Interlaminar Fracture and Fatigue Characterization of Laminated Composites

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Vertical Lift Consortium
TAJI D&DT Technology Interchange Meeting
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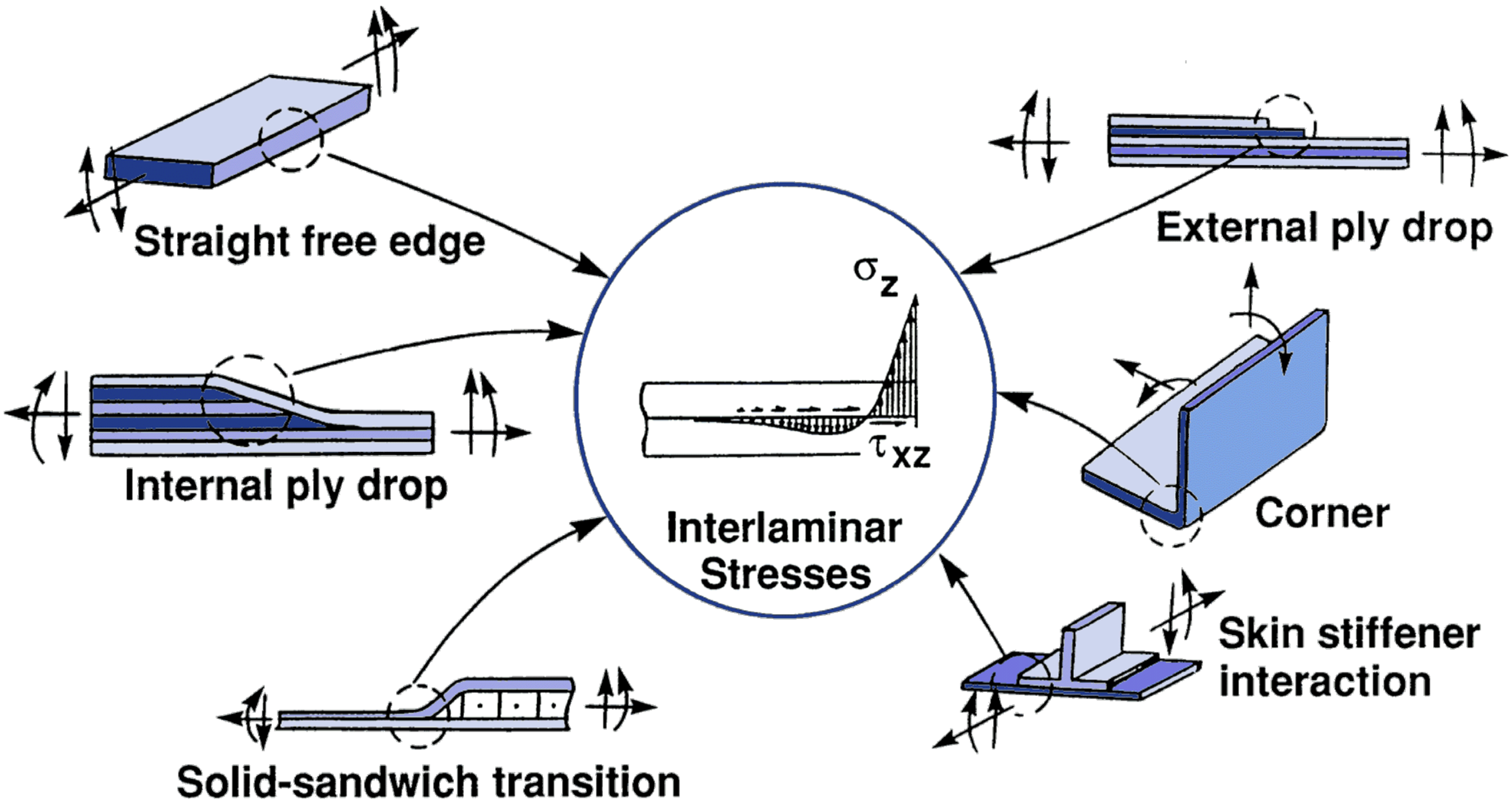
Delamination Sources at Geometric and Material Discontinuities

