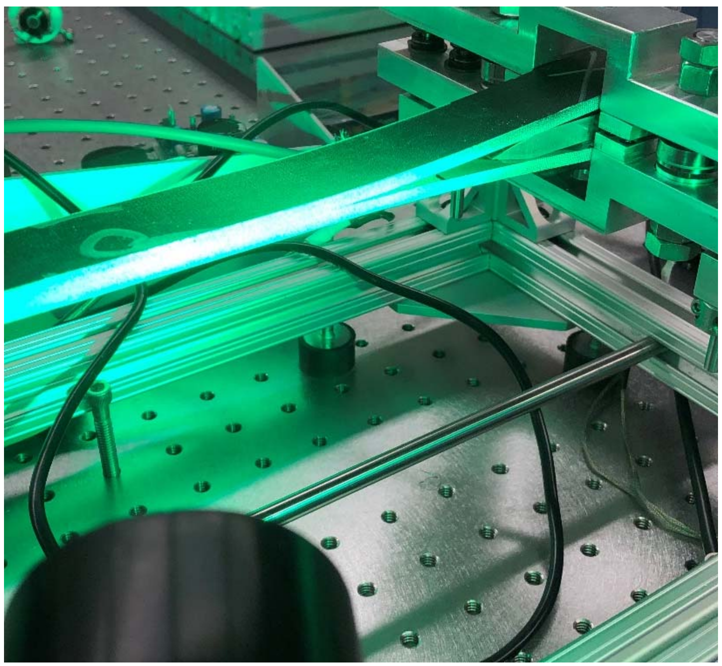


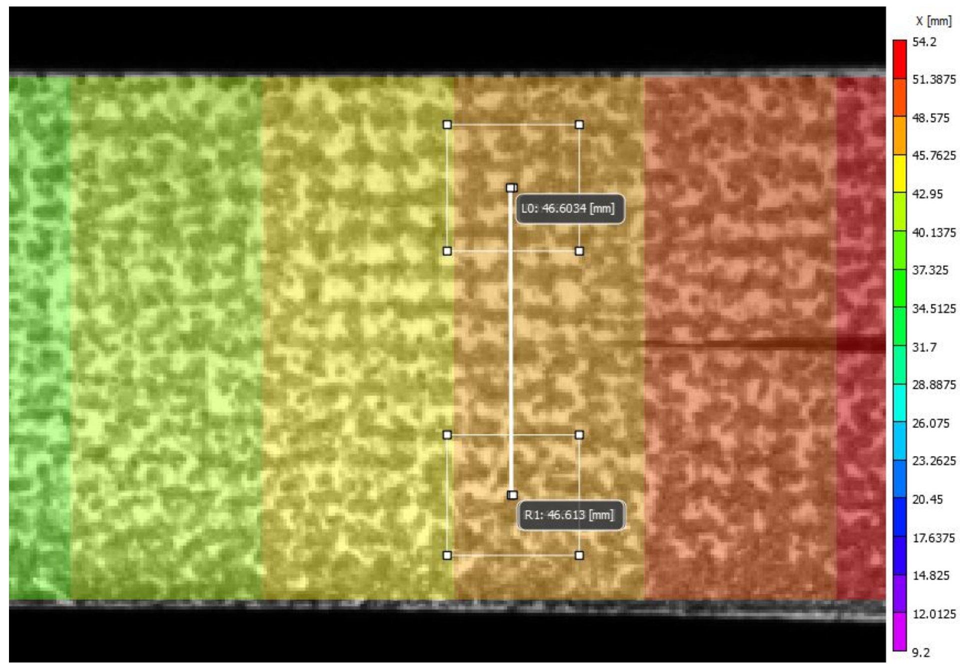
Do not need crack length measurement!

