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Test Method Development for Environmental Durability of Composite Bonded Joints

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AMTAS Autumn 2016 Meeting
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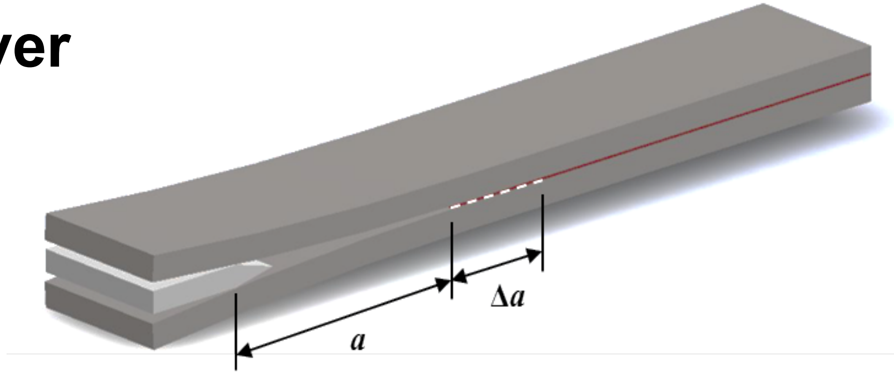
Outline

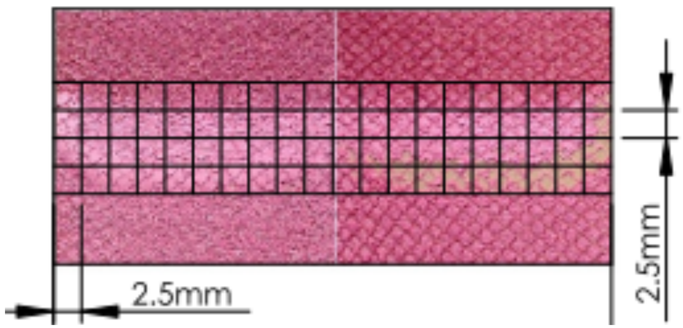
- Updates:
  - Wedge test method for bonded metallic joints
  - ASTM Adhesive Bonding Taskgroup D14.80.01
- Current focus: Environmental durability test methods for composite bonded joints
  - Composite Wedge Test
  - Comparison of results with other test methods
- Plans for upcoming research

Background: The Metal Wedge Test

ASTM D 3762: "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* and % cohesion failure due to environmental exposure measured following prescribed time
- Able to asses bond quality quickly by causing rapid hydration of oxide layers





Updated ASTM D 3762 standard in preparation for ASTM subcommittee balloting by the end of 2016

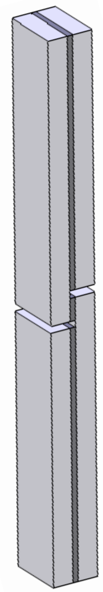
Collaborations with ASTM D14 (Adhesives): Formation of D14.80.01 Task Group

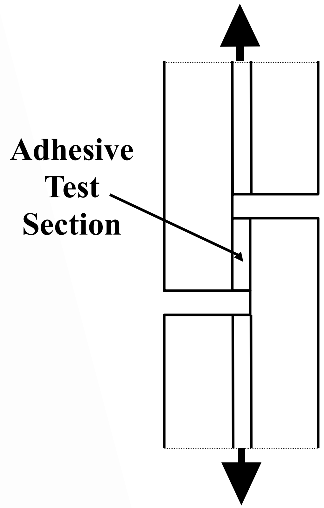
- Includes D14 (Adhesives) and D30 (Composites) members
- Meets concurrently with D30 to allow their participation
  - Initial meeting: April 2016, San Antonio Texas
  - Recently met: Sept. 22, 2016, Williamsburg VA
- Balloting through D14.80 subcommittee and D14 main
- Technical contact(s) from D30 to attend D14 meetings and provide TG status reports

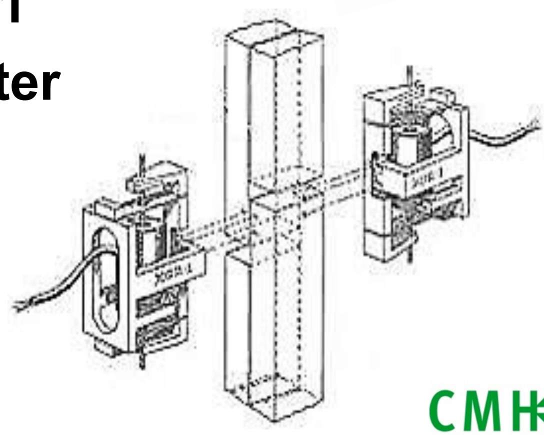
Current Activities:
ASTM D14.80.01 Task Group

Improvements to ASTM D5656–Thick Adherend Lap Shear Test

- **Best practices for shear strain measurement**
  - Replacement for obsolete KGR-1 extensometer
  - Optimal attachment points for shear strain measurement
- **Round-robin investigation initiated**
  - Digital Image Correlation with KGR-1
  - Epsilon 4013 Averaging Extensometer
  - NIAR Extensometer Attachment
- **In conjunction with CMH-17 Testing Working Group**







CMH-17
COMPOSITE MATERIALS HANDBOOK

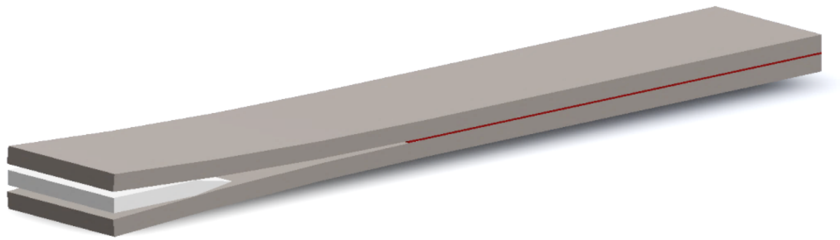
Current Activities:
Development of a Composite Wedge Test:

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



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

Why Environmental Durability Tests of Composite Bonded Joints?