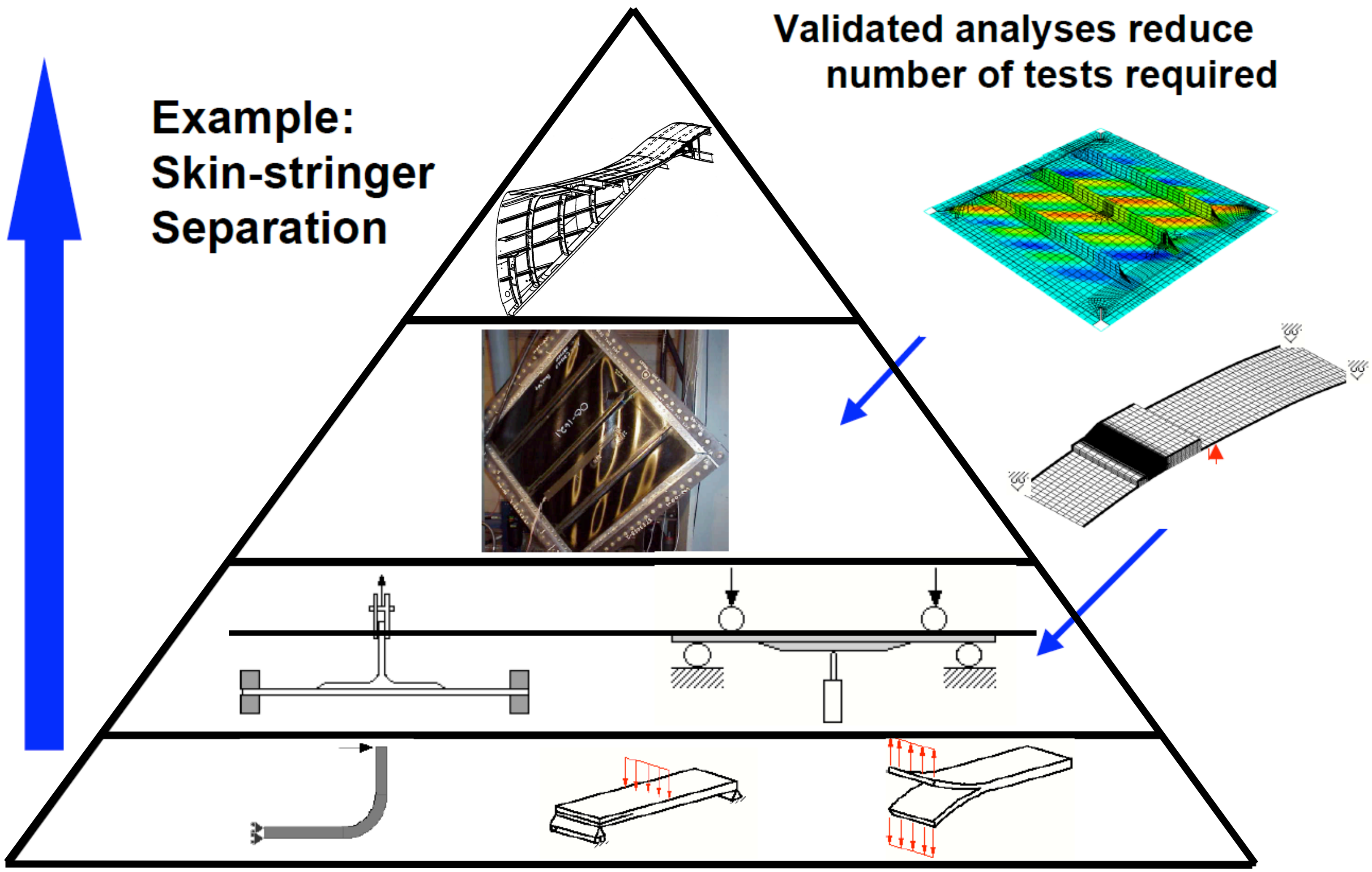


APPROACH

Collaborative research between NASA and U.S. rotorcraft companies through the Vertical Lift Consortium, to design, test, and analyze representative validation test articles.

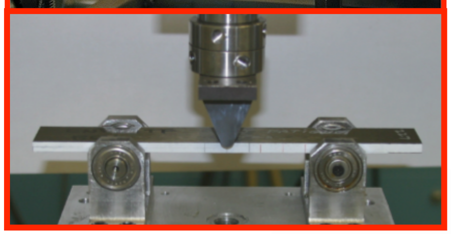
- Representative problems and designs developed with partners
- Validation articles and characterization specimens manufactured by partners
- Develop analytical models to predict delamination behavior using commercial codes, characterization data, and test article data
- NASA Space Act Agreement (SAA1-818) with CRI, August 2007-August 2012; funded through Subsonic Rotary Wing program

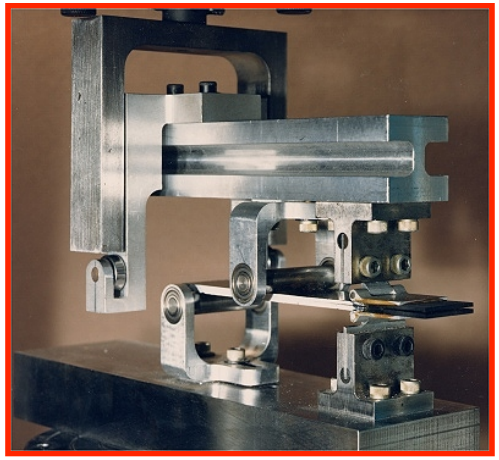
Building Block Approach for Design and Certification



