# The SNL/MSU/DOE Fatigue Program: Recent Results

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Montana State University

2010 Sandia Blade Workshop
July 20-22, 2010

# Thanks

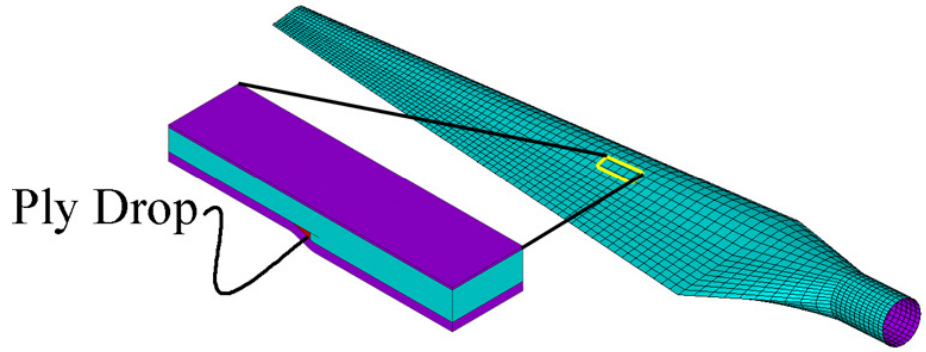
- To Sandia/DOE for support since 1989
- To our many partners in the industry

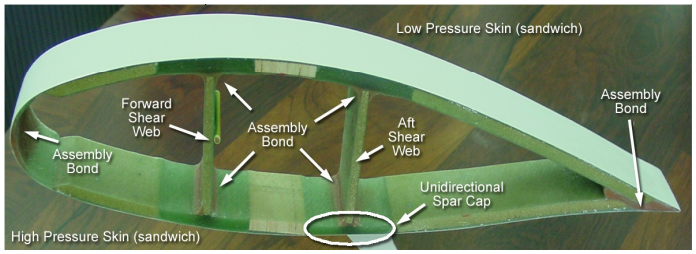
# Research Group

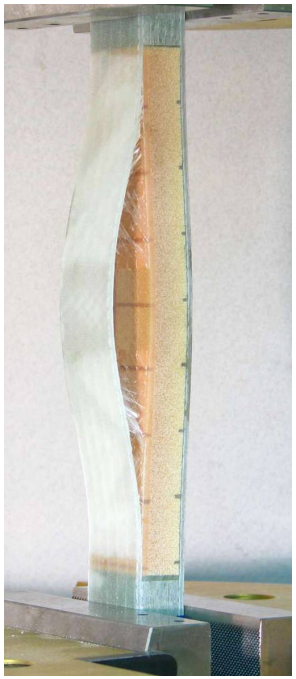
- PI: John Mandell; Current Group:
  - CoPI Research Engineer: Daniel Samborsky
    - Testing, Materials Fabrication
  - Post Doc: Aaron Sears
    - FEA, Adhesives
  - Grad Student: Tiok Agastra
    - Processing, Complex Structure Coupon Testing and FEA
  - Undergraduate Assistants: Patrick Flaherty and David Buswell
- Sandia PI's: Tom Ashwill, Josh Paquette

# Fatigue Topics

- Standard laminates representing spars, skins and webs
- Adhesive joints
- Core/sandwich areas
- Damage growth at flaws
- Ply delamination at details like ply drops and joints, and near adhesive joints
- Resins, fibers, fabrics, adhesives, cores
- Processing effects
- Environment
- Loading conditions/ spectrum loading



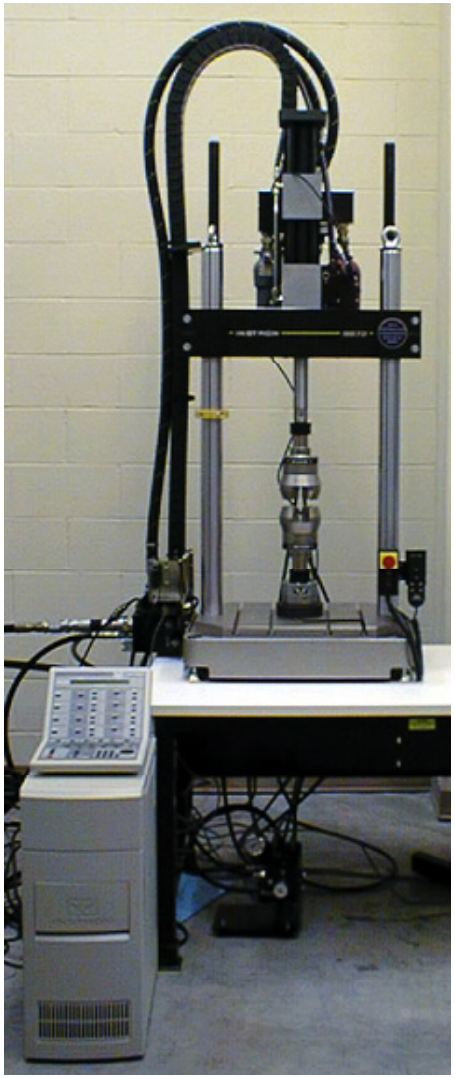



**Sandwich Panel**

# Public Database

- SNL/MSU/DOE Fatigue Database (SNL Website or MSU program website: www.coe.montana.edu /composites/)
  - Over 190 Materials
  - 11,500+ test results
  - Updates each March
  - Trends analyzed in publications and contractor reports on website; Draft of current contractor report



# More Details

**Contractor reports and publications on**

www.coe.montana.edu/composites/; additional information including resins, adhesives, fabrics, etc.

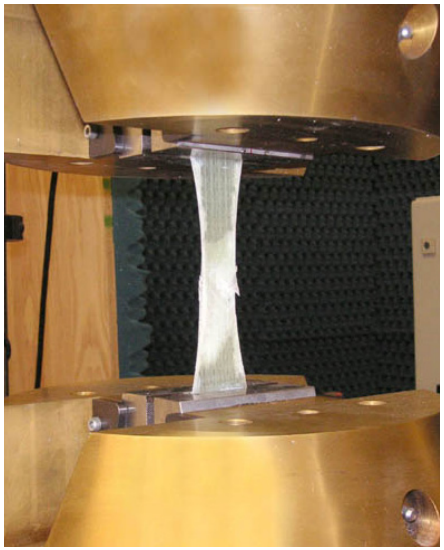
**Contact:** johnm@coe.montana.edu.

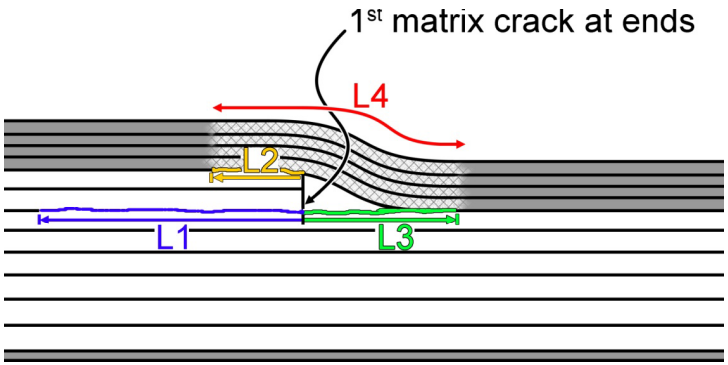
**Contractor Report and Recent Papers on Website:**

1. **2010 Sandia Contractor Report (Draft), Mandell, et al.**
2. 2010 Sandia Blade Workshop Presentation, Mandell.
3. Second International Blade Conference, 2010, Essen, Germany, Mandell and Samborsky, paper and presentation, program overview.
4. SAMPE 2010, Seattle, paper 398, Agastra and Mandell, Complex Structured Coupons.
5. AIAA SDM 2010, Orlando, paper AIAA-2010-2820, Samborsky, et al, Fatigue of Laminates.
6. AIAA SDM 2010, Orlando, paper AIAA-2010-2821, Sears, et al, Adhesives.
7. ACS 2010, Cocoa Beach, Selection of Blade Materials, Mandell, Presentation.

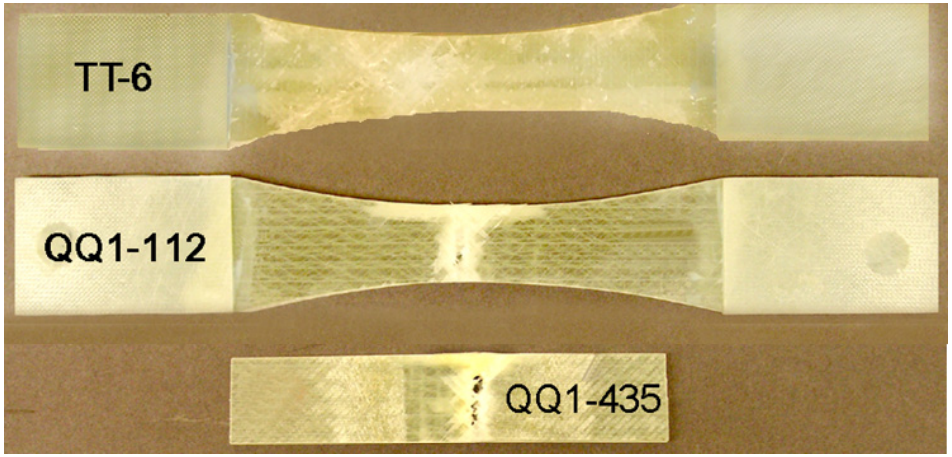
# Presentation Topics

- Summary of recent results:
  1. Standard laminate fatigue: fabric and resin effects.
  2. Ply delamination, complex structured coupons with ply drops (mini sub-structures).
  3. Blade adhesives.