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

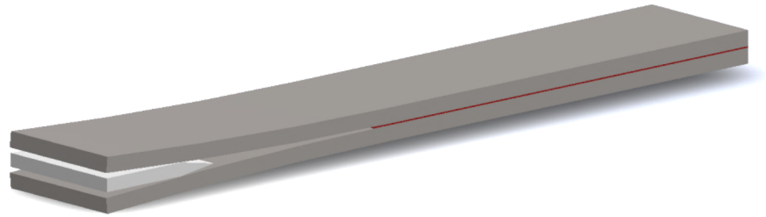
- Ensure longer-term environmental durability of composite bonds
- Investigate effects of environmental exposure on performance of bonded composite joints
  - Failure mode: cohesion versus adhesion failure
  - Estimate fracture toughness reduction
- Evaluate effectiveness of surface preparation

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: $$G_c = \frac{dU}{da}$$

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

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

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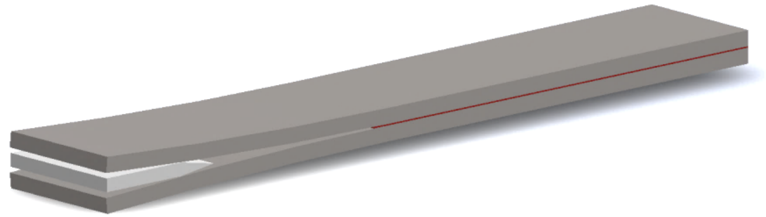

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Strain energy due to bending: $U = \frac{1}{2} T\,\delta$

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

$$G_c = \frac{3\,E_f\,t^2\,h^3}{16\,a^4} \underbrace{\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]}_{\text{Correction factor for crack tip rotation}}$$

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

Is it Really Necessary to Switch From Δa to G_c For Composite Adherends?

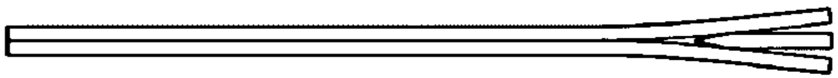
- Consider wedge testing using two adherend thicknesses:

  h = 0.06 in.   h = 0.12 in.

- Assume 50% reduction in G_c from 25 to 12.5 in-lb/in^2

$$G_c = \frac{3\,Ef\,t^2\,h^3}{16\,a^4} \quad \Rightarrow \quad a = \sqrt[4]{\frac{3\,Ef\,t^2\,h^3}{16\,G_c}}$$

For h = 0.06 in.



$a_{initial}$ = 0.88 in.

a_{final} = 1.05 in.

Total Growth Δa = 0.17 in.

For h = 0.12 in.

$a_{initial}$ = 1.48 in.

a_{final} = 1.76 in.

Total Growth Δa = 0.28 in.

Changing the adherend flexural rigidity changes…

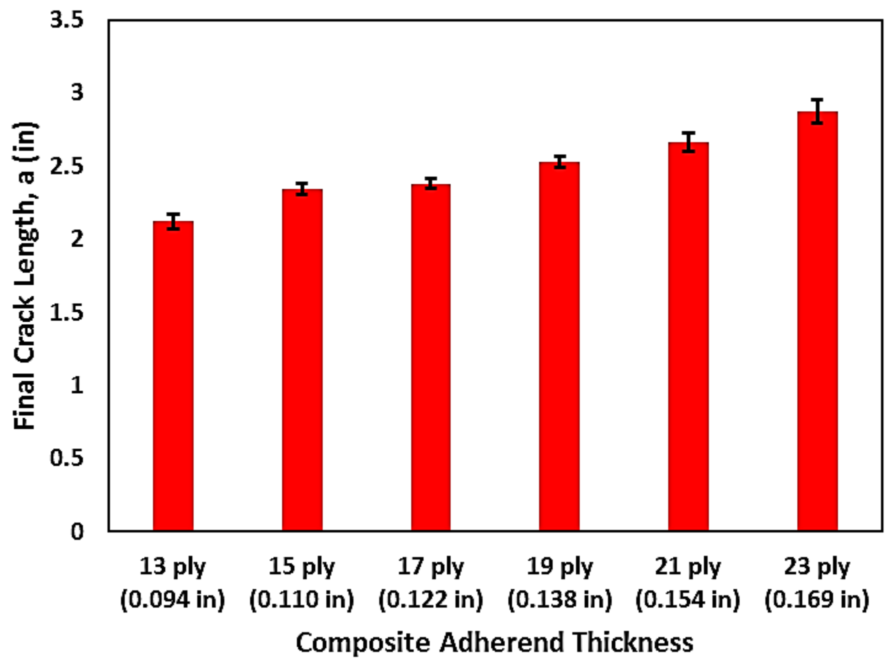
- Initial crack length, a   - Environmental crack growth, Δa

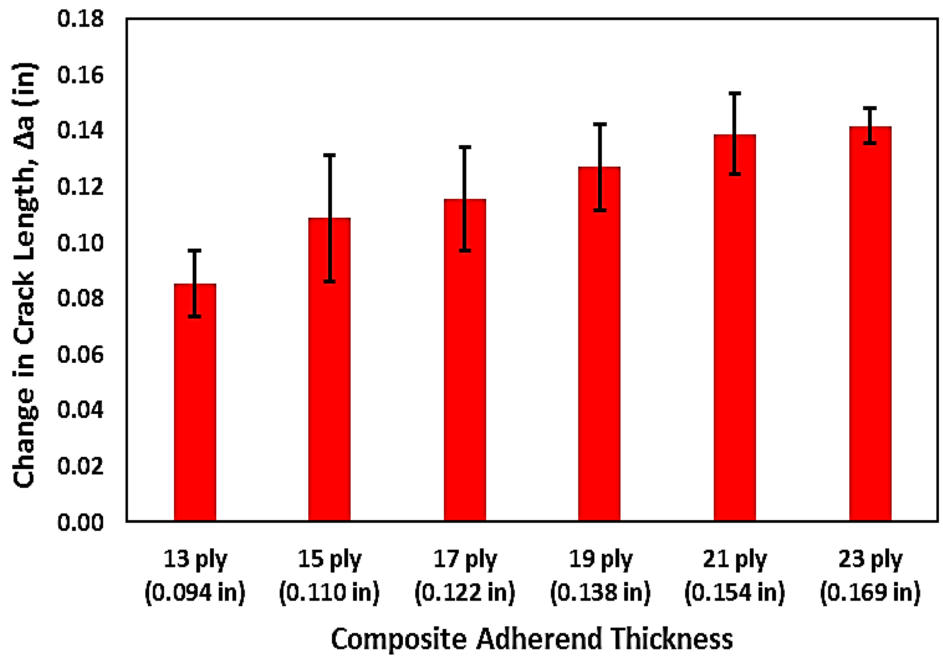
Experimental Investigation:
Composite Wedge Test Development