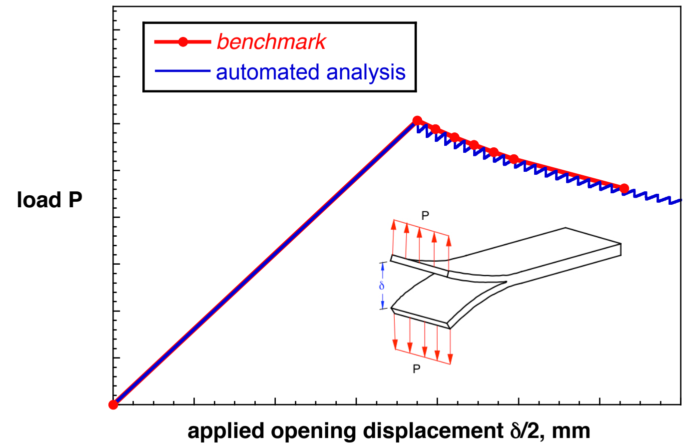
VLC Projects at NASA Langley

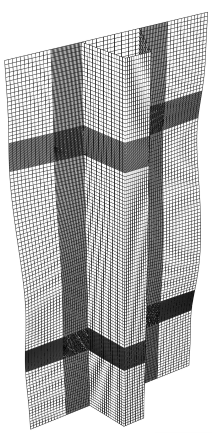
Delamination Characterization

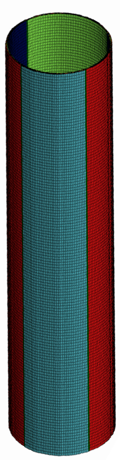




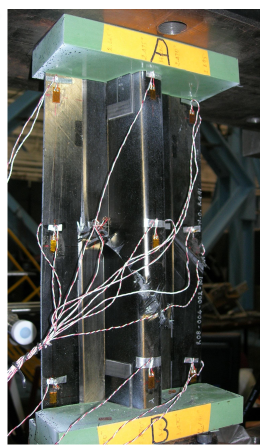
Analysis Benchmarking

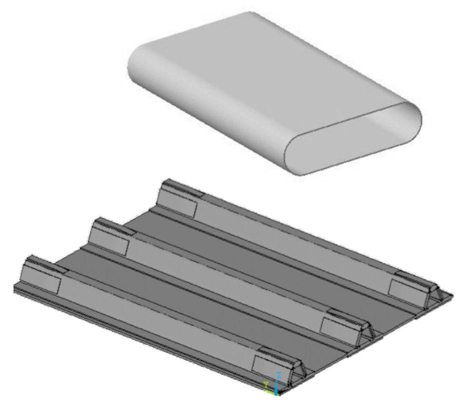






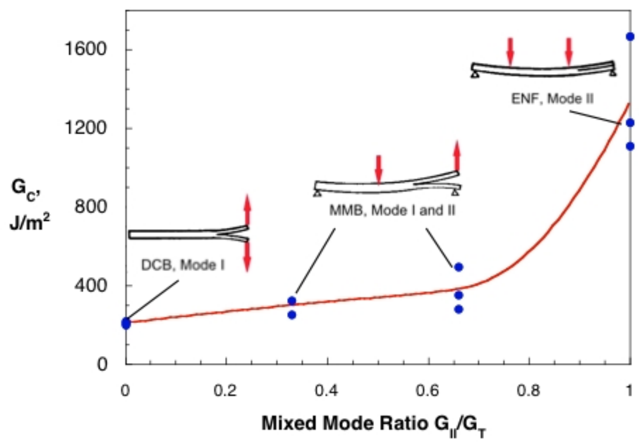
Analysis



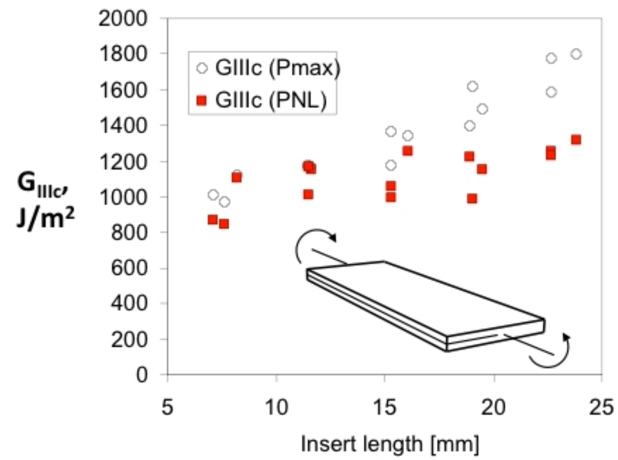


Validation Test Articles

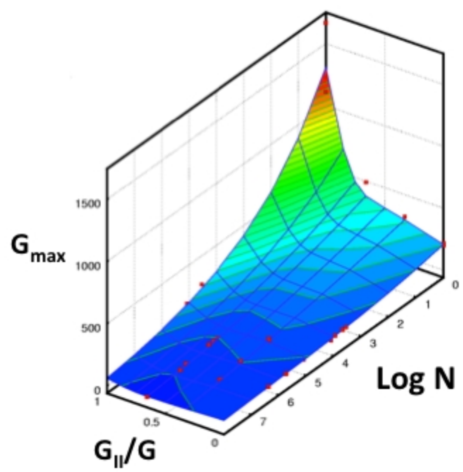
Delamination Characterization



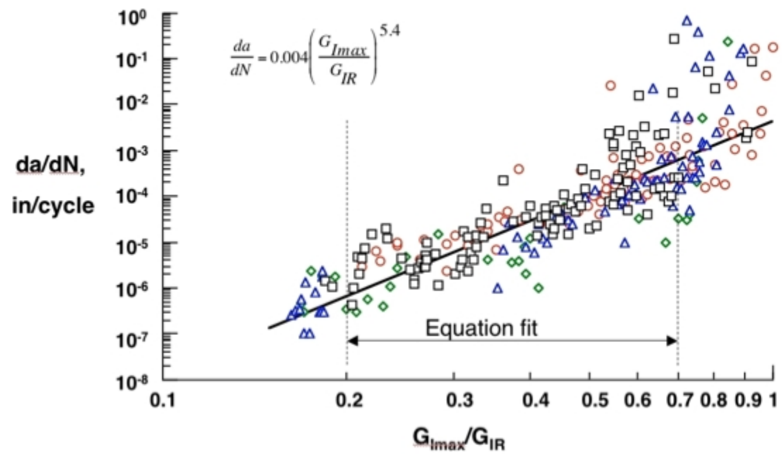
Mode I, II, I&II Fracture Toughness



Mode III Fracture Toughness



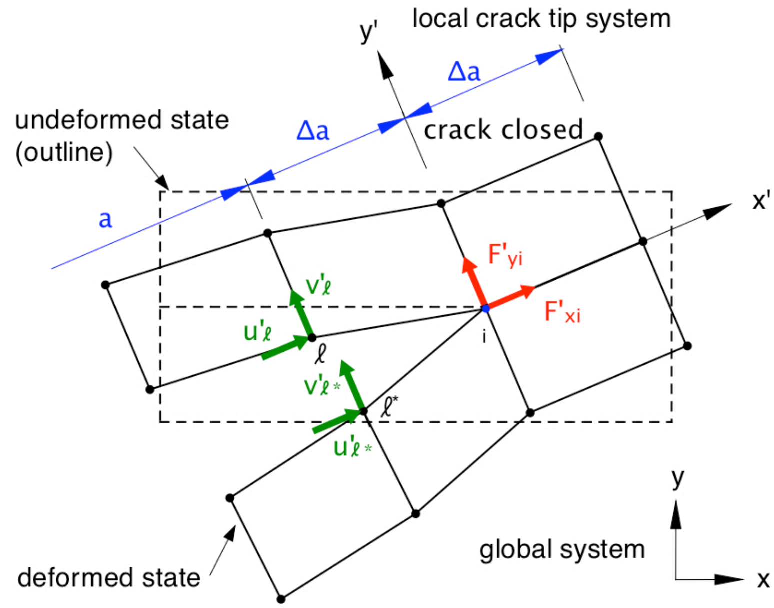
Fatigue Delamination Onset



Fatigue Delamination Growth

Delamination Analysis

- **Virtual Crack Closure Technique (VCCT)***
  - **Based on results from finite element analysis**
    - Two or three-dimensional analysis
    - Nonlinear analysis
  - **Discrete modeling of delaminated area**
  - **VCCT implementation into commercial codes currently in progress**
    - ABAQUS
    - MSC.NASTRAN
    - ANSYS

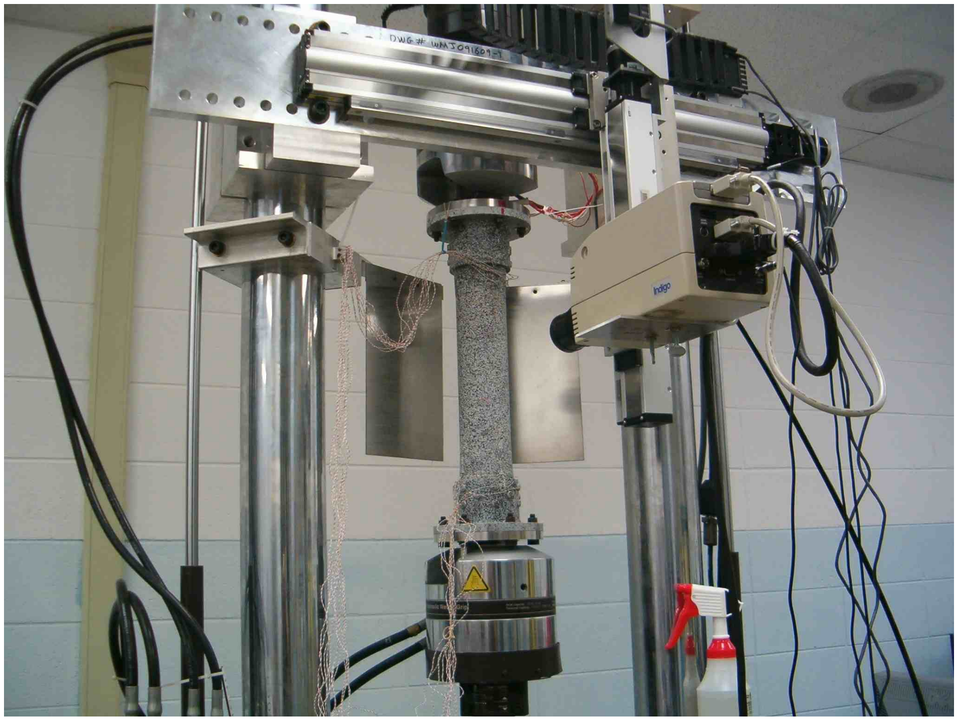


$$G_I = \frac{1}{2\Delta ab} \cdot F_{yi}' \cdot \left(v'_{\ell} - v'_{\ell^*}\right)$$