Smart Wedge Testing:
Digital Image Correlation (DIC) for J-Integral

- **Smart Wedge testing with DIC for J-Integral uses a formula derived for DCB specimens →**

$$J_{IC} = \frac{12P^2a^2(1-\nu_{31}^2)}{b^2E_1h^3} + \frac{P\omega}{b}$$





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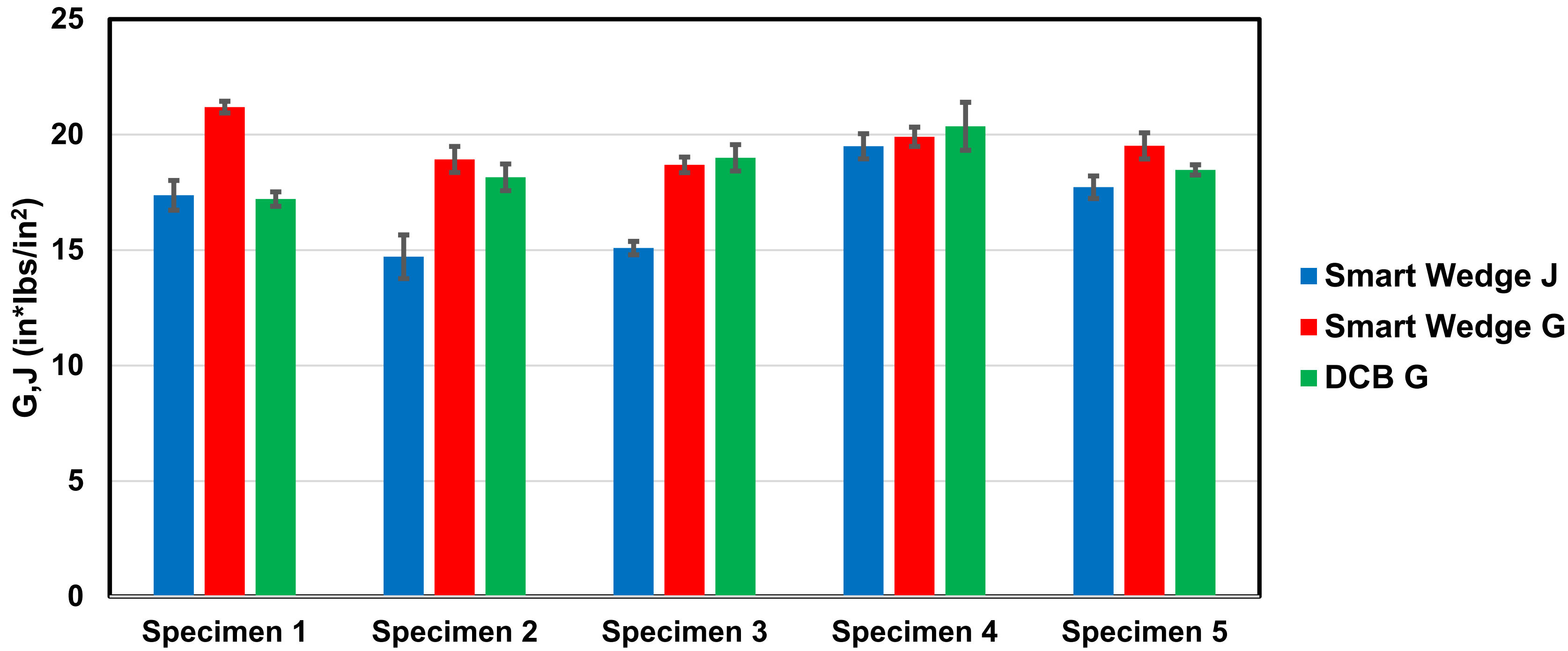
Smart Wedge Results: Comparison of Experimental G_I, J_I



- **3 tests performed on each bonded composite specimen**

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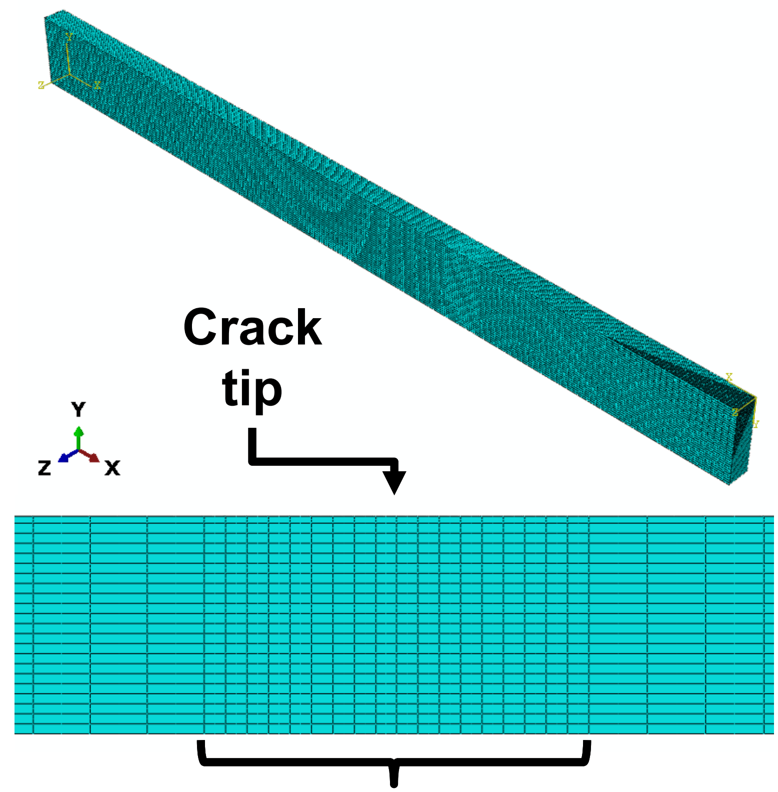
Evaluation of G_c Calculation Methods: Numerical Simulations