- **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**

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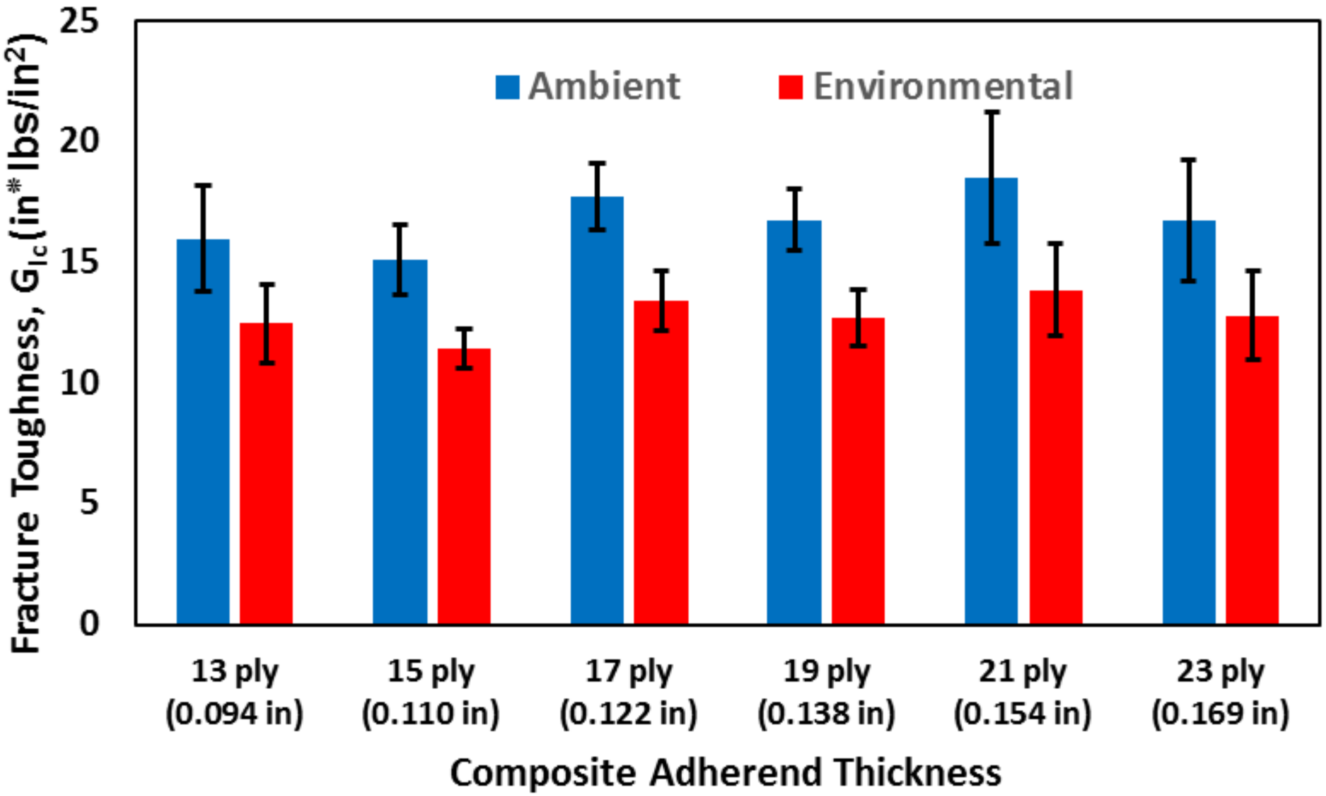
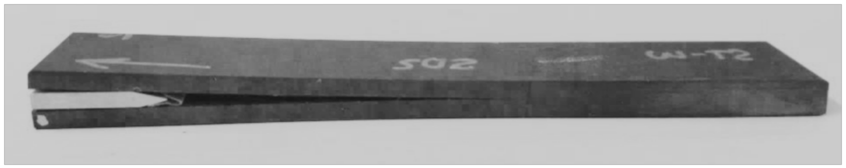
Effects of Composite Adherend Thickness: Fracture Toughness Values



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

Composite Wedge Test Development:
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)