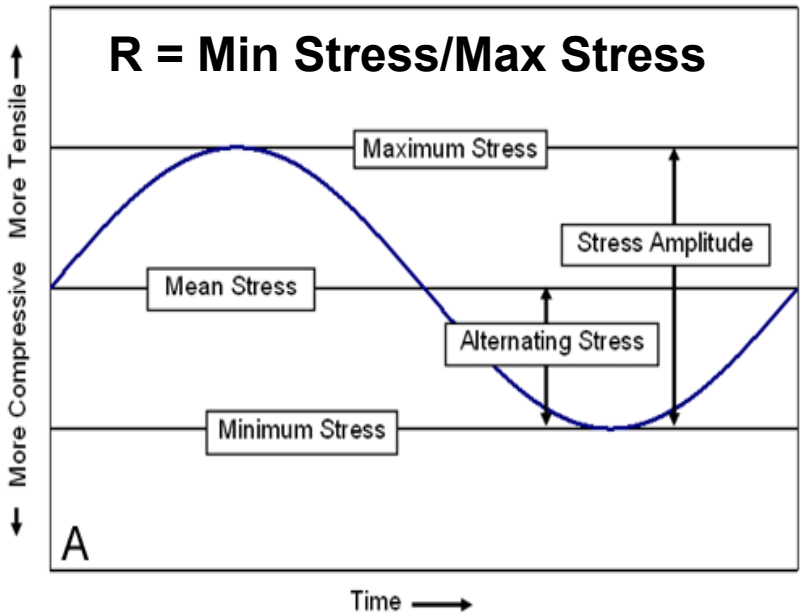
# Standard Laminate Fatigue

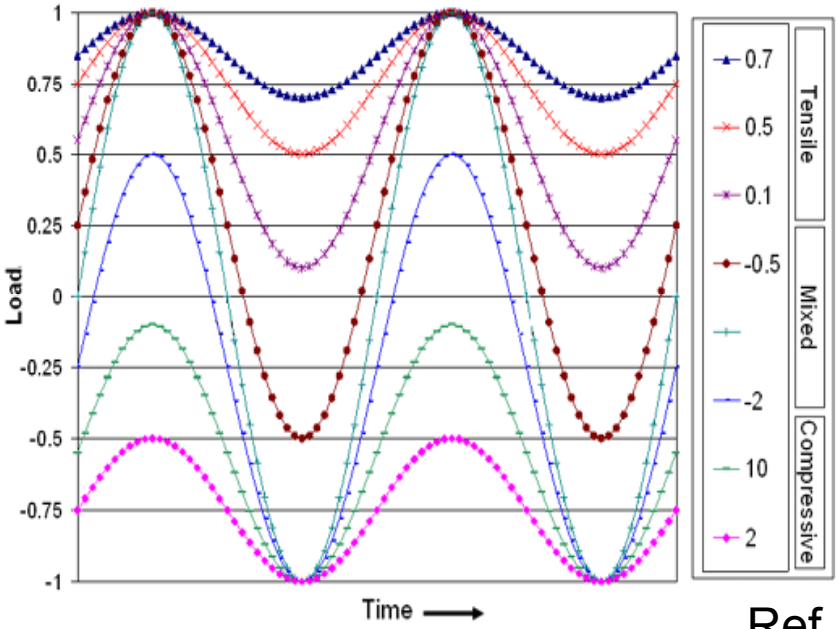



**Tensile Fatigue, R = 0.1:**

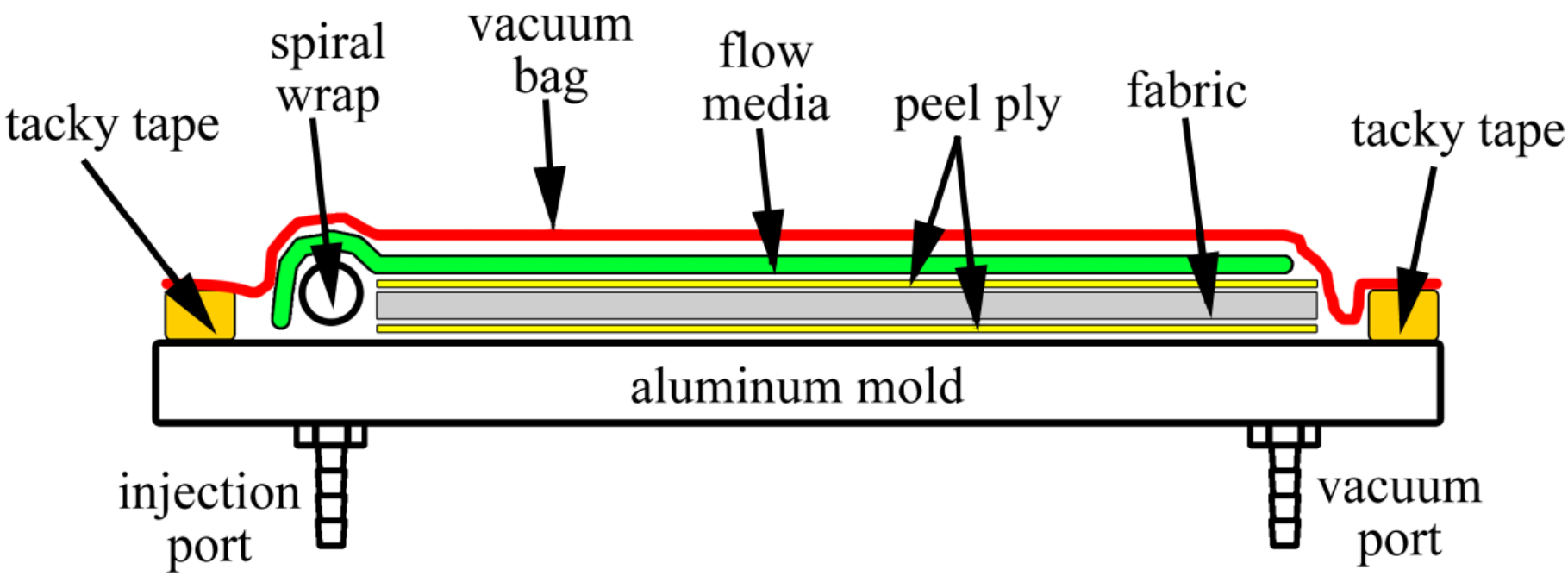
**1. Glass fiber laminates most sensitive to tensile part of fatigue cycles**

**2. "Clean" failure modes for materials comparisons**



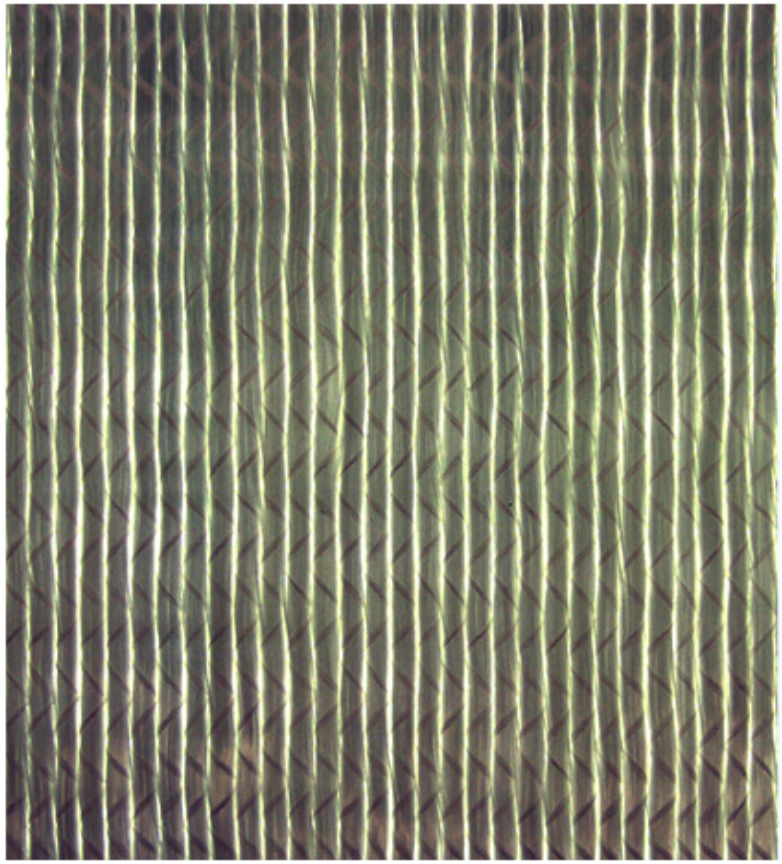

Ref. 1

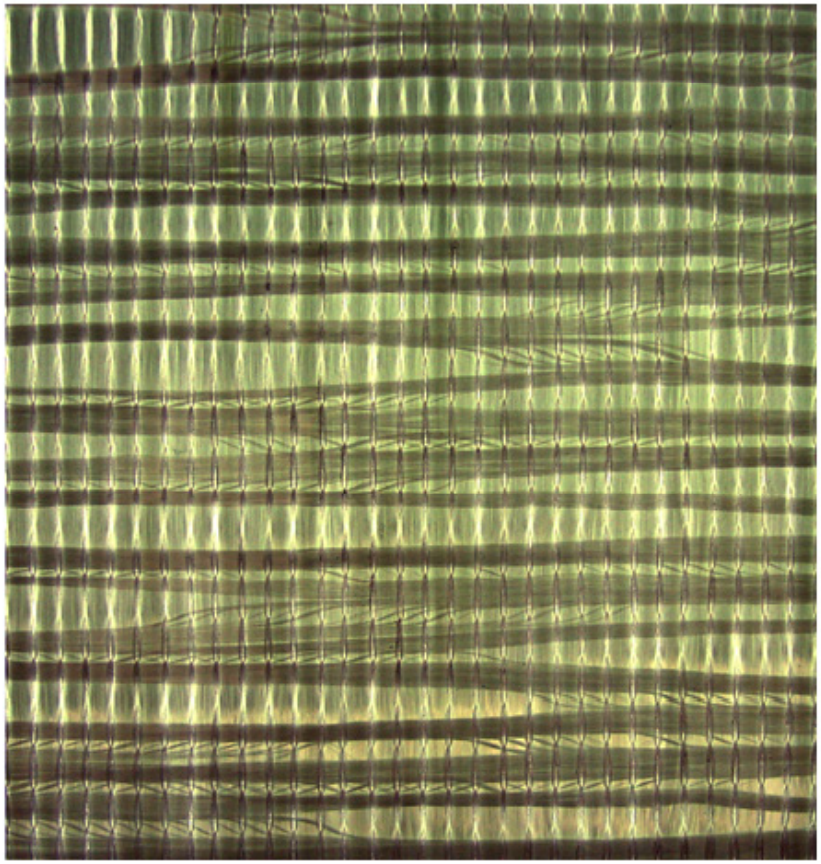



**MSU resin infusion process with hard mold on one side (panels also supplied by industry)**

Ref. 1

# Vectorply E-LT 5500 Fabric, Front and Back Views (MSU Fabric D, 1875 gsm)





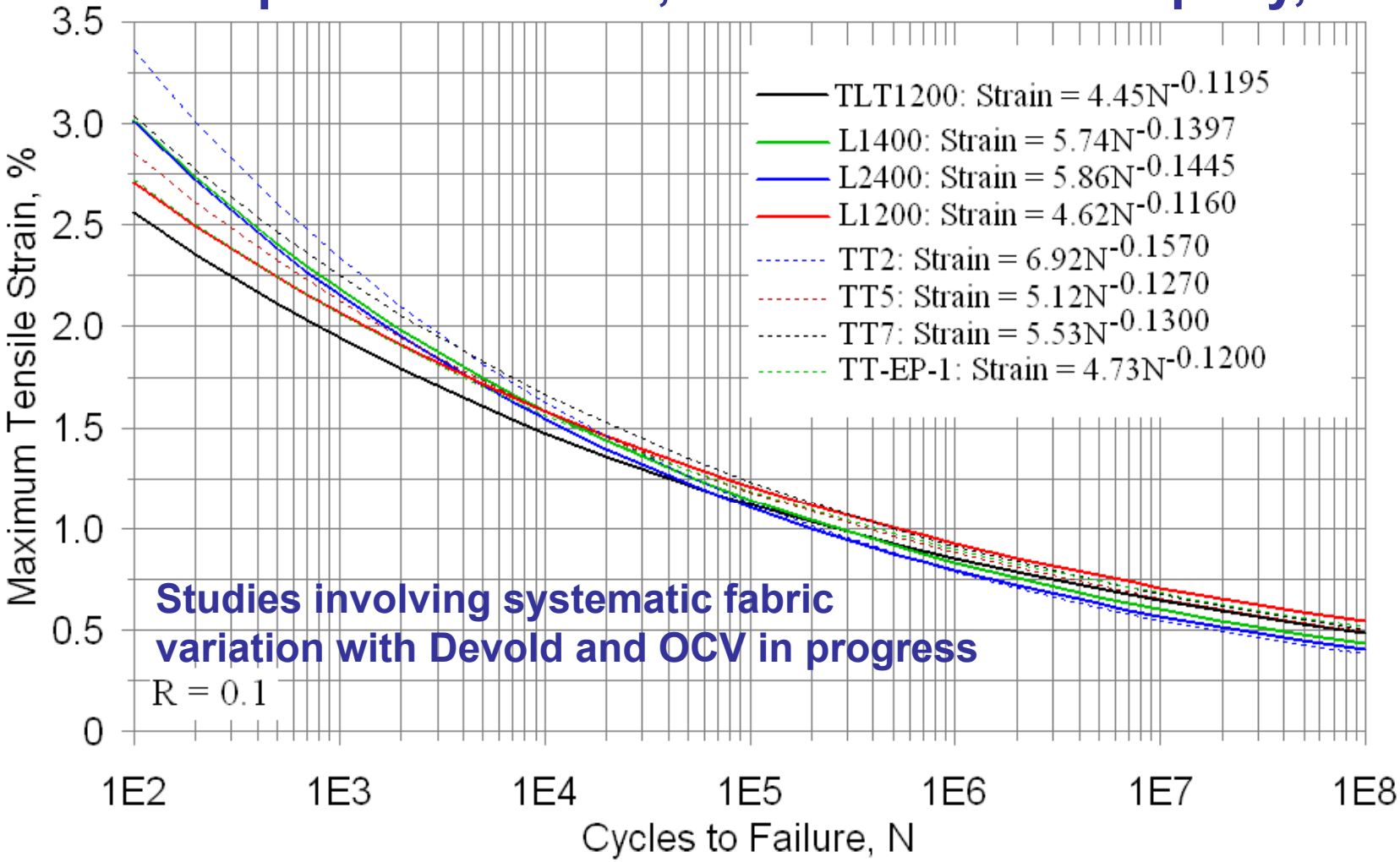
Ref. 5

# PPG-Devold L1200/G50-E07 (MSU Fabric H, 1261 gsm)

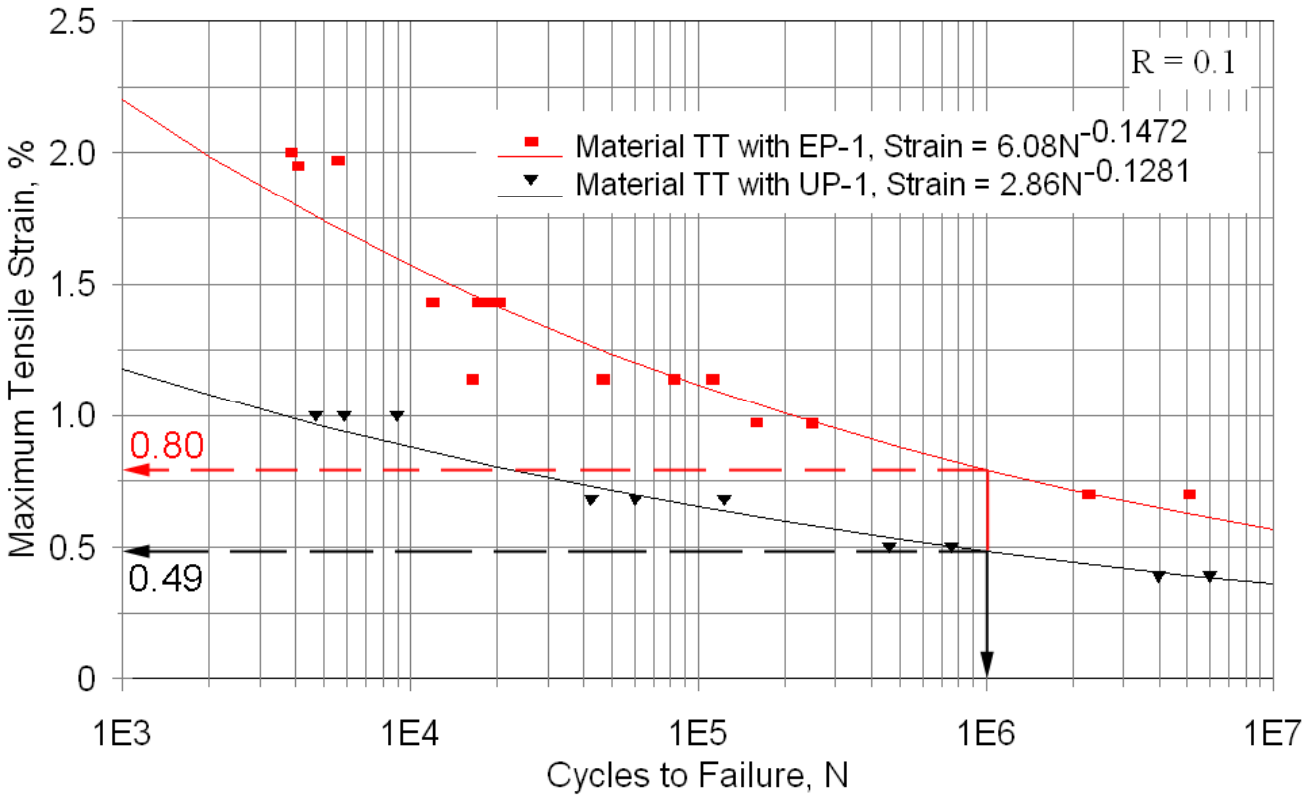
Front

Back

# Strain-cycles trends for eight MD laminates, UD fabrics 1200-2400 gsm, Hybon 2026 sized strands, filament diameters up to 23 microns, Hexion RIMR 135 epoxy, R = 0.1