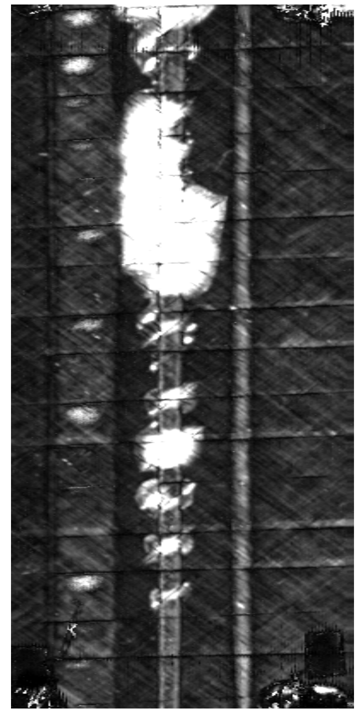
$$G_{II} = \frac{1}{2\Delta ab} \cdot F_{xi}' \cdot \left(u'_{\ell} - u'_{\ell^*}\right)$$

*Rybicki and Kanninen, Eng. Fracture Mech., 1977.

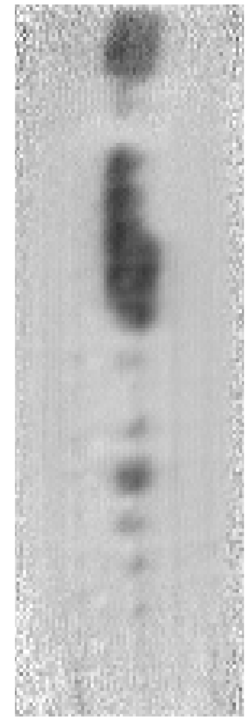
In Situ Nondestructive Evaluation Methods



Thermographic inspection of composite cylinder in torsion load frame



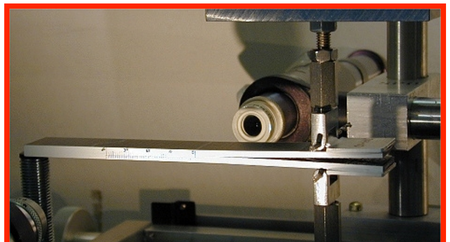
Non-Immersion UT Scan

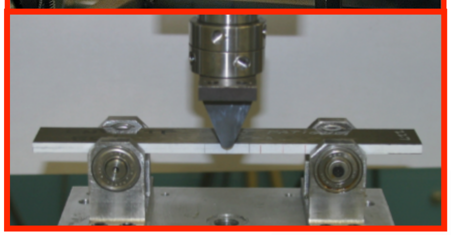


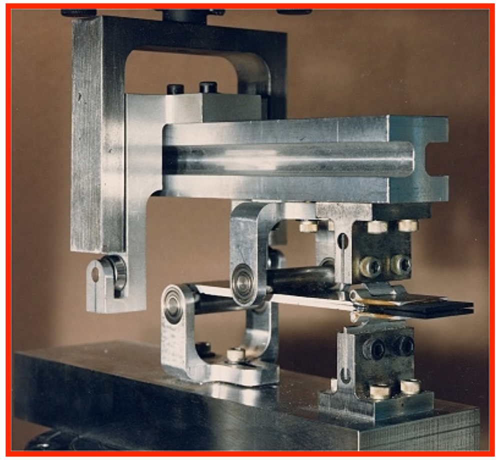
Thermography

VLC Projects at NASA Langley

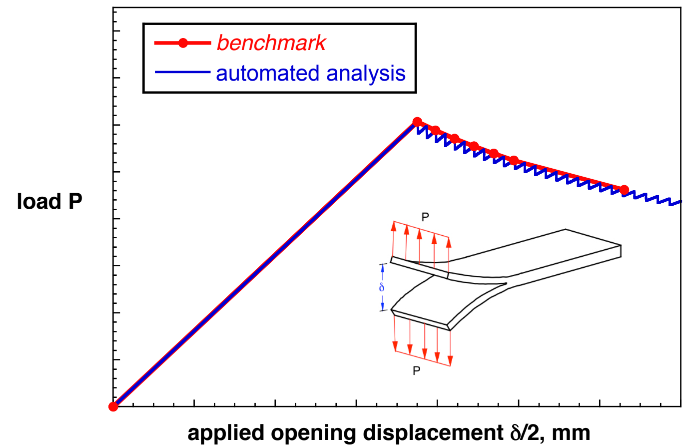
Delamination Characterization: Onset and growth

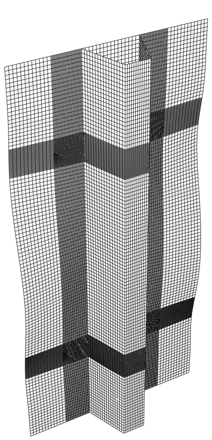


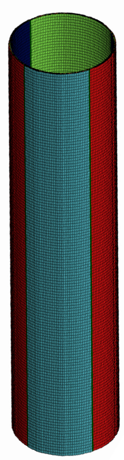




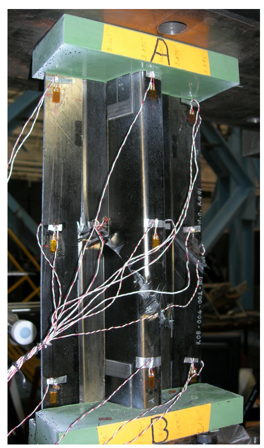
Analysis Benchmarking

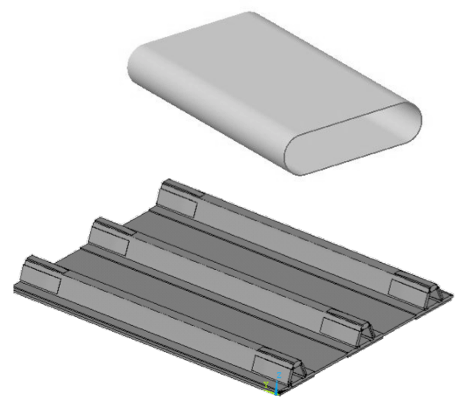






Analysis





Validation Test Articles

Interlaminar Characterization Team

Team Members

T. Kevin O’Brien - NASA Langley Research Center

Gretchen Murri - NASA Langley Research Center

James Ratcliffe - National Institute of Aerospace

William M. Johnston - Lockheed Martin

Objectives of Material Characterization Testing

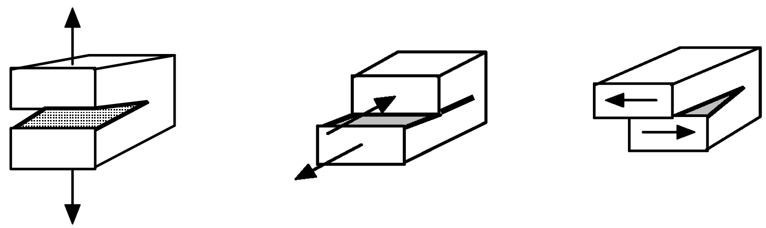
Develop methodologies and validated analysis tools for fatigue life and residual strength prediction for composite rotorcraft structures