- Smart Wedge specimens modeled in ABAQUS
- Reduced computation time
  - Reducing unused length of specimen
  - Symmetry about midplane
  - Only one adherend and half adhesive layer
- Investigate differences in J and G values associated with crack growth

Mesh



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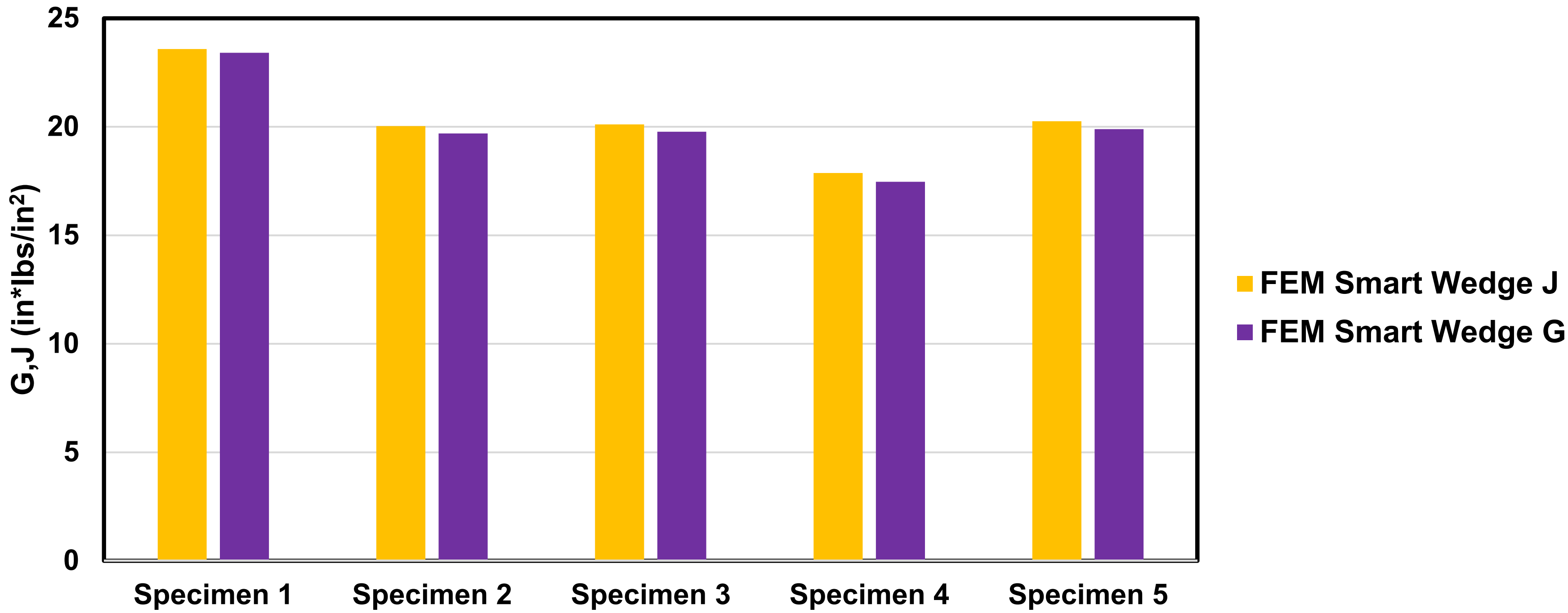
Smart Wedge Results:
Comparison of Numerical G_I, J_I