# Data Representation



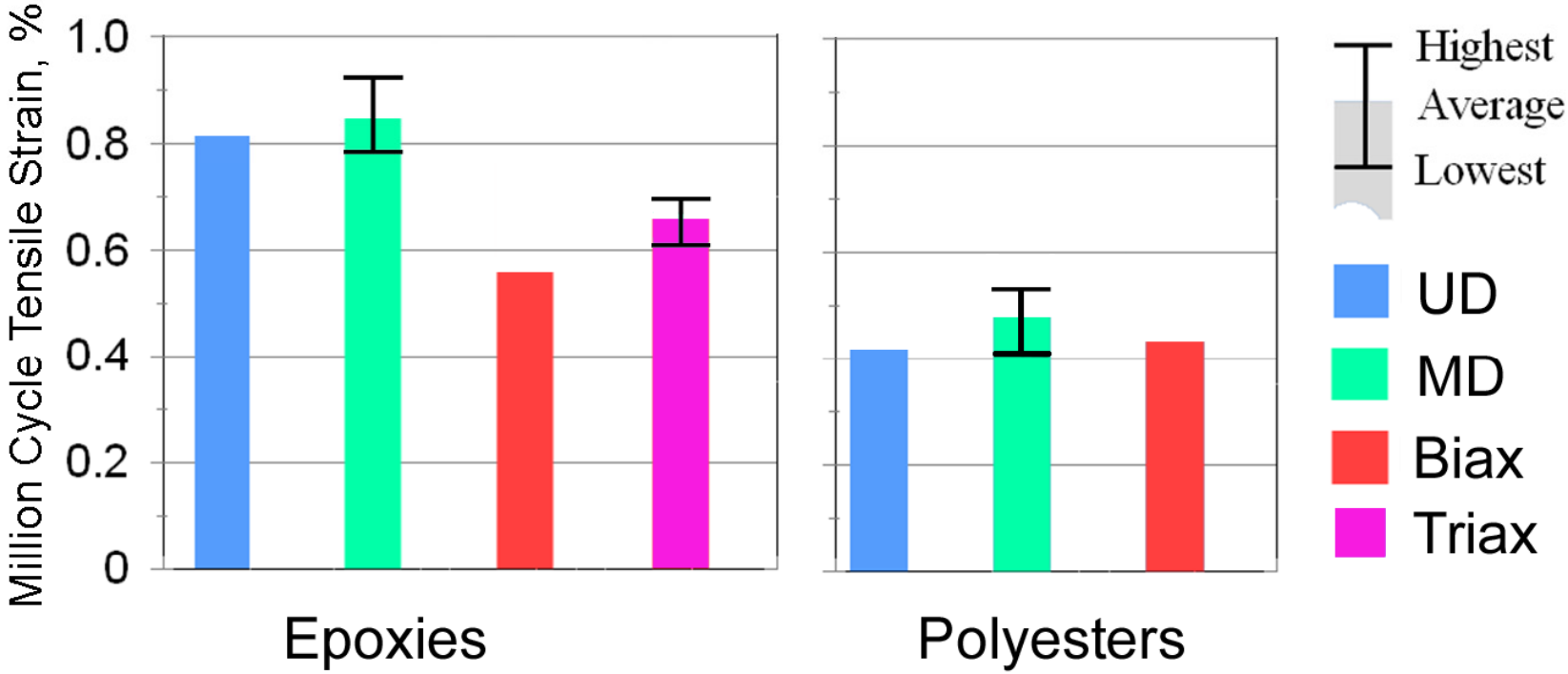

**Million Cycle Strain Parameter, Power Law Exponent, Linear-Log Plots, Polyester (UP) vs Epoxy (EP)**

Note: Strains shown on figures are **Initial Strains** from extensometer in the first few fatigue cycles

Multidirectional Laminates;
TT: Database Laminate Designation;
[±45/0/±45/0/±45]

Ref. 1, 5

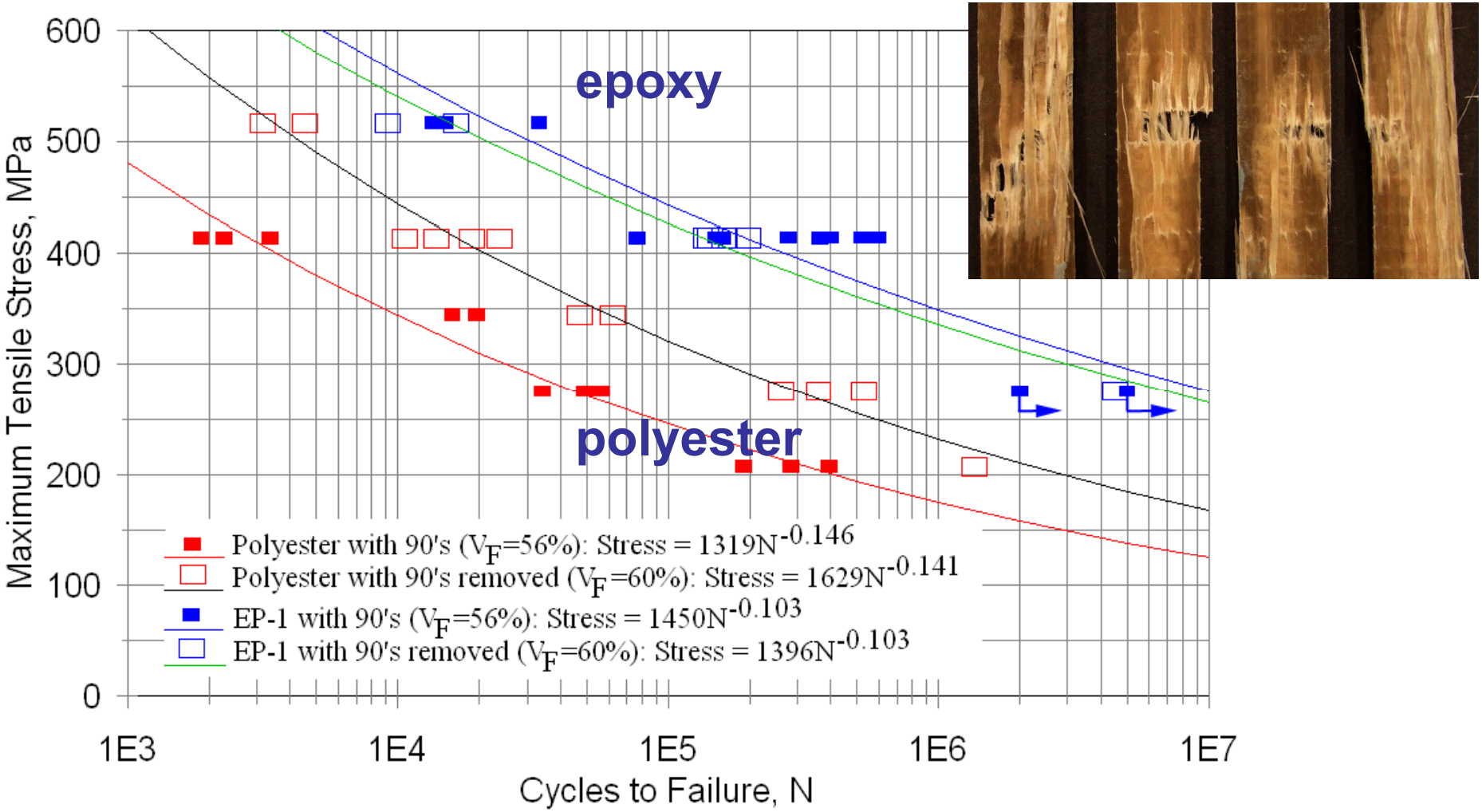
# Resin Comparison, Same Fabrics




**Vinyl esters: intermediate**
**pDCPD (Materia): similar to epoxy**

# UP and EP resins with and w/out 90-strands removed in gage section before infusion, UD laminates

## Significant effect only for UP resin laminates



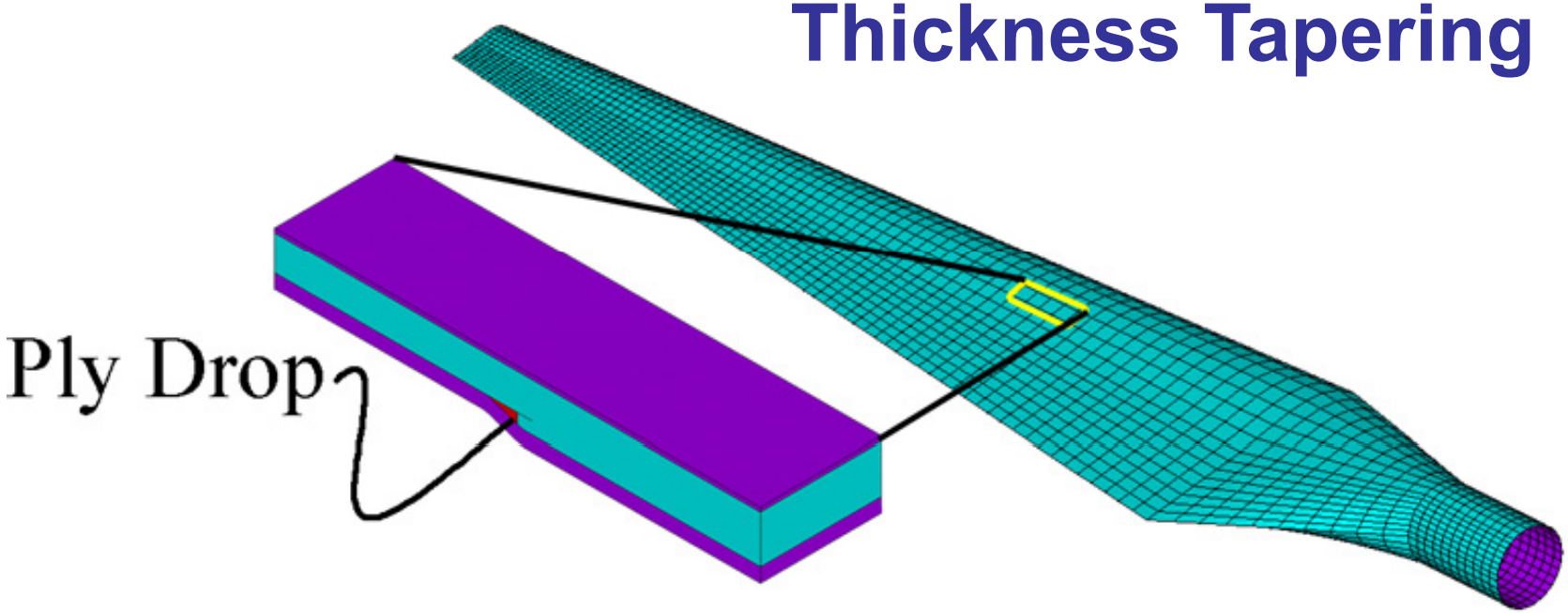
# Typical Infused Laminate Property Ratios Polyester (UP) to Epoxy (EP)*

| Property | Ratio UP/EP |
|---|---|
| Axial Tensile Modulus (UD) | 1.0 |
| Axial Tensile Modulus (MD) | 1.0 |
| Axial (UD) Static Tensile Strength | 0.90 |
| Axial (MD) Static Tensile Strength | 0.95 |
| Transverse (UD) Static Tensile Cracking Strain | 0.42 |
| Axial (UD) $10^6$ Cycle Strain (R = 0.1) | 0.51 |
| Axial (MD) $10^6$ Cycle Strain (R = 0.1) | 0.65 |
| Axial (MD) $10^6$ Cycle Stress (R = 0.1) | 0.61 |
| Axial (Biax) $10^6$ Cycle strain (R = 0.1) | 0.91 |
| Interlaminar $G_{Ic}$ (0-0 interface) | 0.55 |
| Interlaminar $G_{IIc}$ (0-0 interface) | 0.48 |
| Complex Coupon Ply Drop Delamination, Threshold Fatigue Strain (R = -1) | 0.74 |