- Provide material properties for input to validate delamination modeling of test articles
- Refine existing standards and develop new test methods for evaluating interlaminar fatigue and fracture in laminated composites
- Understand the mechanics of delamination failure to ensure that valid, applicable, and reliable mechanical property data is developed

Background - Delamination Characterization

Energy Release Rate

$$G = \frac{P^2}{2B}\frac{dC}{da}$$

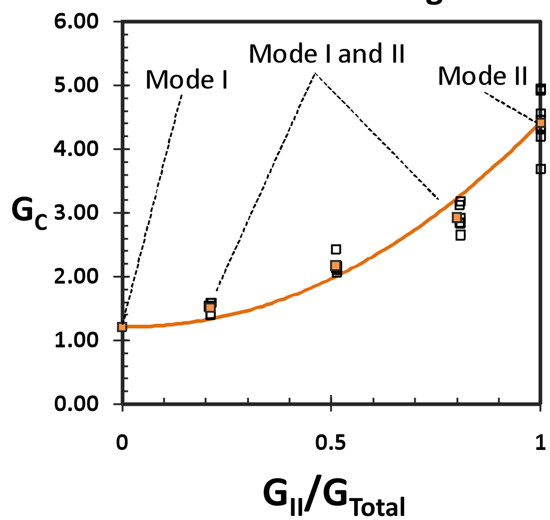


opening Mode I | in-plane shear Mode II | tearing Mode III

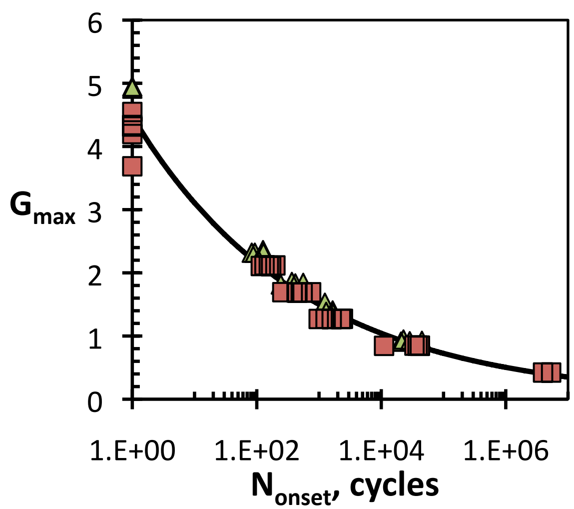
Properties

- *Fracture Toughness*
- *Fatigue Onset*
- *Fatigue Delamination Growth*

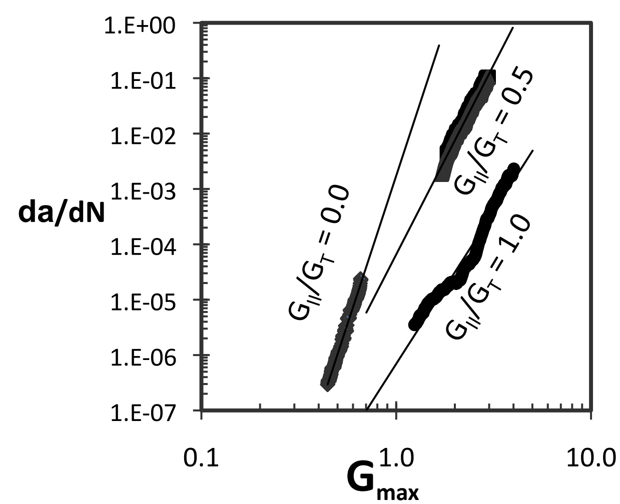
Mode I, II, I&II Static Fracture Toughness



Fatigue Onset

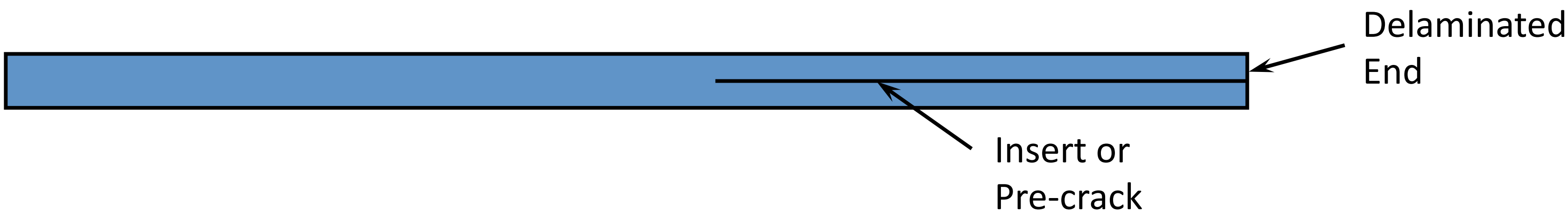


Fatigue Delamination Growth

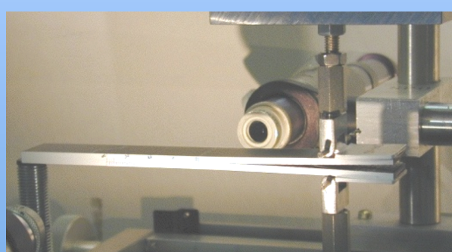


Specimens and Interlaminar Test Methods

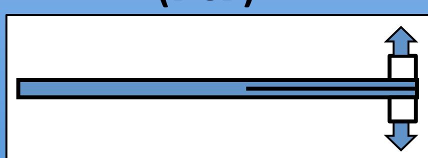
- 24-ply unidirectional laminate with Teflon insert embedded at mid-plane at one end as starter delamination
- Table-top hydraulic load frames
- Automated system records load, displacement, compliance, and cycle count



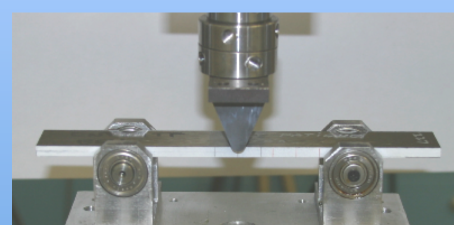
Mode I



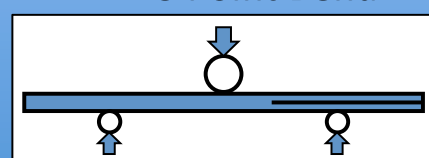
Double Cantilever Beam (DCB)