- **G_I, J_I determined from simulation of Smart Wedge testing**
- **Simulation of initial crack growth only (one crack length)**

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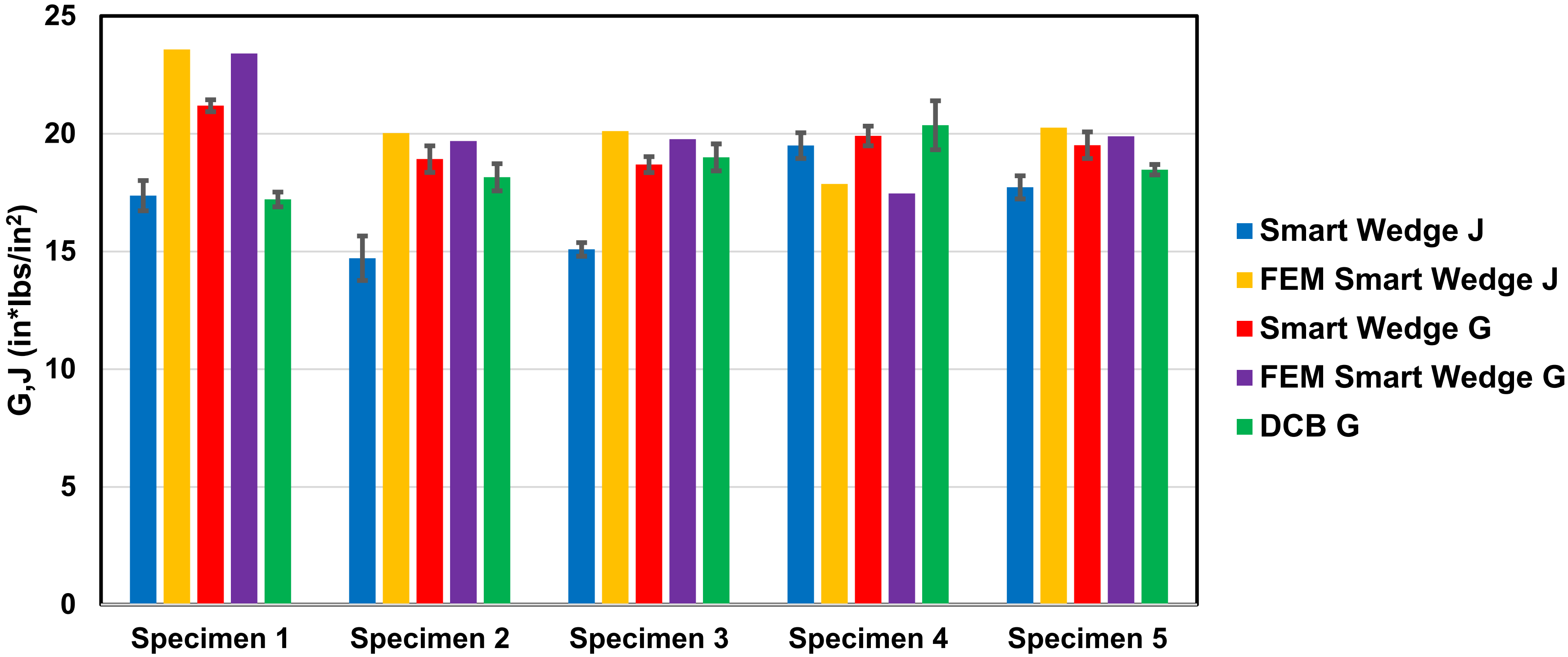
Smart Wedge Results:
Comparison of Experimental & Numerical G_I, J_I



- **3 tests performed on each bonded composite specimen**
- **Numerical modeling of J, G shown without error bars**

Smart Wedge Testing:
Specimen Manufacturing with Weak Bond Regions

- **Evaluate use of Smart Wedge to detect regions of weak bonds**
- **Variable levels of grit blasting on prescribed regions of one adherend**
- **Standard adhesive application and cure**

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Smart Wedge Test Results: Detection of Weak Bond Regions

- Significant reduction in Gc associated with weak bond region
- Further testing to focus on less significant degradations in bond strength

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

Questions?

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