*$V_f$ = 0.5 to 0.6, UD Fabrics D and H, Biax Fabrics M and P

# Complex Coupons With Ply Drops

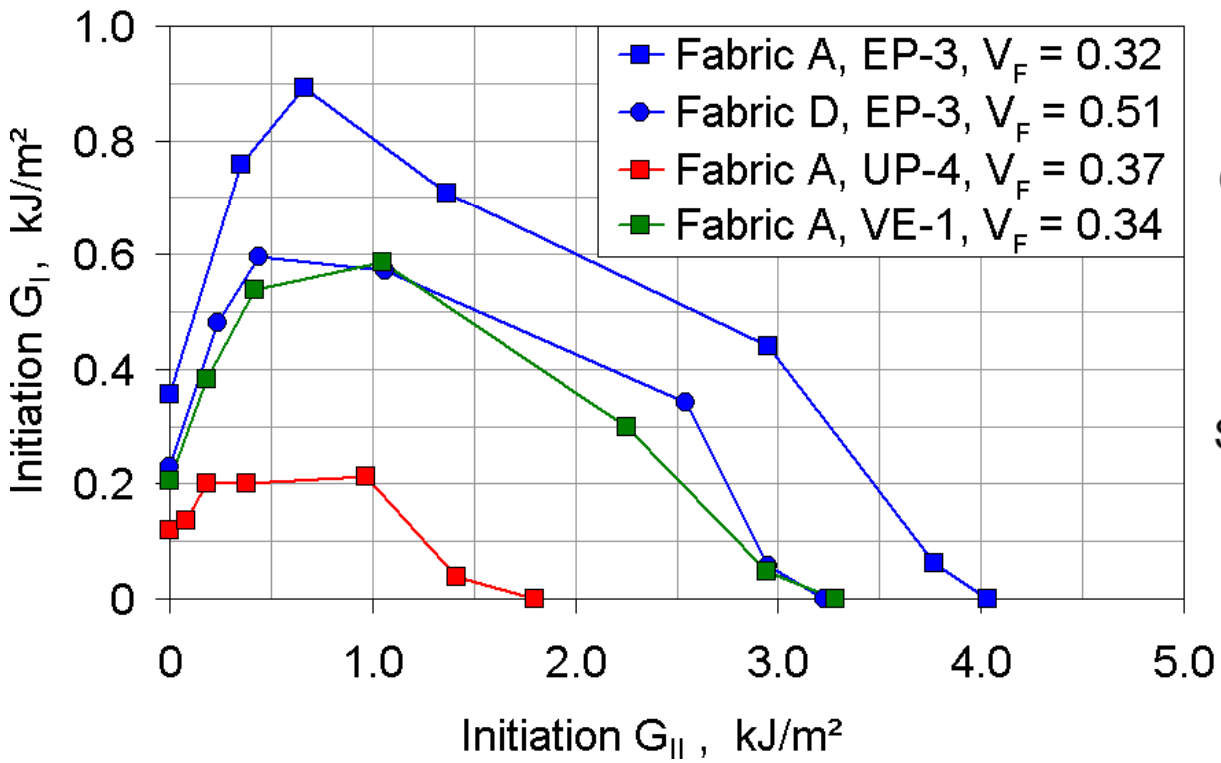
## Thickness Tapering

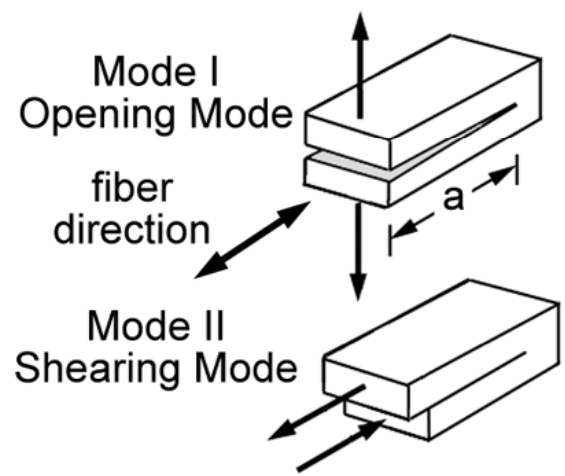



Ref. 4

# Delamination Testing

## Mixed Mode Delamination Testing, Different Resins




Ref. 1, 5

# Complex Structured Coupons with Ply Drops, Resin Infusion

**Purpose:** Mini-substructure test. Simplified, less costly approach to substructure testing. Efficient comparisons of resins, fabrics, geometric details in structural context.

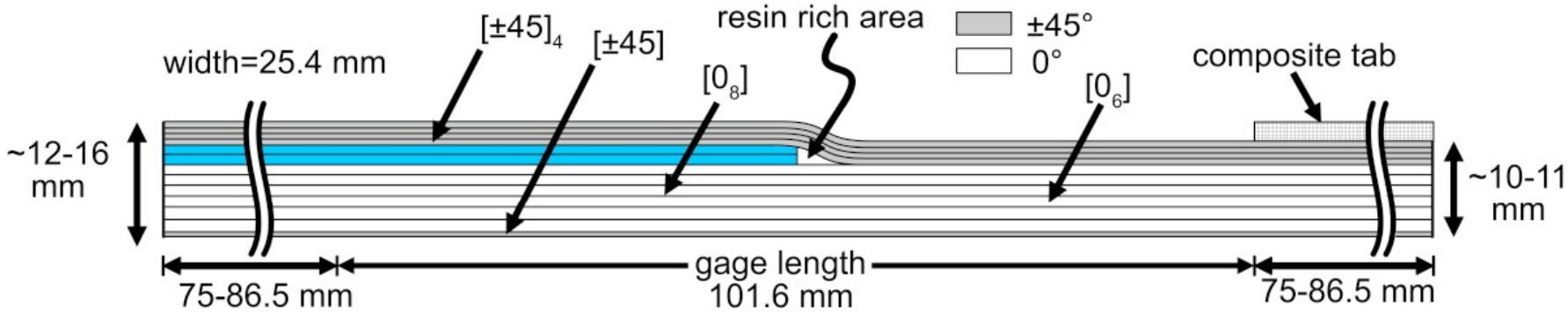
.

coupons represent more realistic internal (infused) blade structural detail areas than standard laminate tests

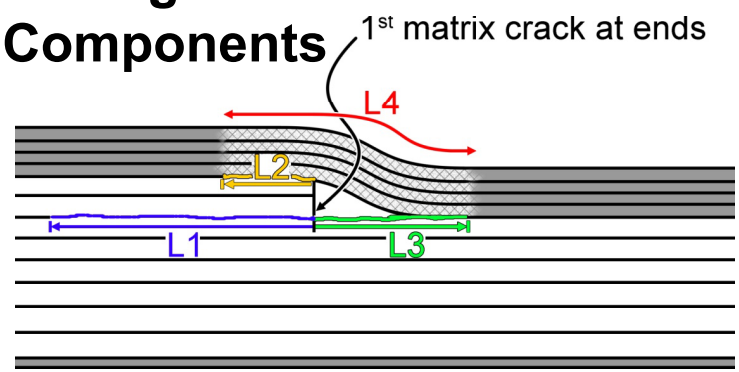
Ref. 1, 4

# Complex Structured Coupon with Ply Drops

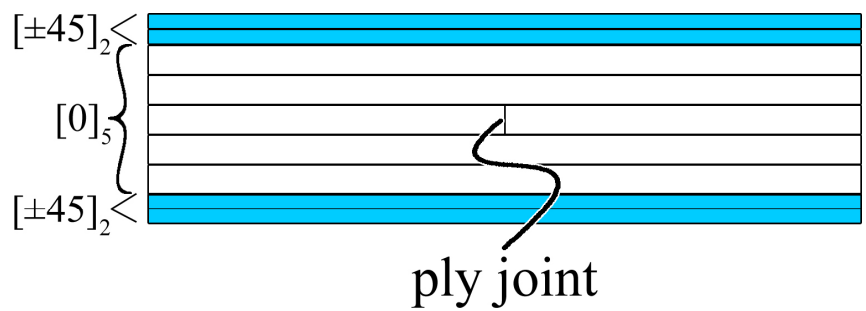
**(See 2009 SDM, AIAA-2009-2411; and 2010 SAMPE paper 398)**