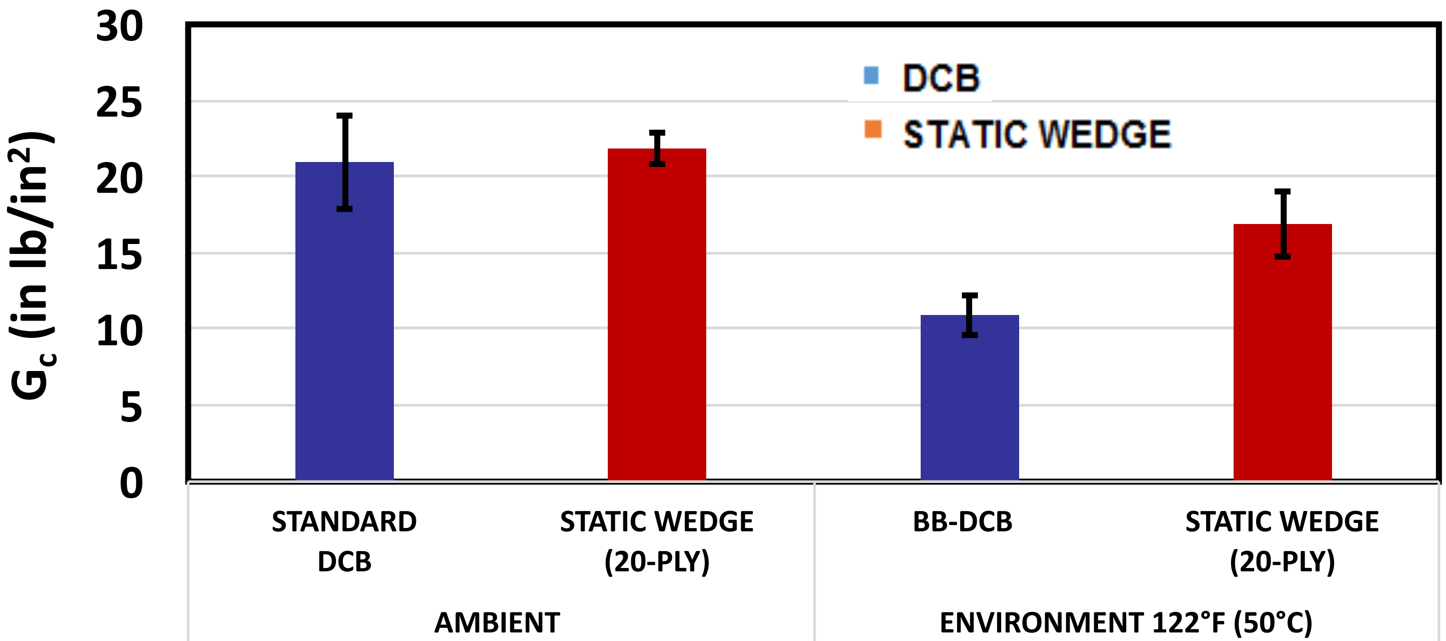


Composite Wedge Test

Double Cantilever Beam (DCB) Test

Back-Bonded DCB vs. Static Wedge Test: Initial Fracture Toughness Comparisons

- Higher fracture toughness values at ambient conditions
- Good agreement at ambient conditions
- Significant differences at environment using back-bonded DCB specimens
- Additional testing underway



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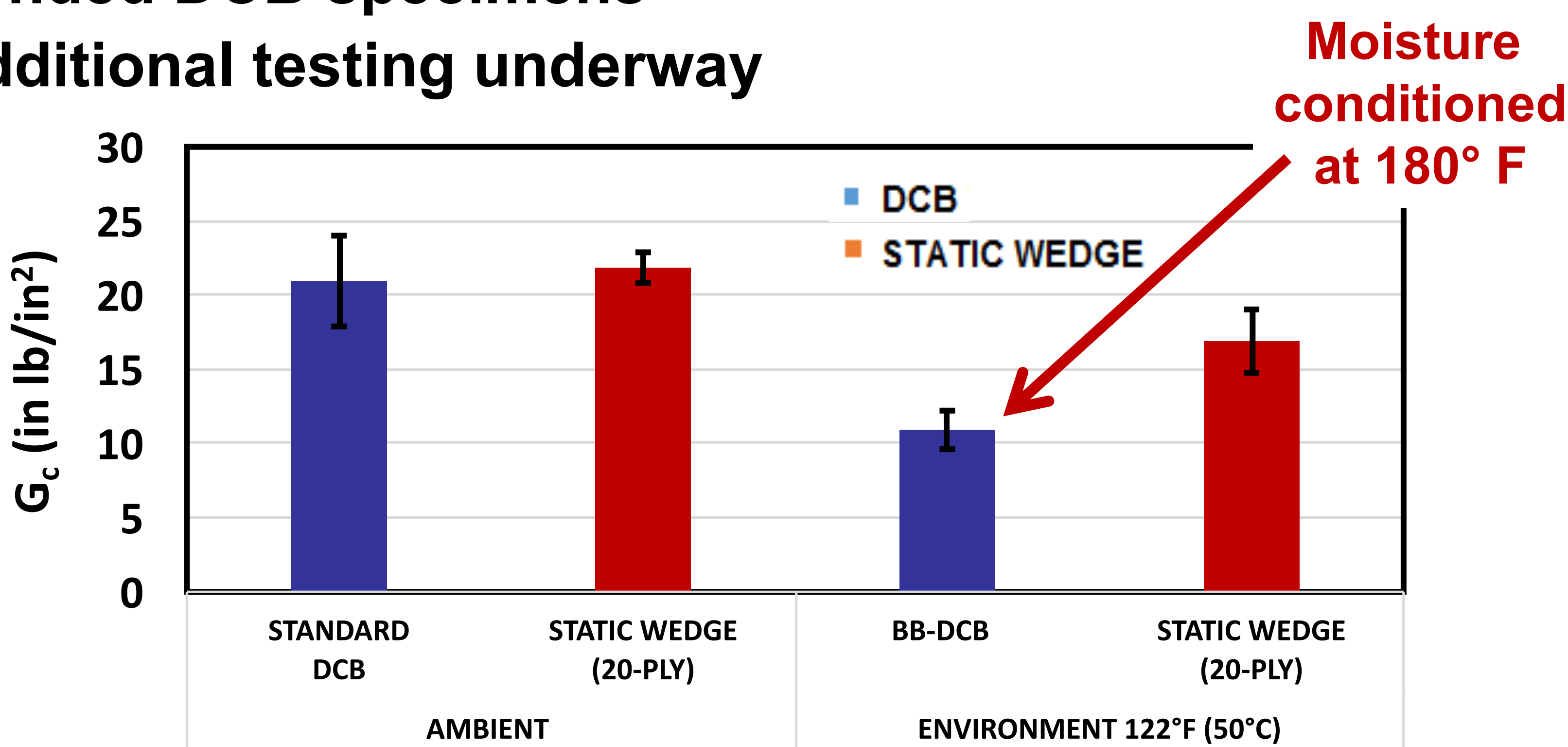
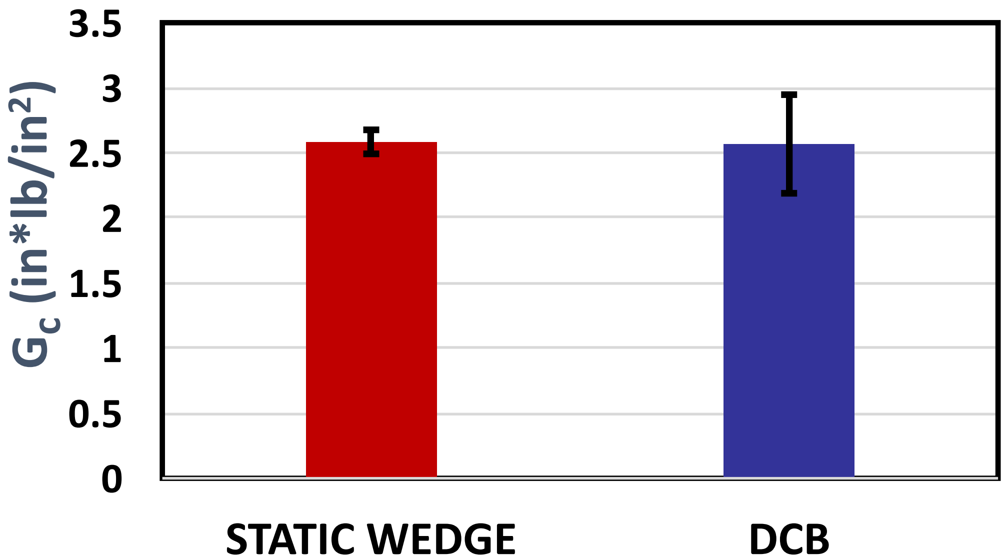
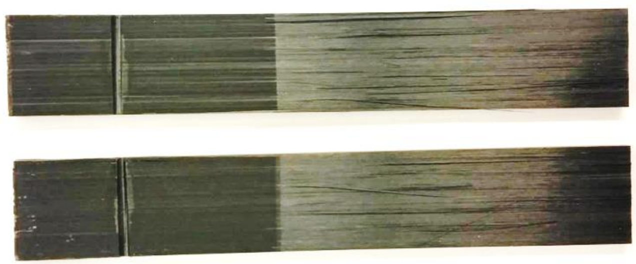