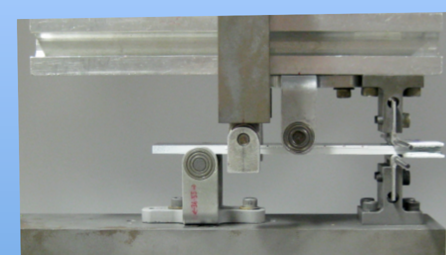
Mode II



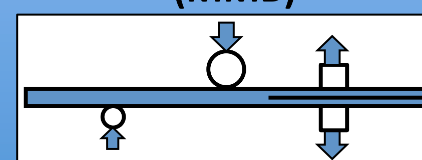
End Notch Flexure (ENF) 3 Point Bend



Mixed Mode I/II



Mixed Mode Bending (MMB)



Interlaminar Test Procedures

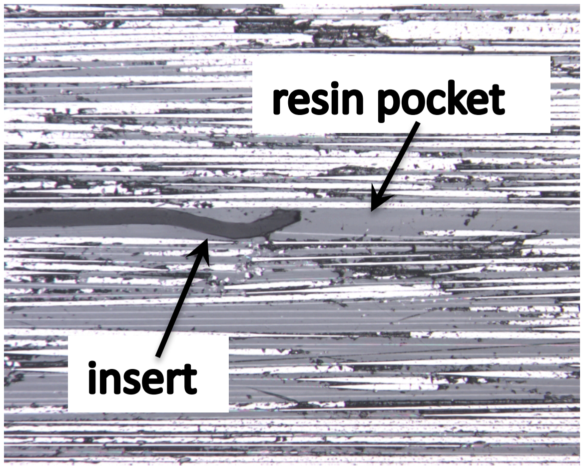
Characterization Methods

- *Established Standards*
- *Draft Standards and ASTM Round Robin activities*
- *Internal Methods*

ASTM Standards	Fracture Toughness	Fatigue Onset	Fatigue Delamination Growth
DCB (Mode I)	D5528	D6115	Draft*
ENF (Mode II)	Draft*	None	None
MMB (Mixed Mode I/II)	D6671	None	None

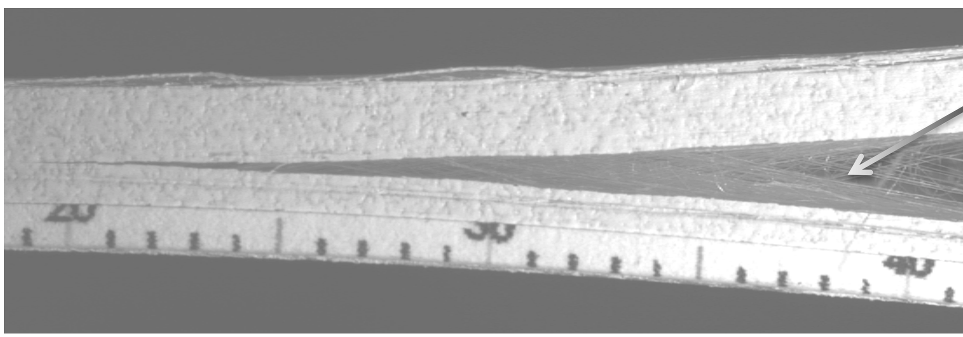
* Currently participating in Round Robin testing through ASTM committee D30.06

Precracking vs. Testing from Insert



Problem: Imperfections at insert tip can influence G measurement

Solution: Pre-crack specimen before testing, to create sharp delamination tip



However: Pre-cracking in Mode I causes fiber-bridging , increasing energy release rate as delamination grows

Precracking? Mode I ✗ Mode II ✔

Mode I and II Fracture Toughness of IM7/8552

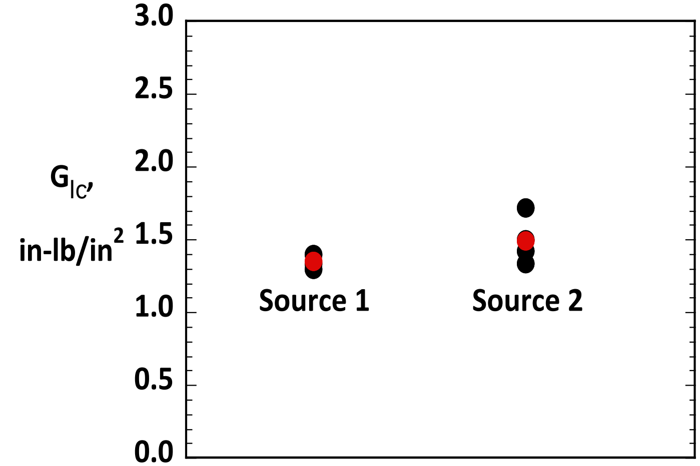
Test Matrix

- Tested IM7/8552 specimens from 2 different manufacturers for Mode I and Mode II
- Mode I specimens tested from insert only
- Mode II specimens tested from insert and precrack

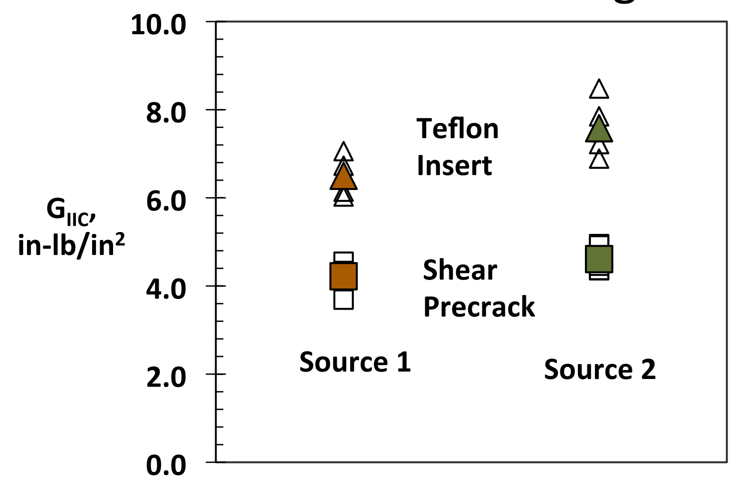
Results

- Similar toughness values from 2 different manufacturers for Modes I and II
- Mode II specimens yield higher toughness values from insert than from precrack