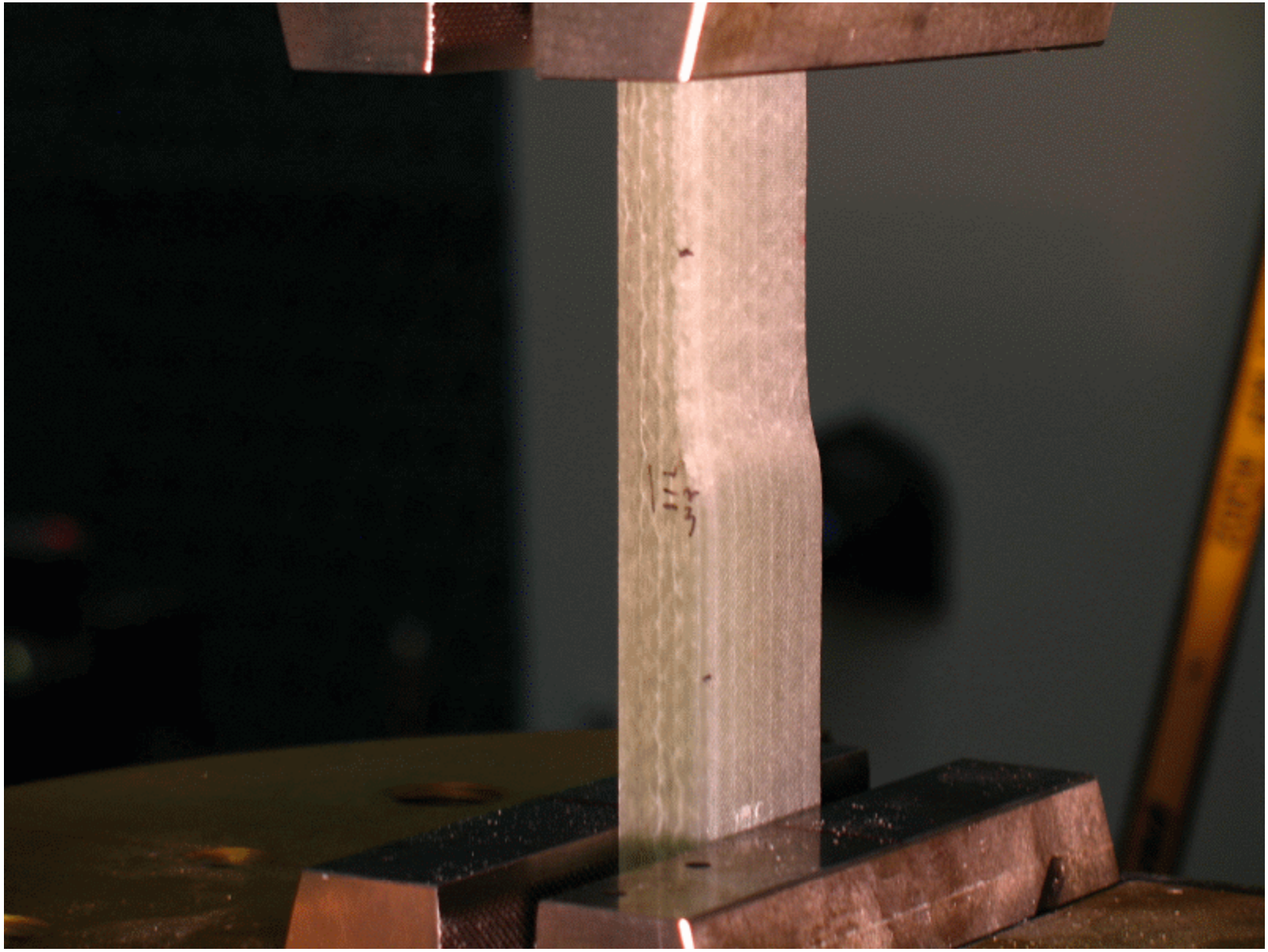

## Damage Components



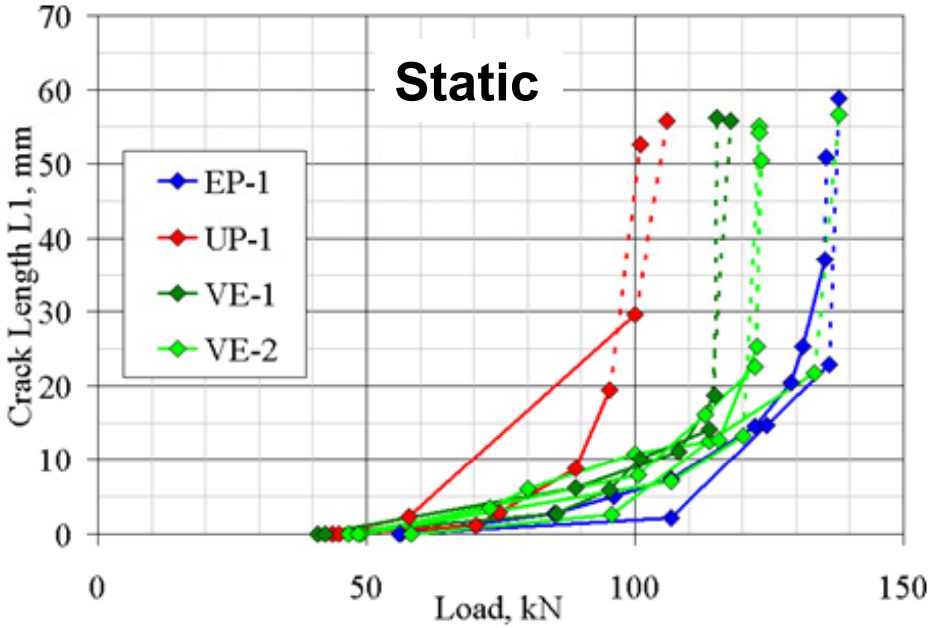

## Alternate Geometries

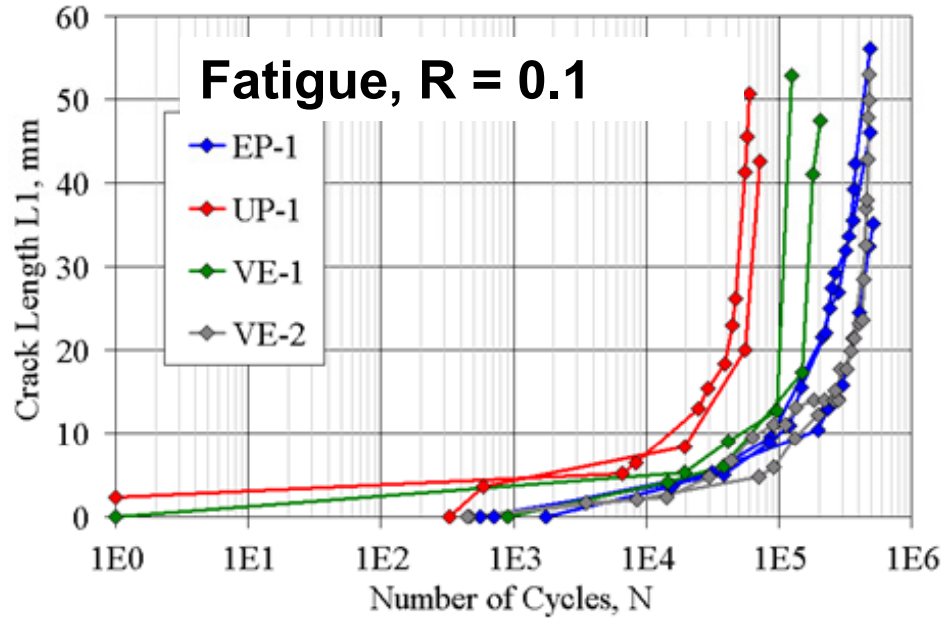


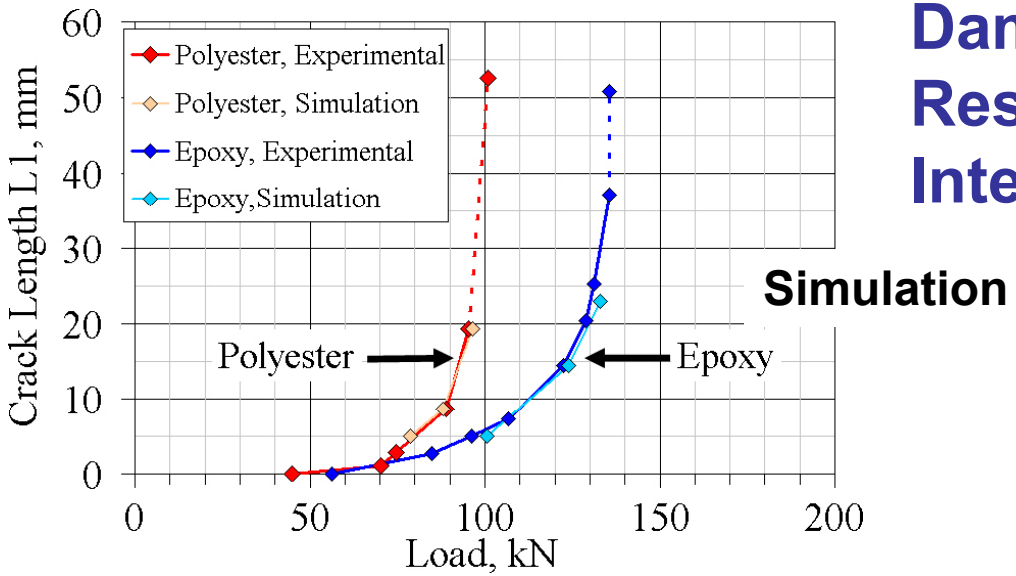

Ref. 1, 4



# Damage Growth Curves



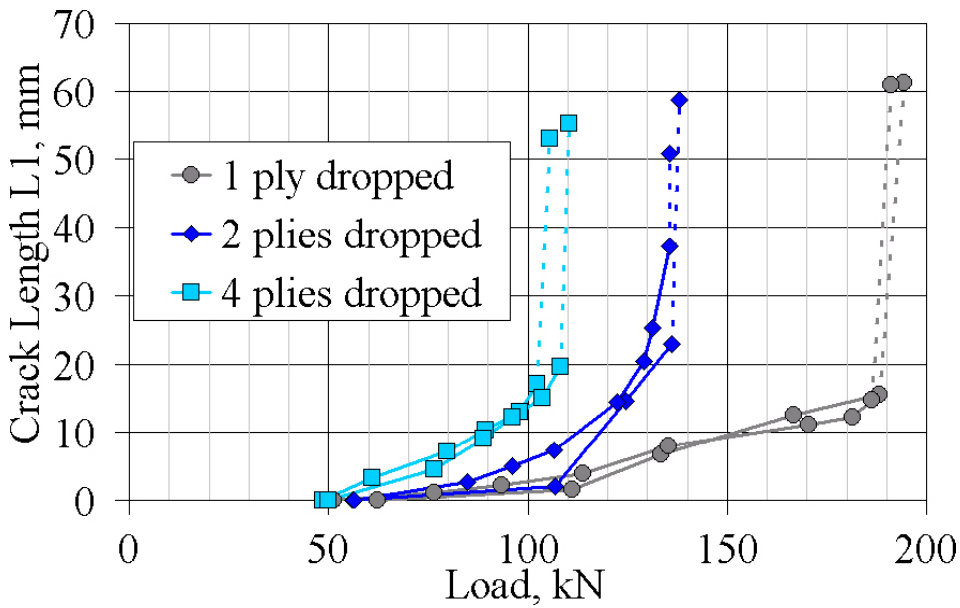



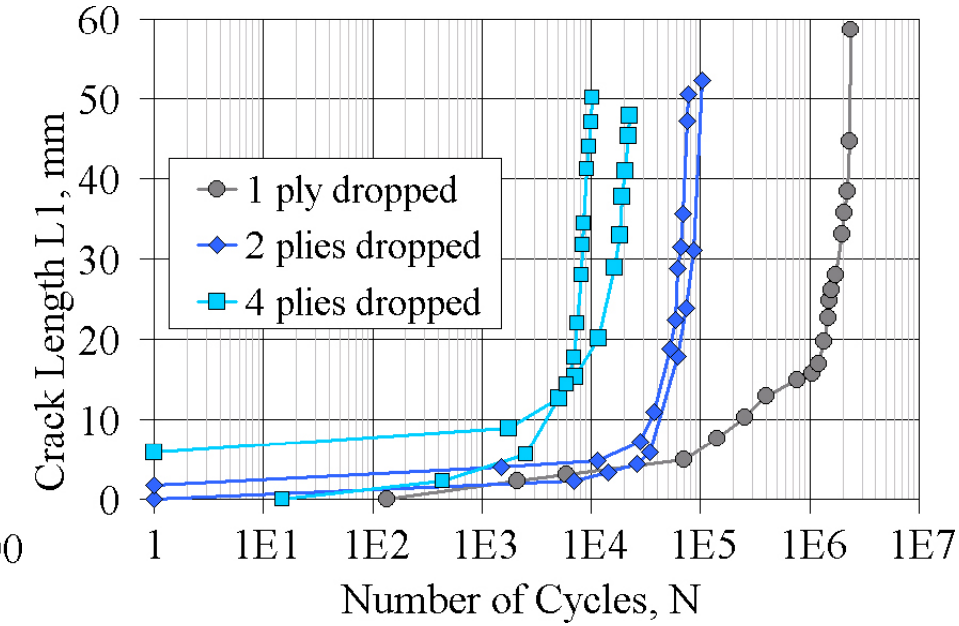

## Damage Growth with Different Resins Correlates with Interlaminar $G_{Ic}$, $G_{IIc}$

Ref. 4

# Effect of Number of Plies Dropped




Static




Fatigue

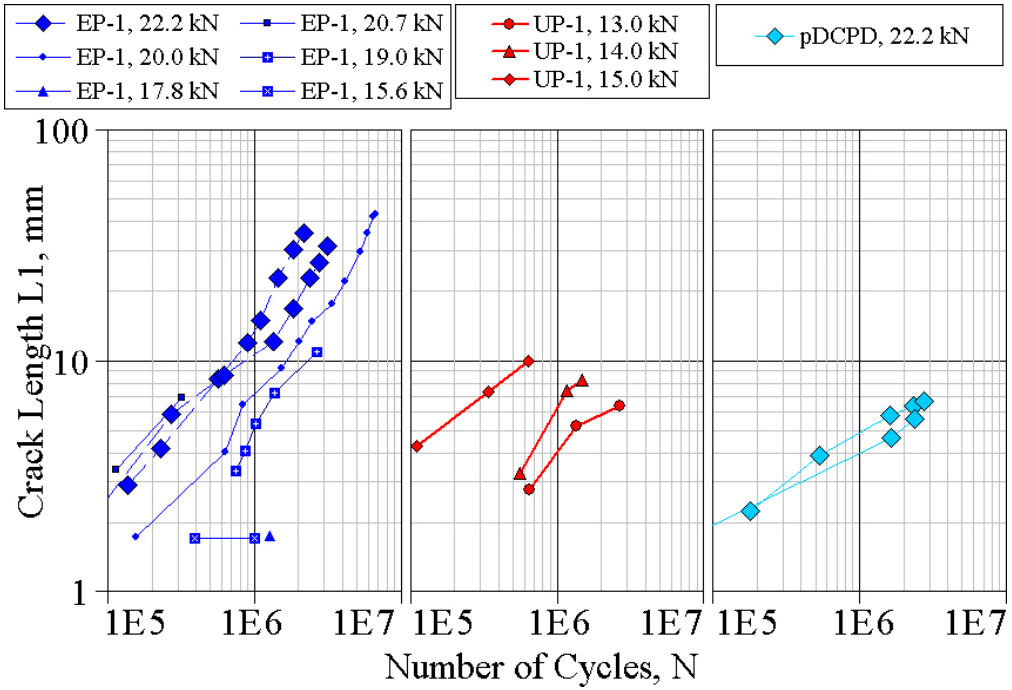
($R=0.1$, $P_{max}=55.6$ kN)

- 1 PD = 1.3 mm
- 2 PD = 2.6 mm
- 4 PD = 5.2 mm

Ref. 1, 4

# THRESHOLDS

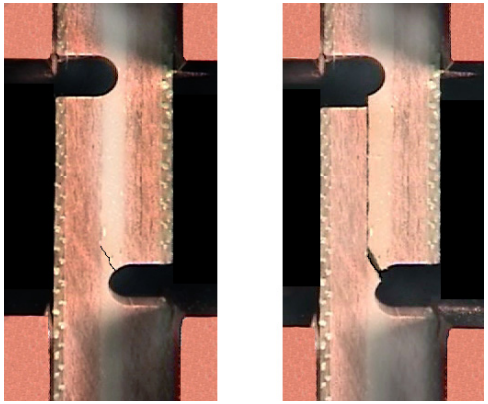
**Near-threshold damage growth results for three resins: epoxy (EP-1), polyester (UP-1) and pDCPD; R = -1.**




**Near threshold results (5-mm delamination length L1 in $10^6$ cycles), R = -1, two plies dropped at one position.**

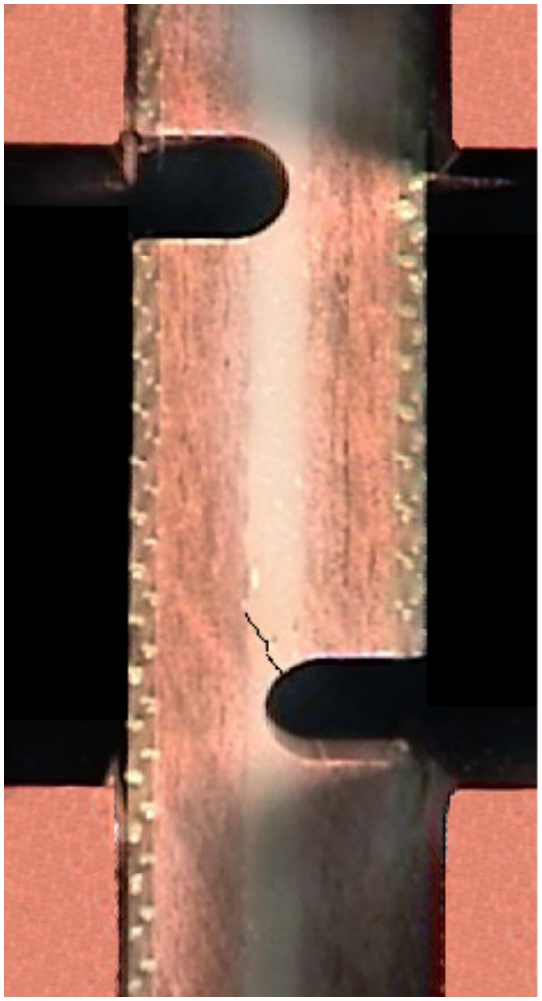
| Resin | Max. Force, kN, and thin side average strain (%) | Force Change From Epoxy | Observed Damage |
|---|---|---|---|
| Epoxy EP-1 | 19 (0.18%) | ___ | L1, L2, crack at ply ends |
| Polyester UP-1 | 14 (0.13%) | -26% | L1, L2, biax cracking, crack at ply ends |
| pDCPD | 22 (0.21 %) | +16% | L1, crack at ply ends |

# Blade Adhesives



- Initial Test Parameters
  - Characterize Nominally Good Quality Joints (Most Contain Significant Porosity)
  - Range of Uniaxial Loading Conditions (R-values)
  - Range of Crack Mode Mixity ($G_I/G_{II}$)
  - Failure Modes; Crack initiation and Growth Location
  - Strength-lifetime or Fracture Mechanics-da/dN