Comparison With DCB Test:
Composite Specimens – No Adhesive

- Initial results at RT/Ambient conditions
- Similar appearance on fracture surfaces
- Further testing underway at RT/Ambient and 50°C (122°F) / 95% RH using back-bonded DCB specimens



Composite Wedge Test Specimen



Double Cantilever Beam (DCB) Specimen

Determination of Flexural Modulus, E_f: Effects of Environmental Exposure

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

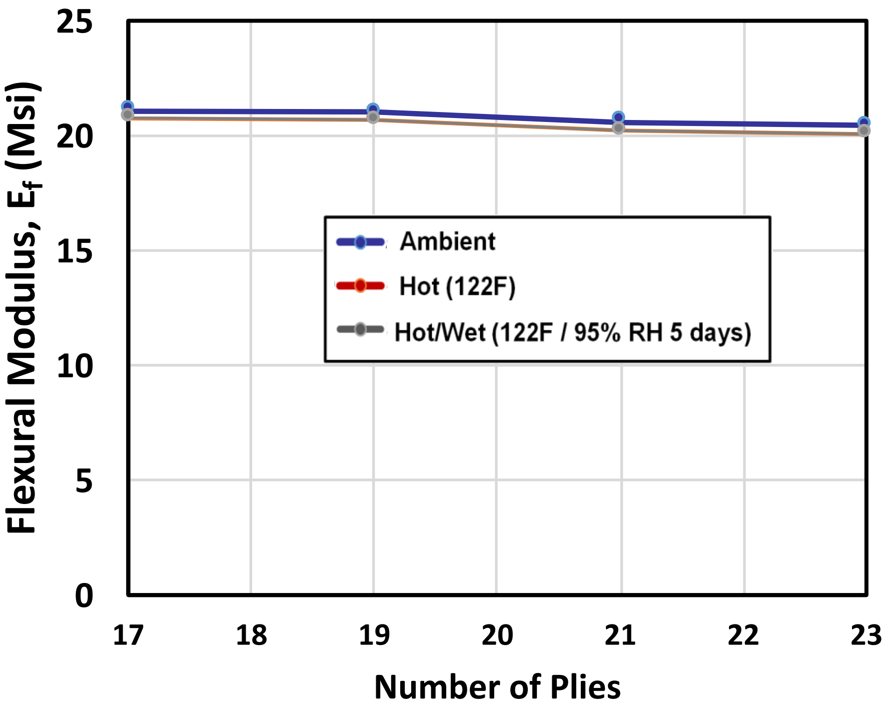
$$G_c = \frac{3\,E_f\,t^2\,h^3}{16\,a^4}\left[\frac{1}{(1+0.64\,\frac{h}{a})^4}\right]$$