Mode I Fracture Toughness



Mode II Fracture Toughness



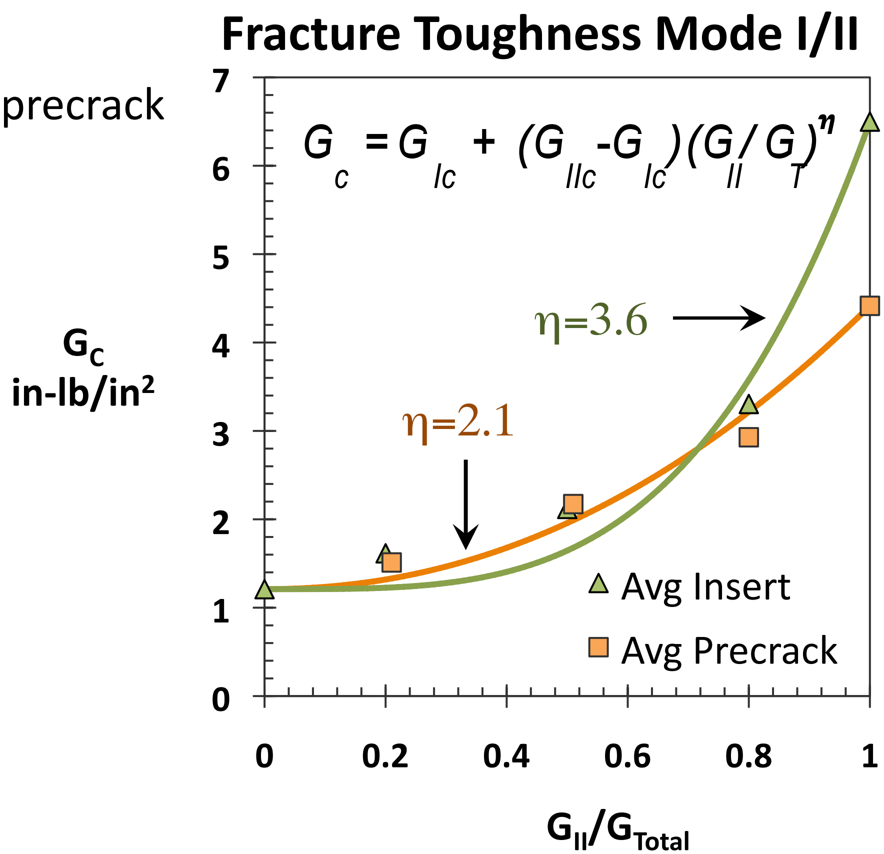
Mixed Mode Fracture Toughness of IM7/8552

Test Matrix

- Specimens from Source 1 only
- Specimens tested from insert and precrack
- 3 mixed mode ratios
  G_{II}/G_C = 0.2, 0.5, 0.8