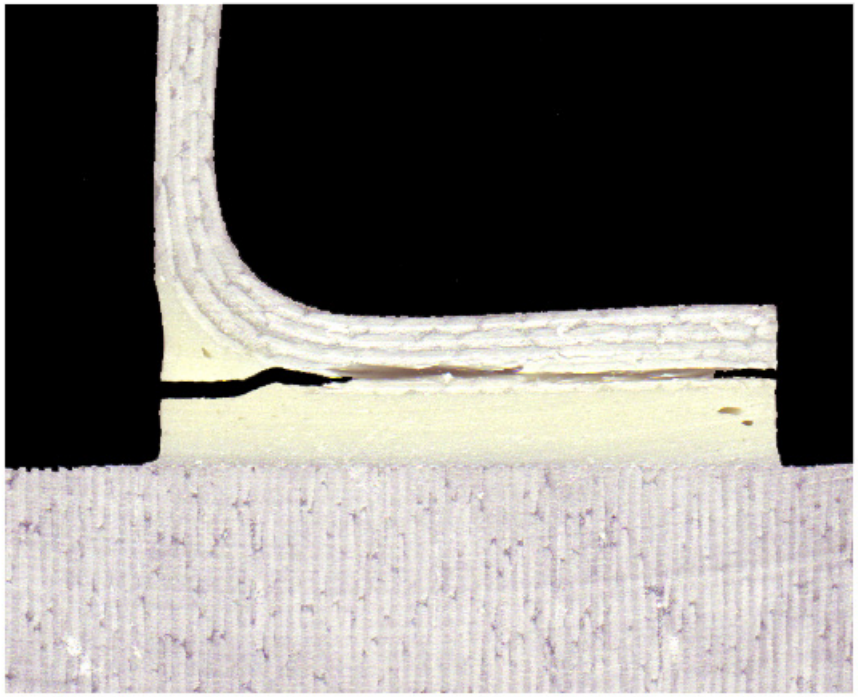
# Strength-Lifetime Lap Shear Test

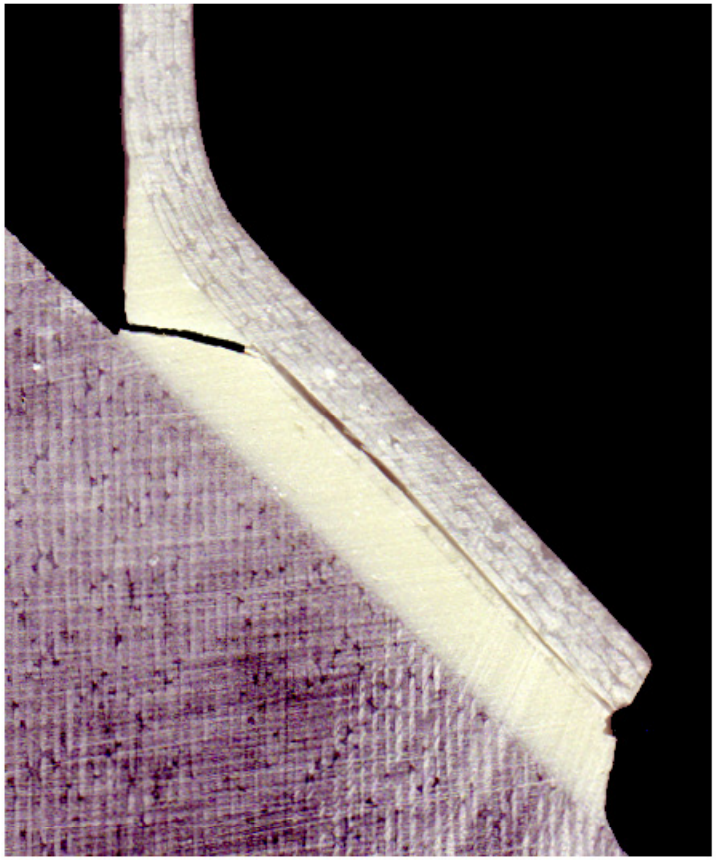


**Adhesive ADH-1, 3004 Cycles (left), 3006 Cycles (right)**
**(Non-symmetrical Specimen Clamped in Hydraulic Grips)**

Ref. 1, 6

## Simulated blade joint study, see AIAA paper AIAA-2009-1510





Joint strength statistics and critical flaws; failure modes; geometry
Fatigue exponents
Porosity modeling

Ref. 1, 6

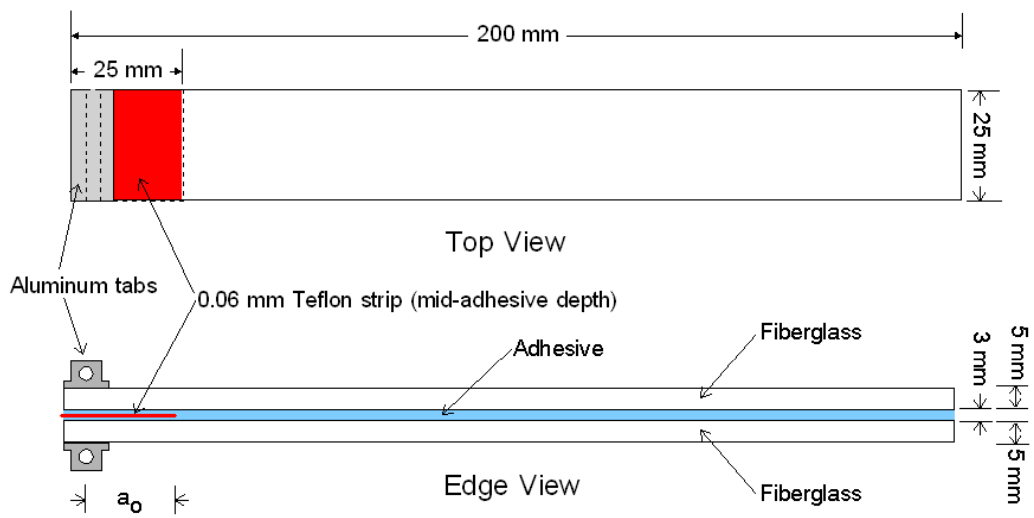
# Fracture Mechanics Based Tests

- Mode I, Double Cantilever Beam (DCB) Test
- Mode II, ENF Test
- Mixed Mode I and II Cracked Lap Shear (CLS) Test

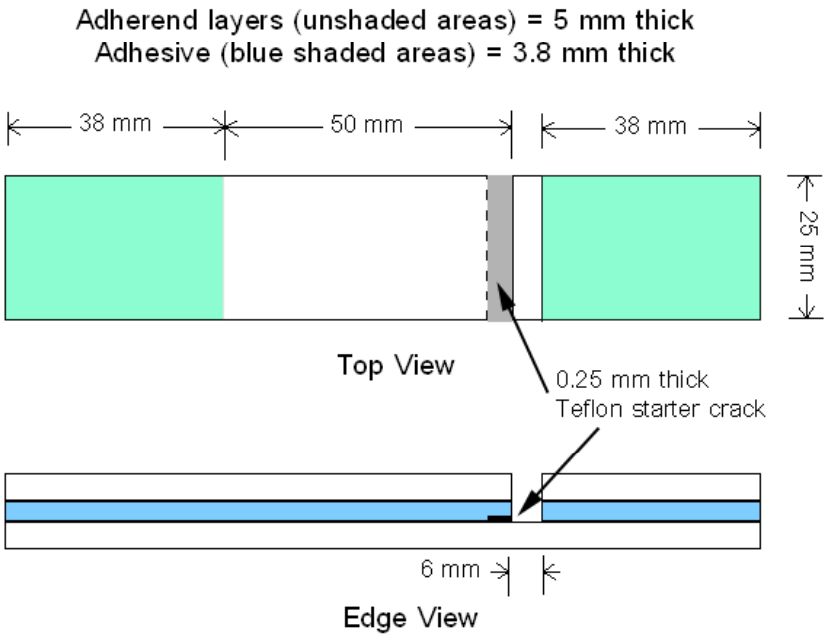
# Adhesives and $G_{Ic}$ from DCB Test

| Designation | Adhesive | Cure temp (°C) | $G_{Ic}$, J/m$^2$ |
|---|---|---|---|
| ADH-1 | Hexion EP135G3/EKH1376 | 70 | 581 |
| ADH-5 | Rhino 405 | 70 | 938 |
| ADH-6 | 3M W1100 | 70 | 1626 |