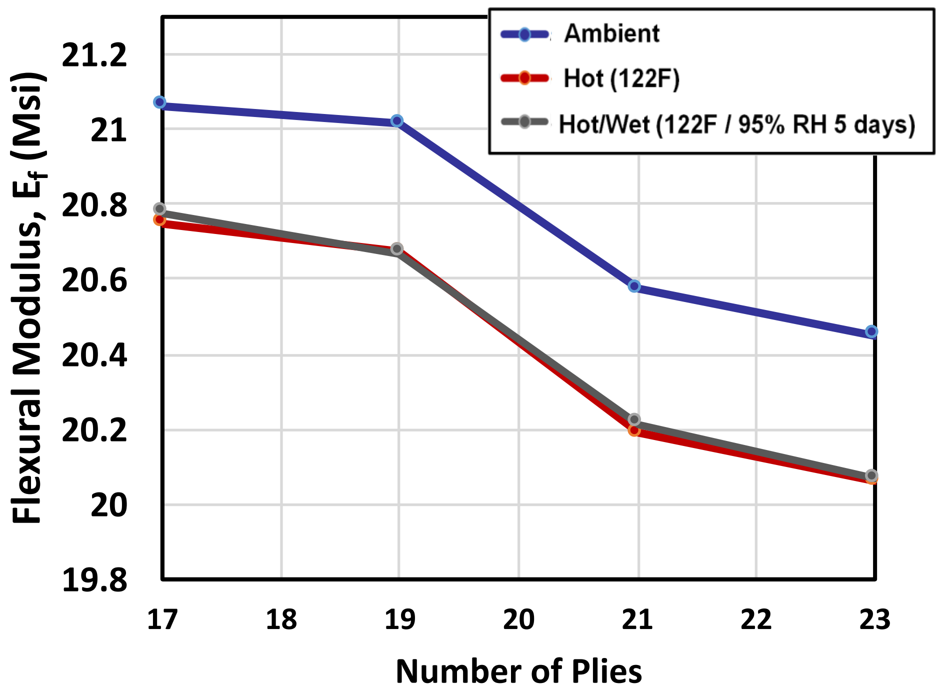
- E_f value should be representative of that experienced during wedge testing
  - Initial crack stabilization at room temperature/ambient conditions
  - Environmental crack growth at hot/wet conditions (122° F/95% RH)
- Can be measured using three-point flexure testing

- How does environmental exposure affect E_f?

- Can RT/ambient E_f measurement be used?

Flexural Modulus (E_f) of Composite Adherends: Environmental Conditioning Effects





- **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***

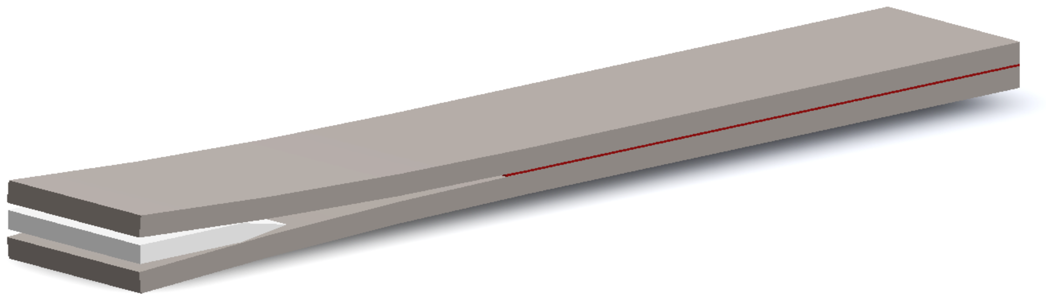
Composite Wedge Test Development:
Testing of Multidirectional Laminates

- **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 currently underway…

Composite Wedge Test Development:
Upcoming Work

- Determination of acceptable range of flexural rigidities (E_f * I) for composite adherends
  - Further investigate multidirectional laminates
  - Use of other composite materials
- Investigate candidate methods for “cantilever correction factors” for composite wedge test
- Further comparisons with other test methods
- Investigate usage for metal-to-composite bonds



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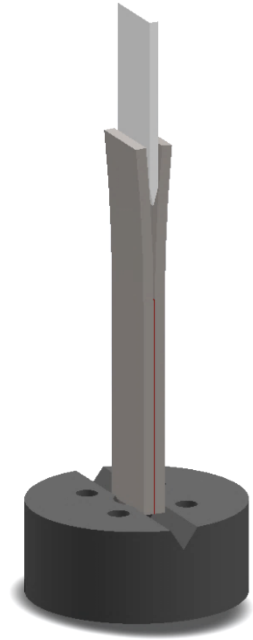
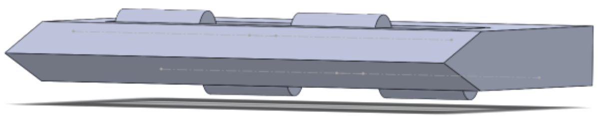
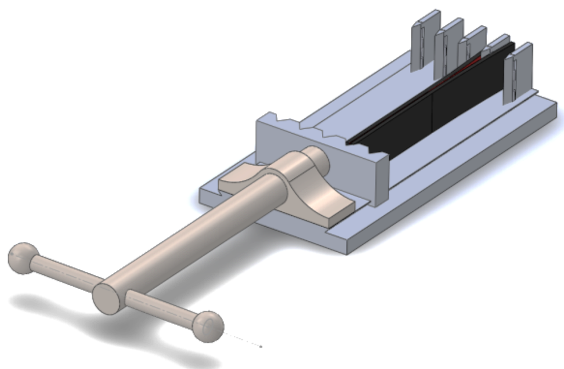
Environmental Durability Assessment:
Investigation of "Hybrid" Test Methods

- **Coupling of composite wedge test with another type of bond assessment**
  - **DCB / Wedge test**
  - **Traveling / Conventional Wedge test**
- **Force measurements without load frame during traveling wedge testing to estimate G_c**
  - **Longer version of static wedge specimen, potential to assess relatively large bond area**
  - **Periodic environmental durability testing via static wedge configuration**