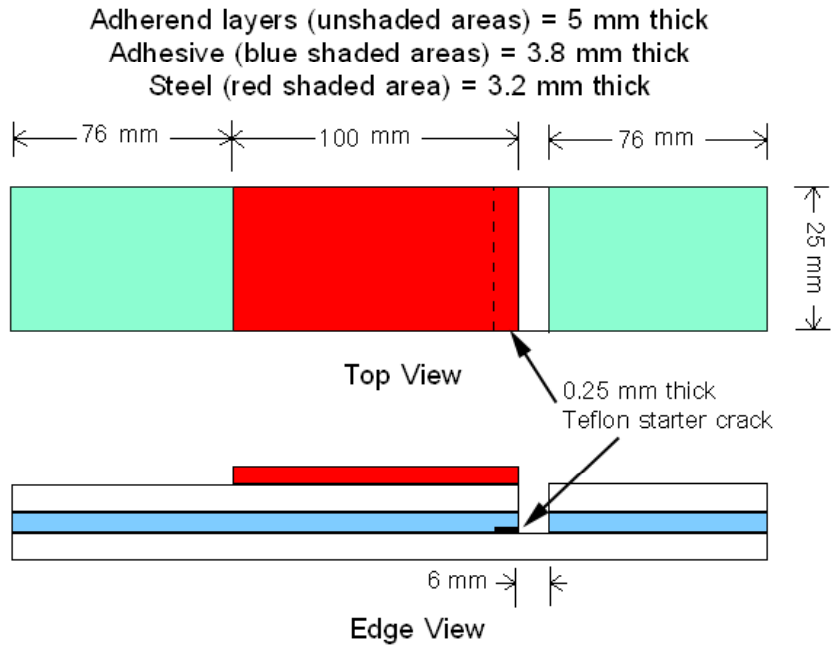
## DCB Test



# CLS Adhesive Fracture Specimens

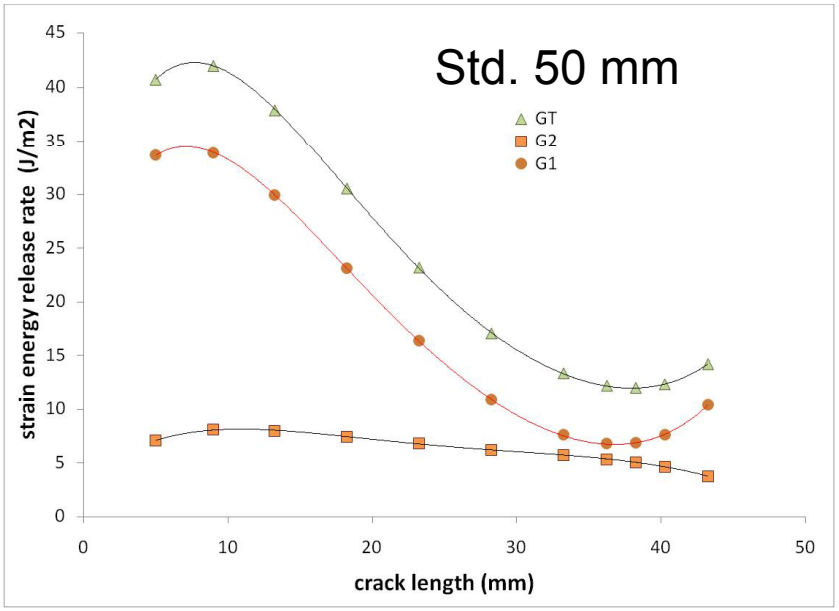


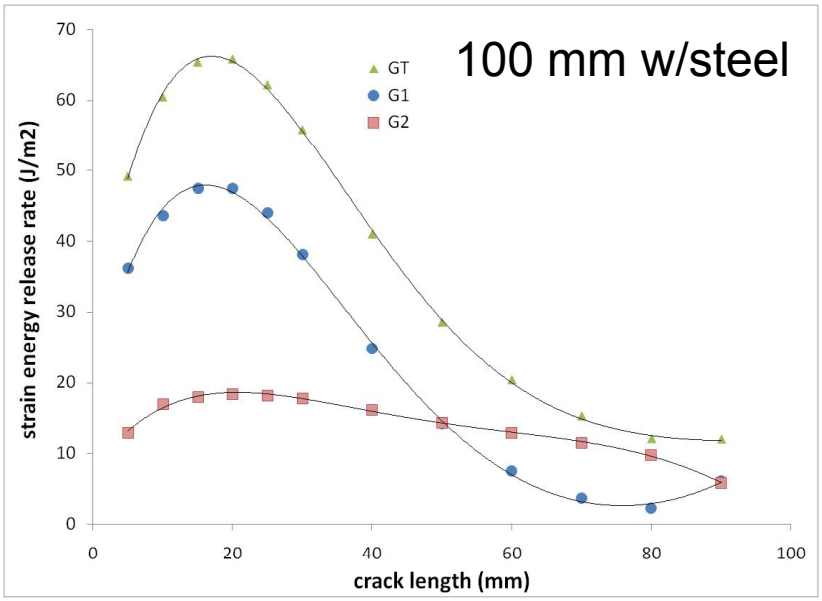

Standard Coupon

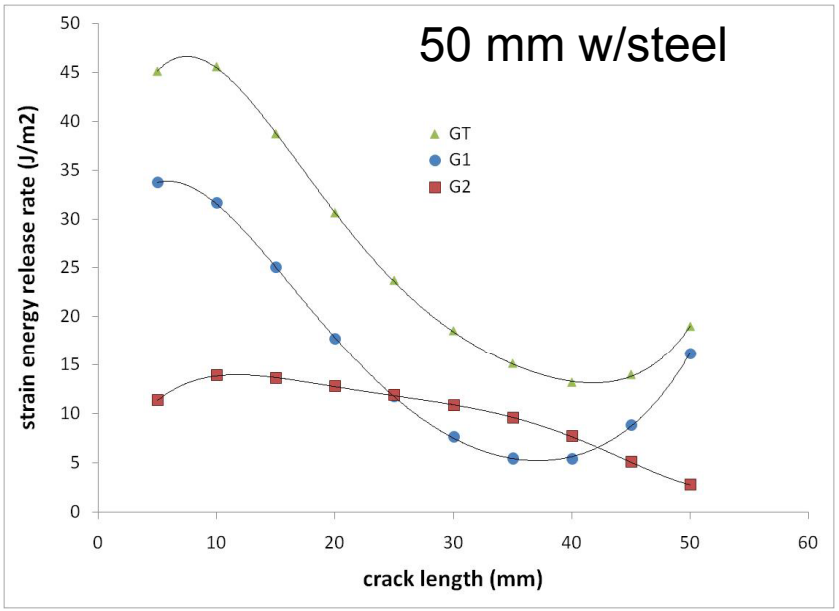



Coupon with Steel Reinforcement

Ref. 6



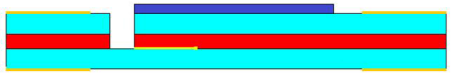



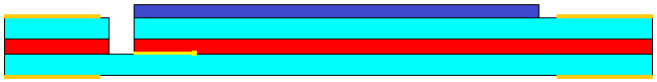

## G-Calibrations of CLS Specimens at 4.45 kN Tension Load

Std. 50 mm

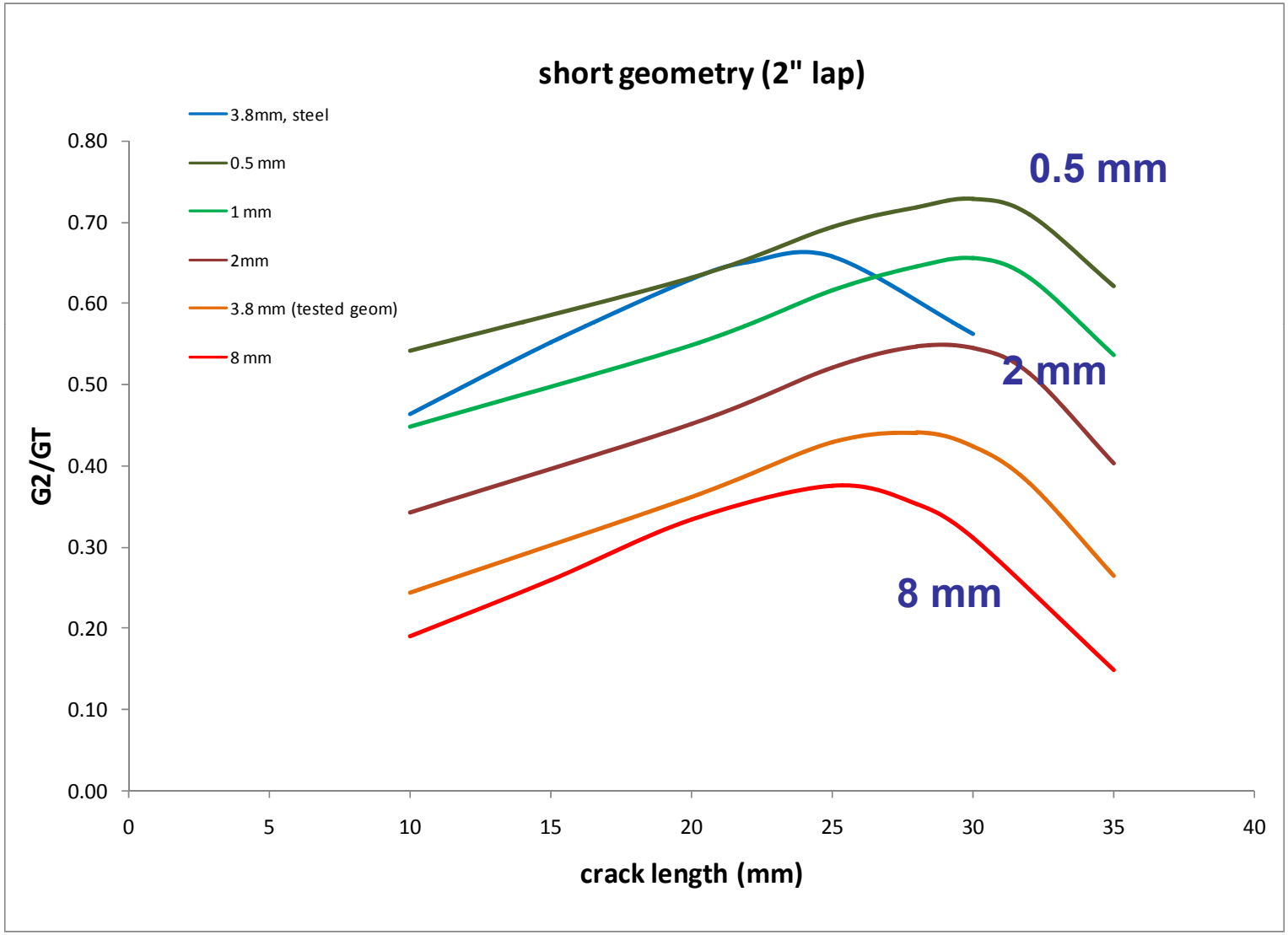
50 mm w/steel



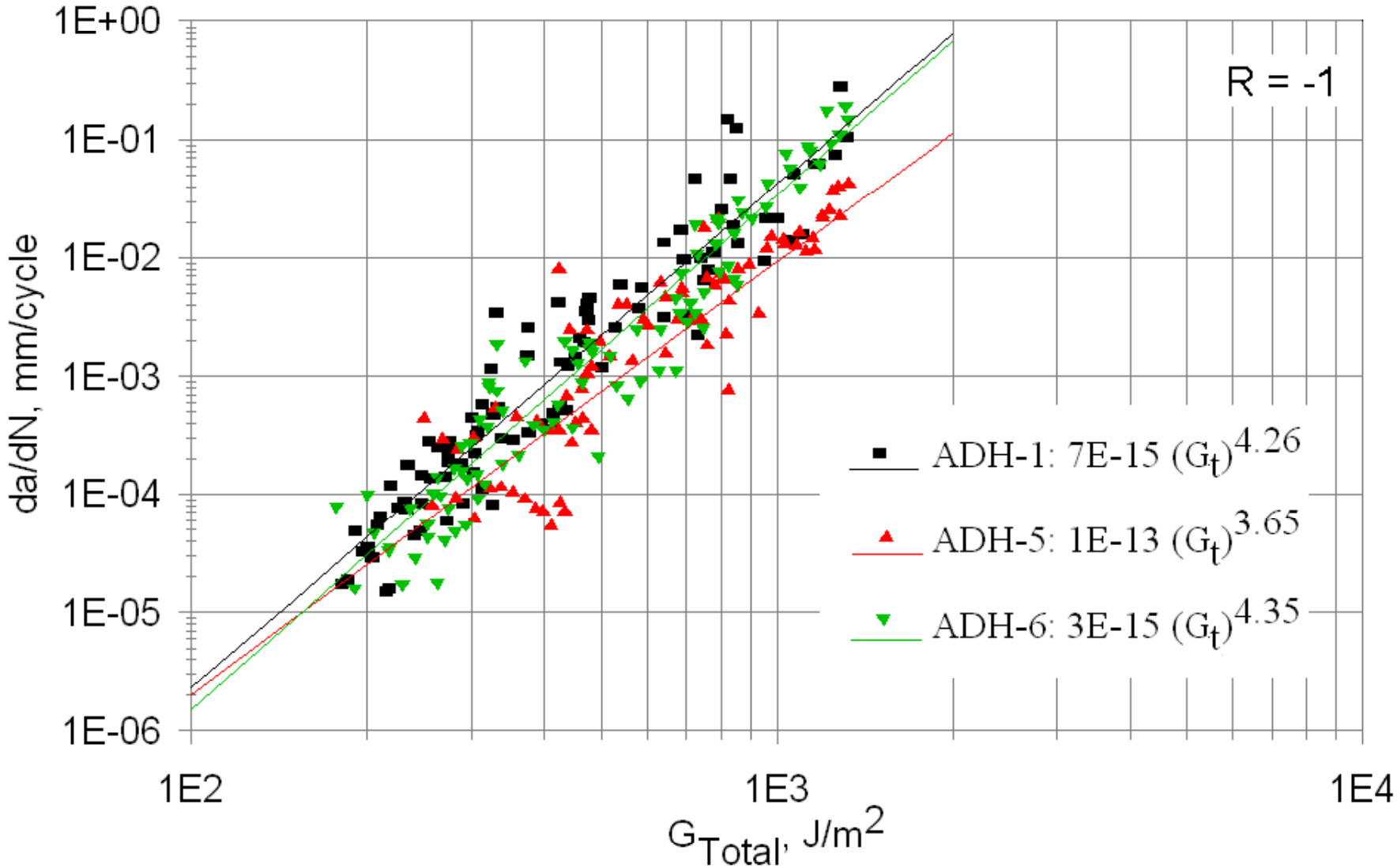
100 mm w/steel



# Adhesive Thickness Effect on Mode Mixity

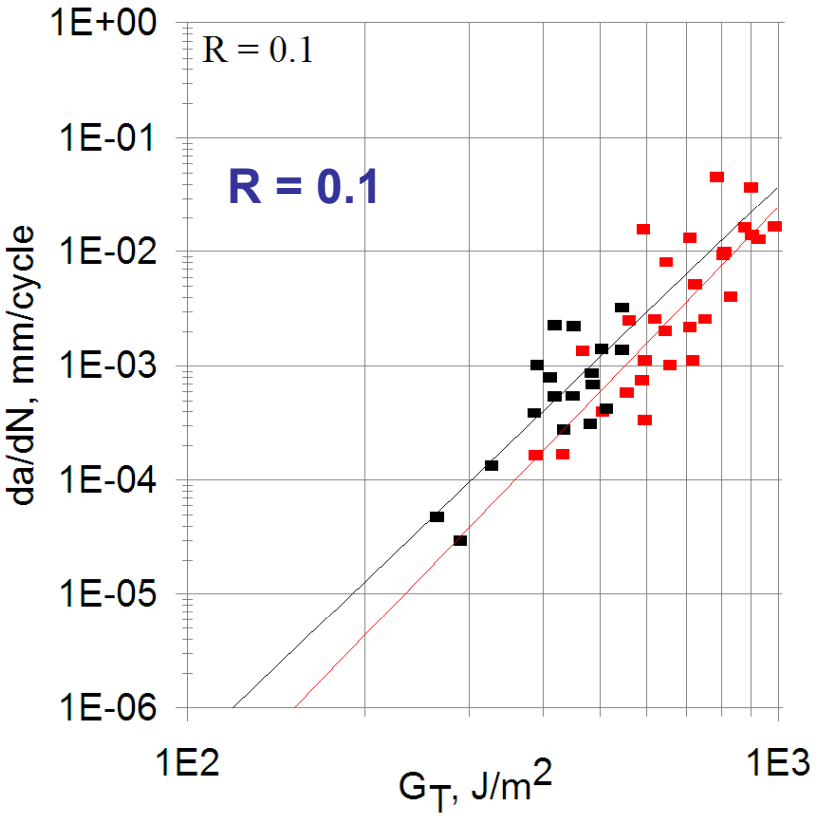


# Maximum $G_T$ (tension half of cycle) vs da/dN, R = -1



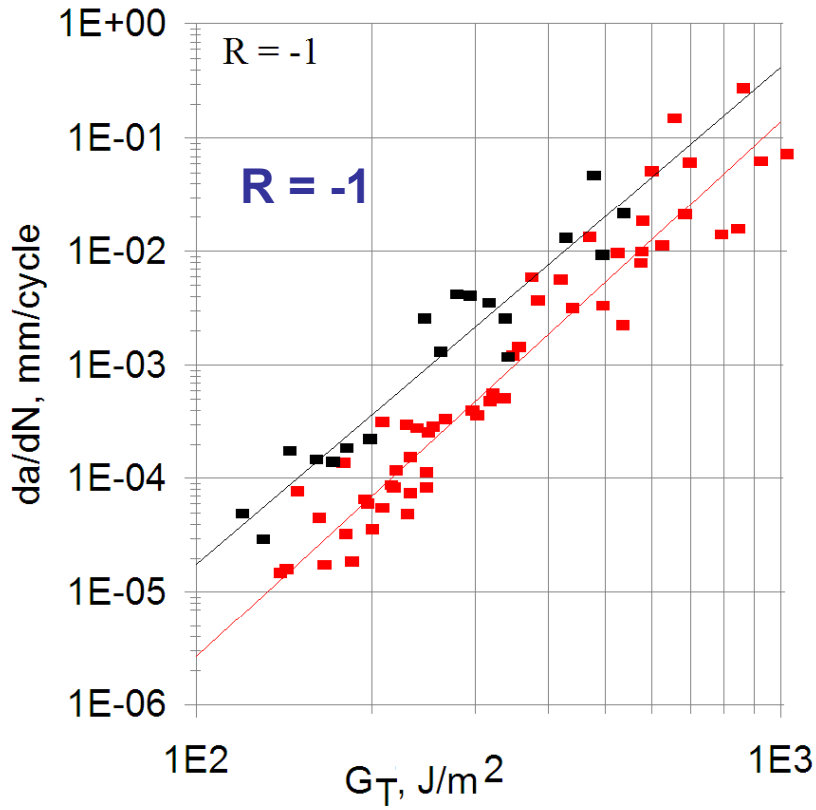

Ref. 6

# ADH-1 Adhesive, R = 0.1 and -1, separated by Mode Mixity Range (reversed loading 10X higher crack velocity)



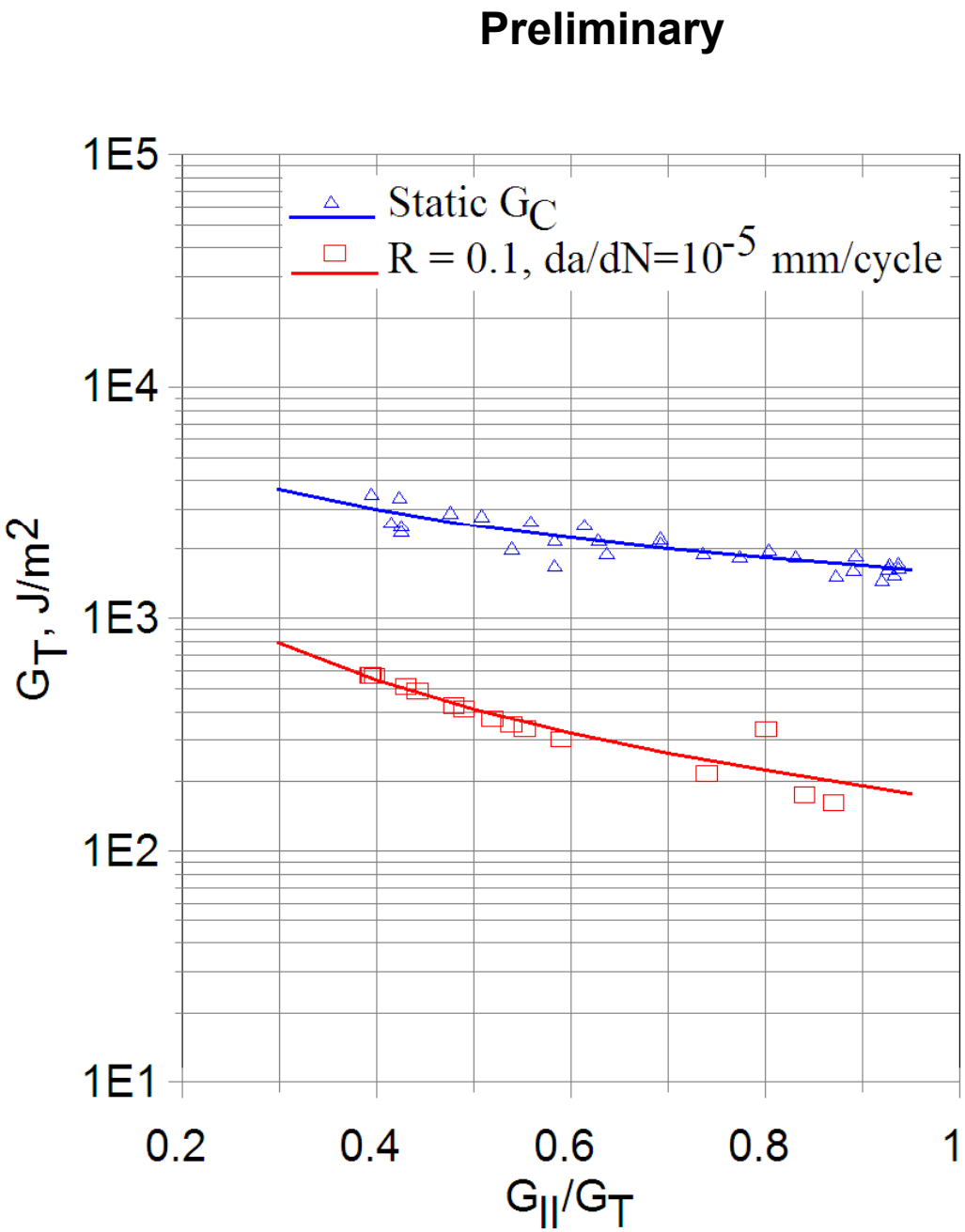

$G_{II}/G_T$ = 0.2 - 0.3 $da/dN = 2E^{-18} (G_T)^{5.36}$

$G_{II}/G_T$ = 0.3 - 0.4 $da/dN = 5E^{-17} (G_T)^{4.96}$



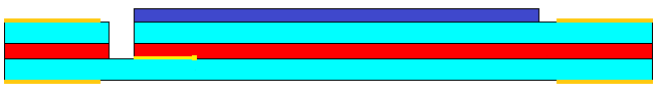

$G_{II}/G_T$ = 0.2 - 0.3, $da/dN = 1E^{-15} (G_T)^{4.72}$

$G_{II}/G_T$ = 0.3 - 0.4, $da/dN = 3E^{-15} (G_T)^{4.38}$



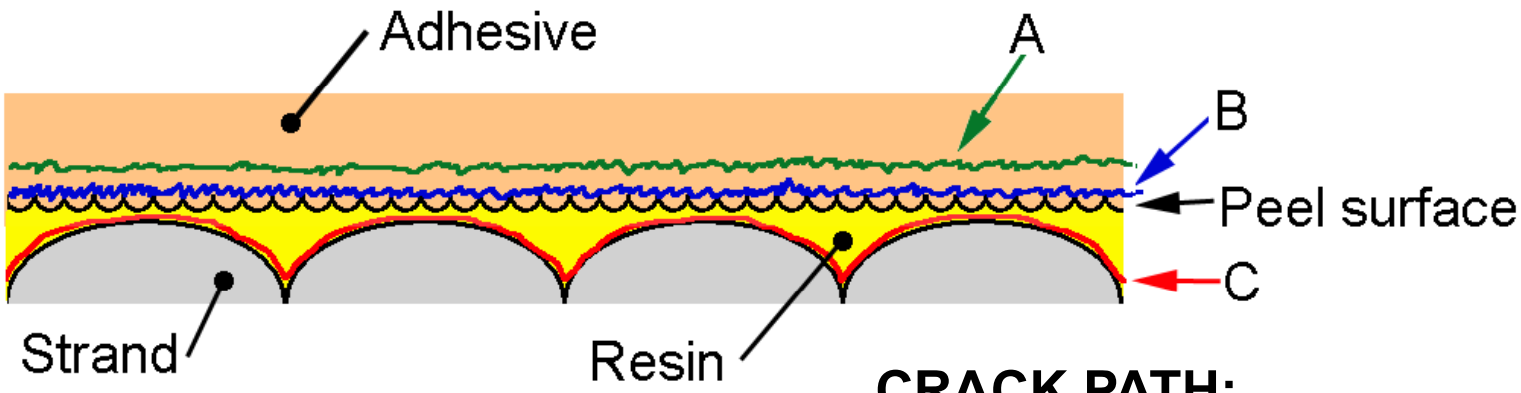

## In Progress:

**Define static $G_c$ and fatigue crack growth thresholds over full range of modes ($G_I/G_{II}$) and R-values experienced in blade joints (data for ADH-1).**



# Crack Path (Normal to Crack Direction)

## CLS Crack Paths on Section Normal to Crack Direction Near Adhesive / Laminate Interface

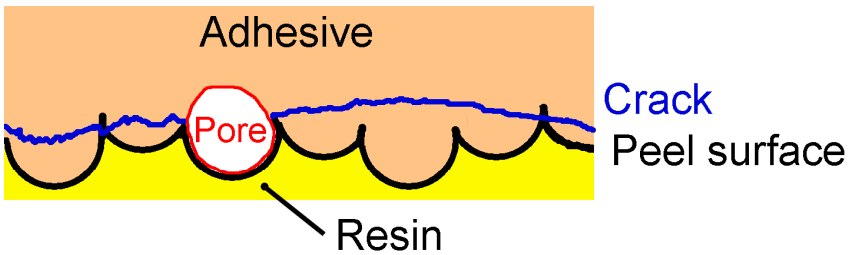



**CRACK PATH:**

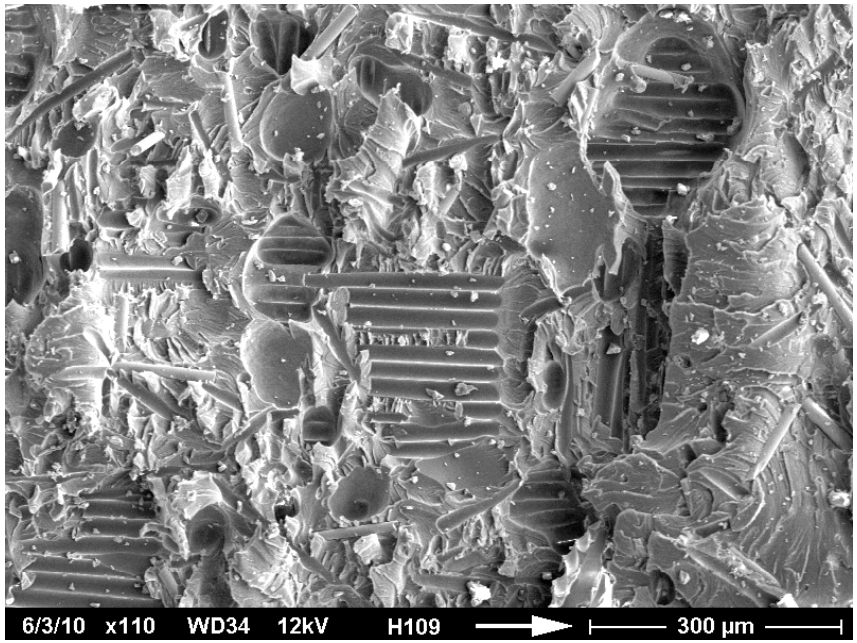
**A. Cohesive in adhesive**

**B. Cohesive along peel surface**

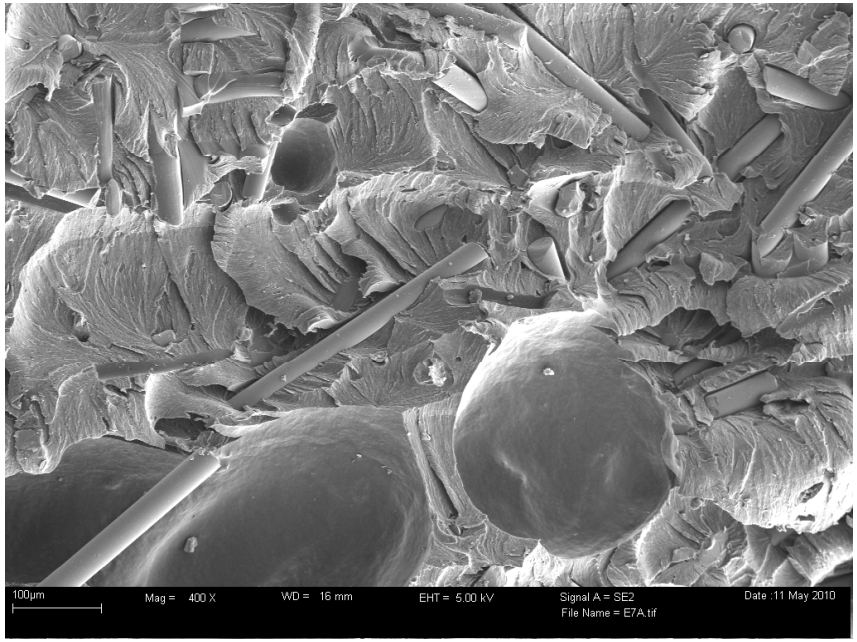
**C. Adhesive along strand surface**



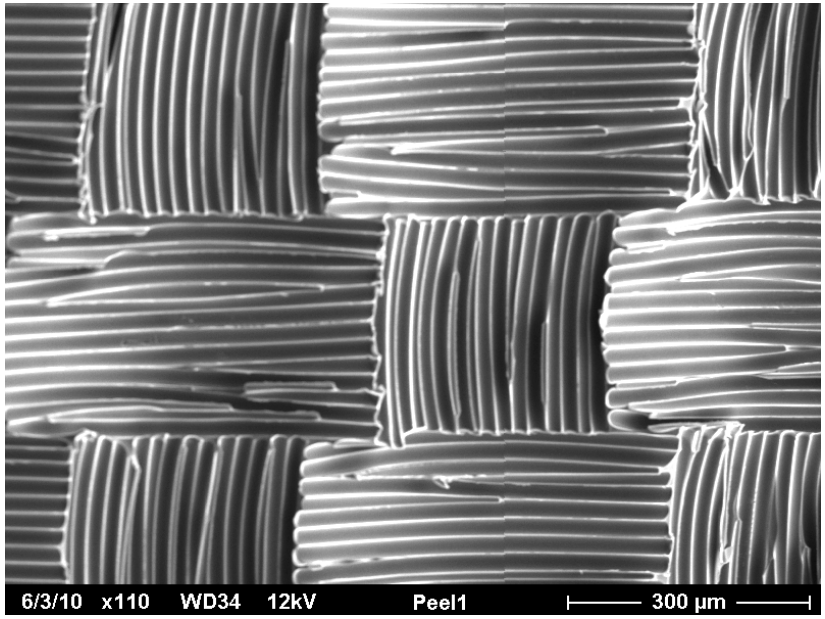

**Expanded View of Path B**



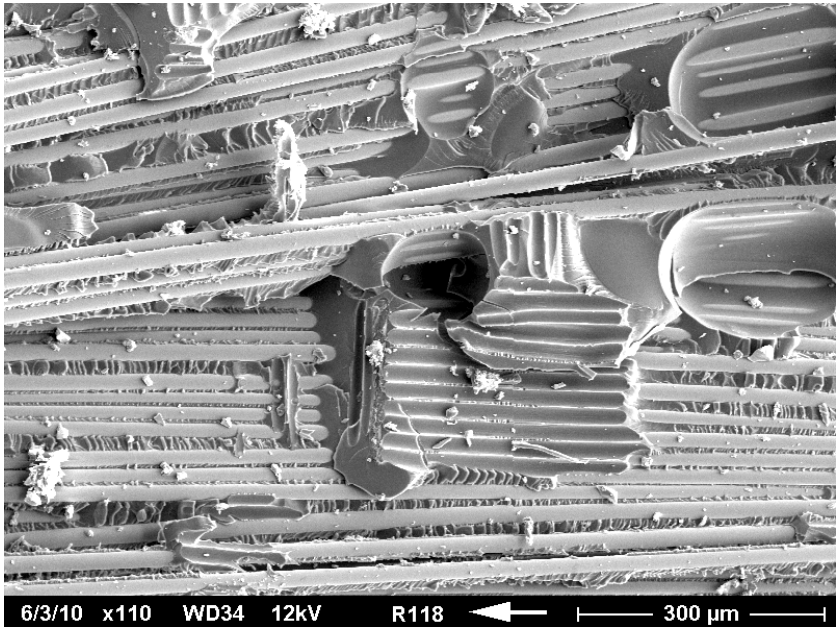

CLS, ADH-1, laminate side




CLS, ADH-1, adhesive side




Peel Surface




CLS, ADH-5, laminate side

# Future Adhesives Work

- Laminate, Adhesive, Peel Ply Variations
- Environment
- Modeling
- Further Test Development