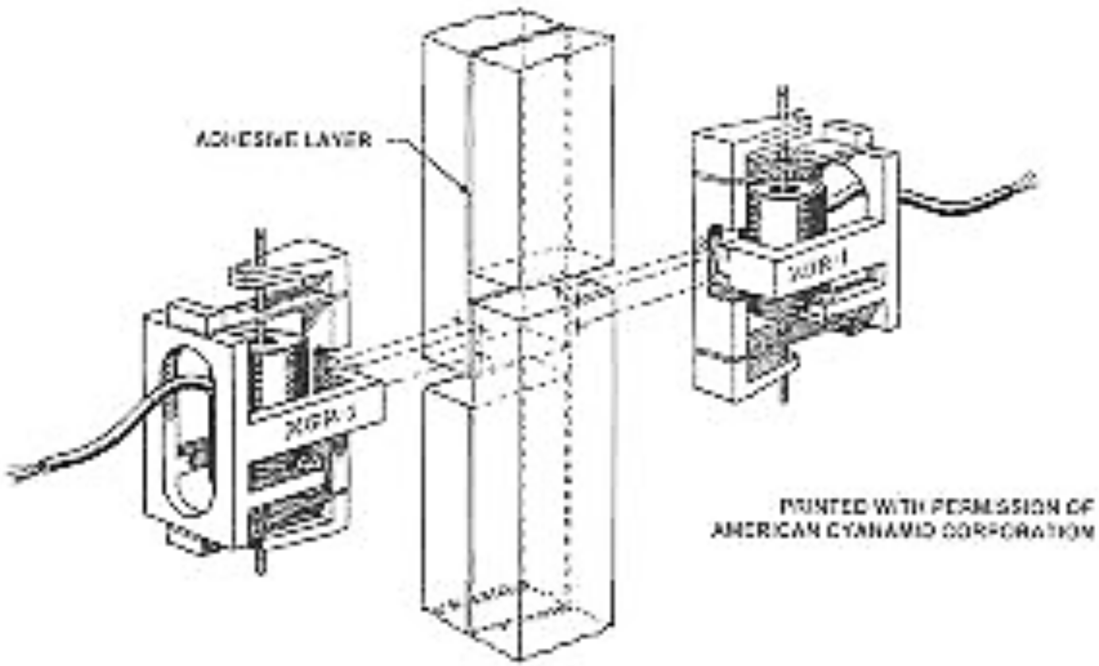


Thank you for your attention!

Questions?

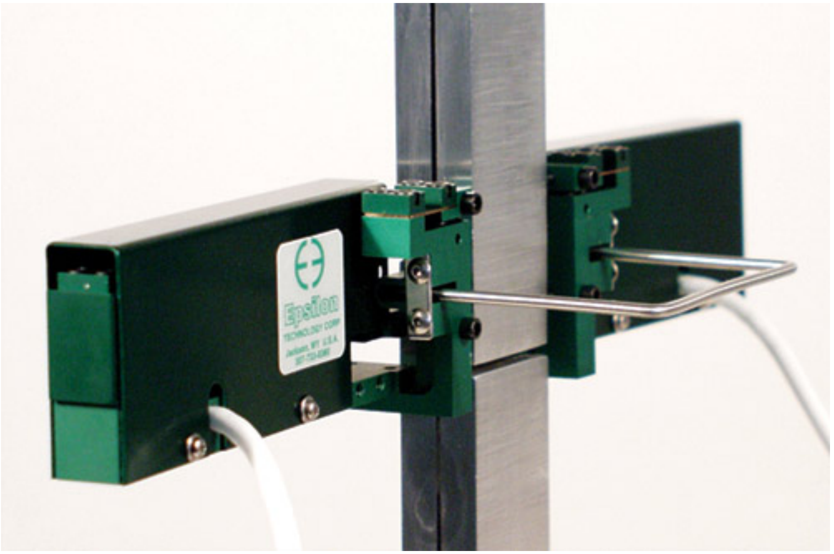
Improvements to ASTM D 5656
Shear Strain Measurement

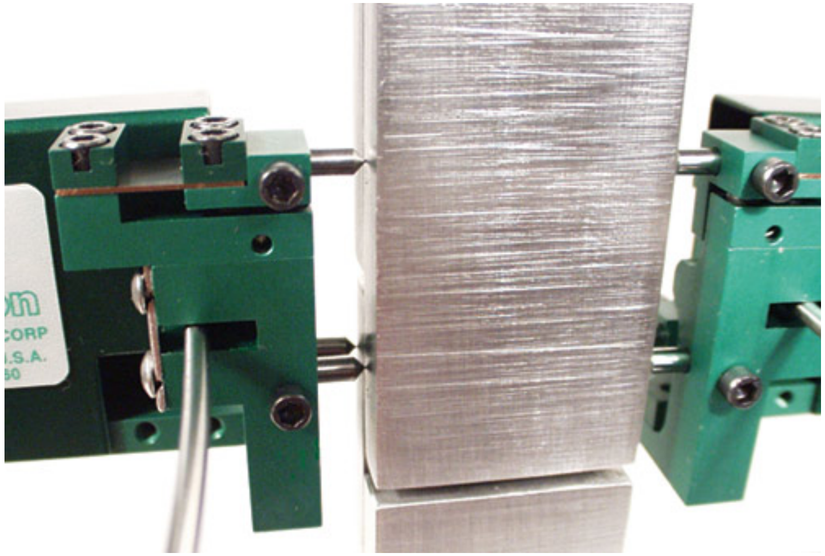
Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading



Other methods of shear strain measurement:

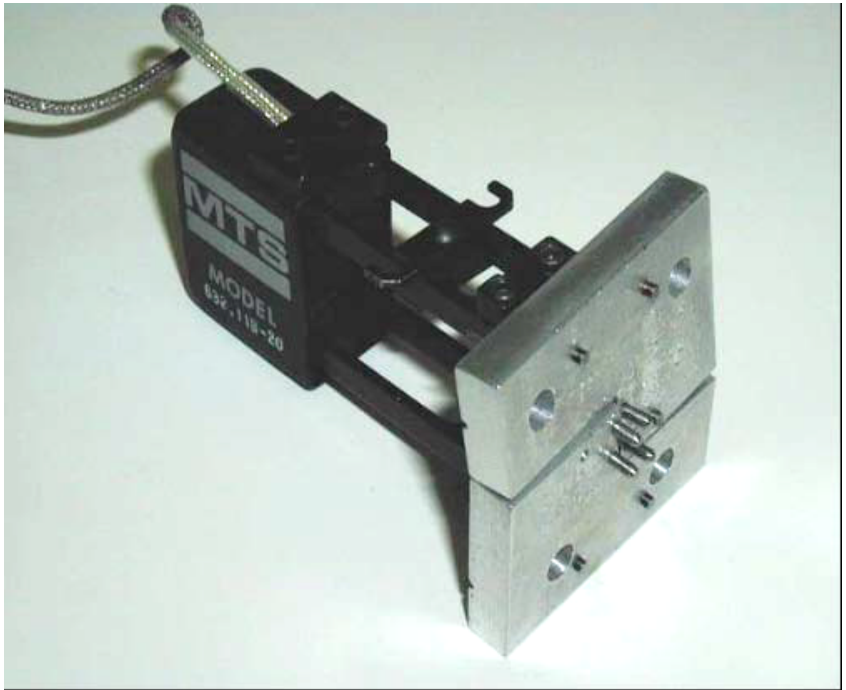
Epsilon 4013 Averaging Extensometer

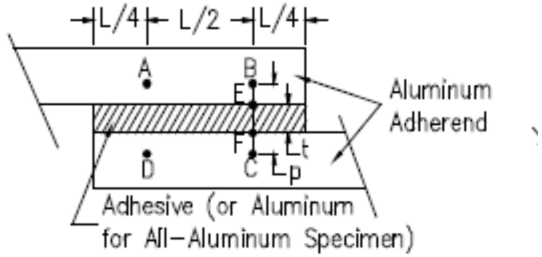


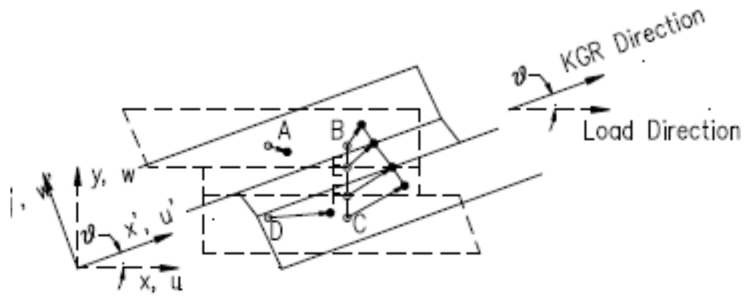


"The Model 4013 extensometer meets or exceeds the requirements of ASTM D5656 for measuring the strain properties of an adhesive in shear. It uses different contact point spacing compared to the extensometer shown in D5656. This makes it much easier to mount and eliminates the slippage problems associated with the design shown in the ASTM standard."

Other methods of shear strain measurement:
NIAR Extensometer Attachment

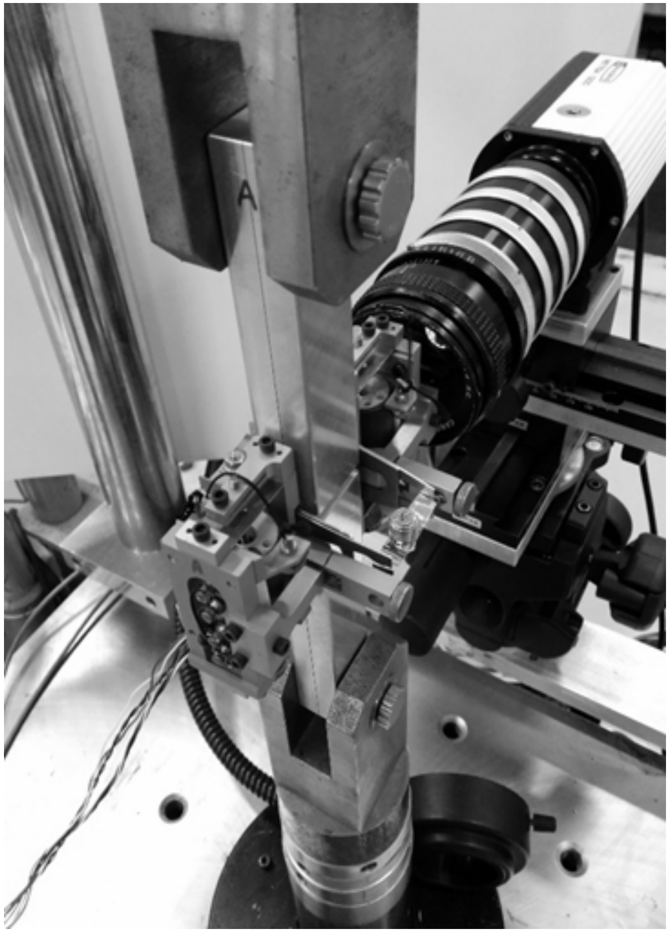






Points A, B, C and D are the quarter point mounting locations for the 'KGR-type' extensometer. Measure relative displacement between midpoints of AB and CD (assuming a linear displacement field)

Other methods of shear strain measurement:
Digital Image Correlation



Rick Cole, NRC Canada

Other methods of shear strain measurement:
Boeing Patented Extensometer Attachment

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2006/0248959 A1**
Bohlmann et al. (43) **Pub. Date: Nov. 9, 2006**

(54) **APPARATUS AND METHOD OF MEASURING SHEAR STRAIN OF THICK ADHESIVE BONDLINES**

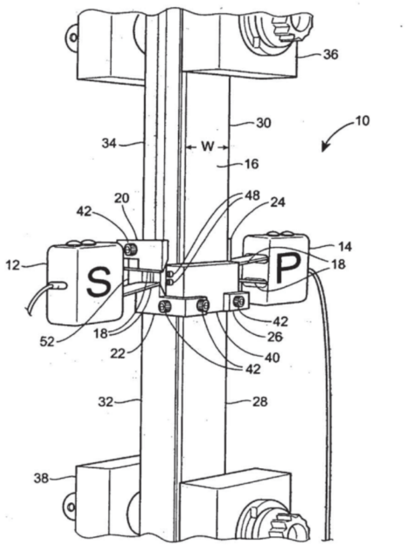
(75) Inventors: **Raymond E. Bohlmann**, Creve Coeur, MO (US); **Milton D. Hurd**, Cool Valley, MO (US); **Jeff Wollschlager**, Maryland Heights, MO (US)

(22) Filed: **May 6, 2005**

Publication Classification

(51) **Int. Cl.**
G01N 3/24 (2006.01)

(52) **U.S. Cl.** **73/841**



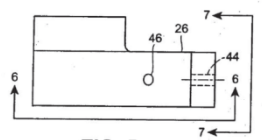


FIG. 5

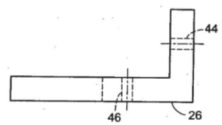


FIG. 6

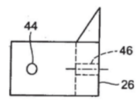


FIG. 7