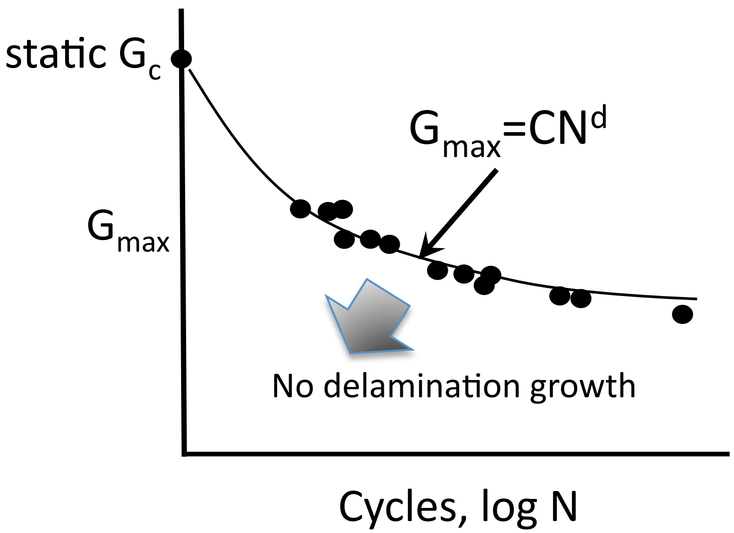
Results

- Tests from inserts and precracks were similar for tests at 20% and 50% mode II

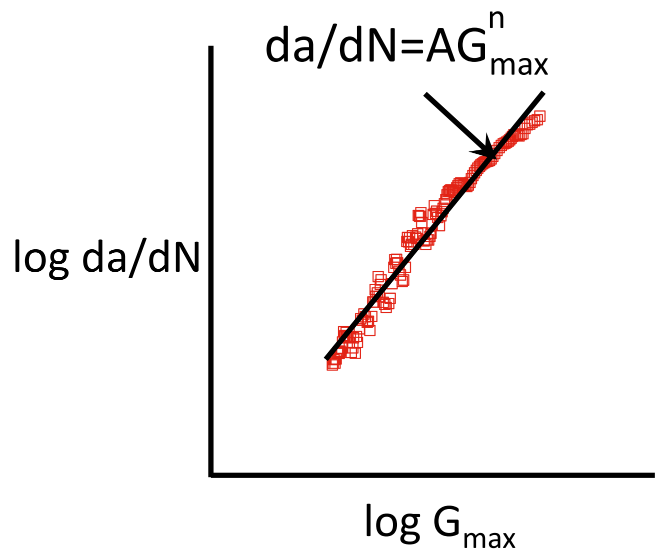


Composite Fatigue Delamination Testing

Delamination Onset Testing

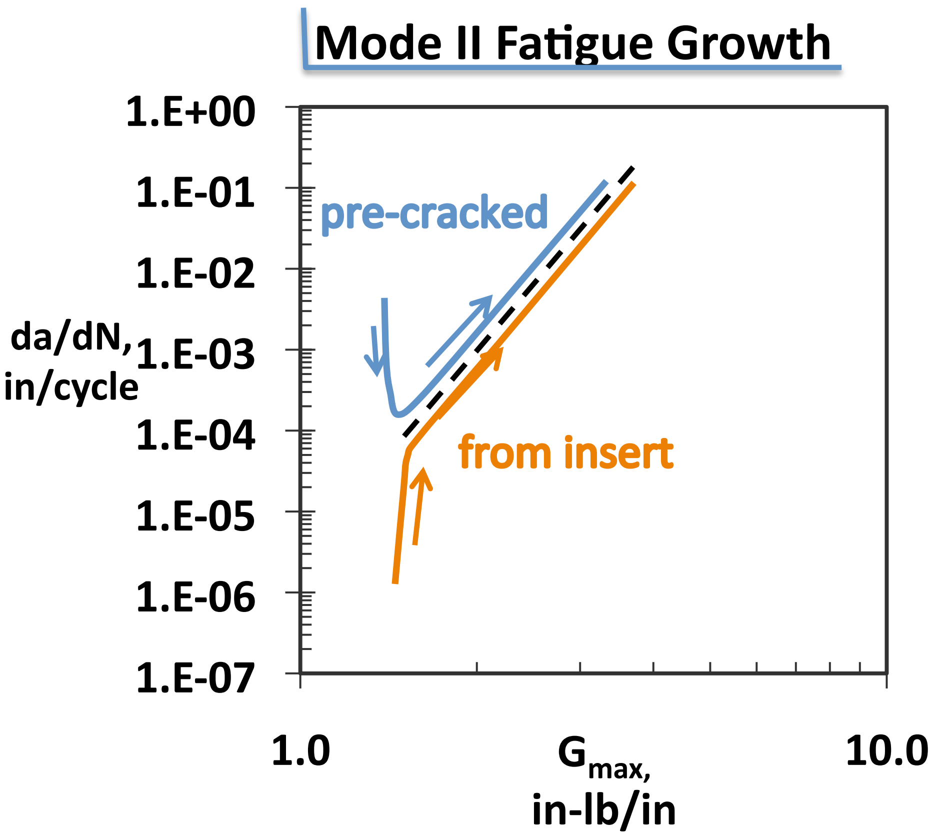


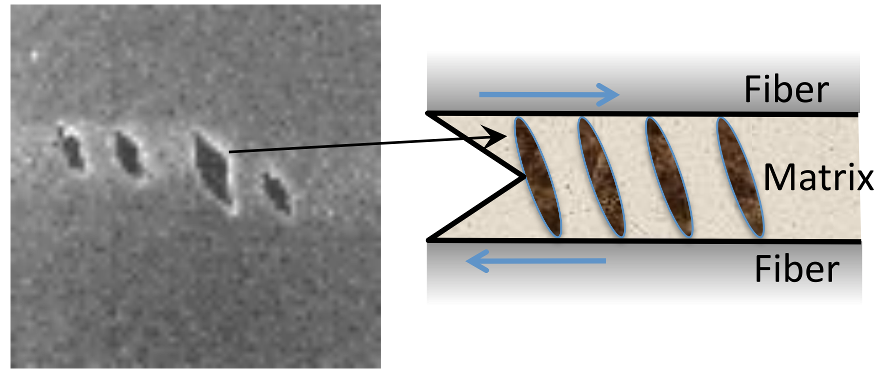
Delamination Growth Testing



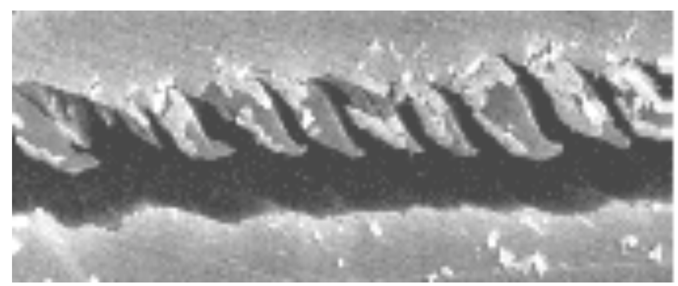
- One specimen used for both types of data
- Load levels chosen as percentage of G_c
- Typically define onset as percentage increase in compliance

Fatigue Onset Response of ENF Specimens





Fatigue causes formation of micro-tension cracks ahead of delamination tip

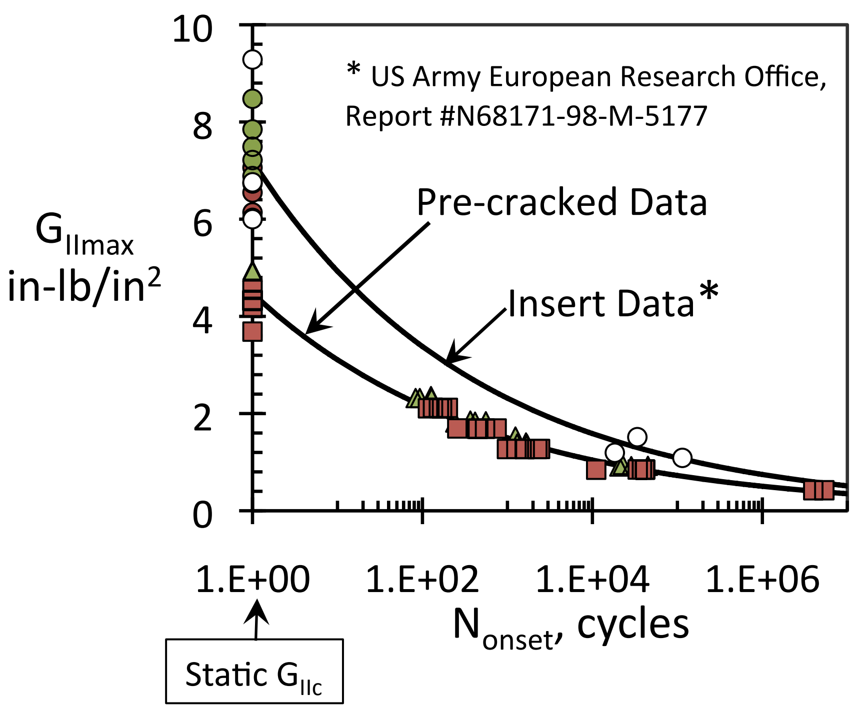


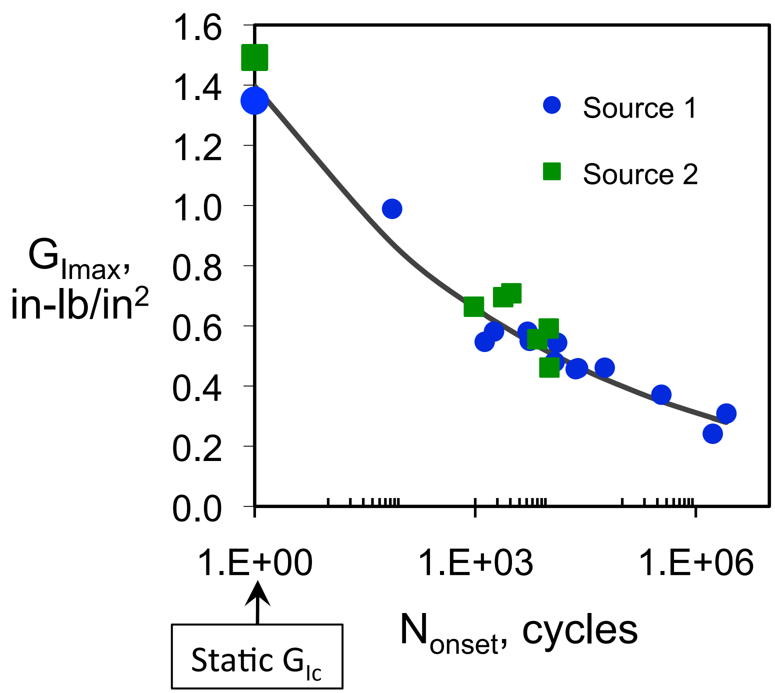
Micro-cracks coalesce to form the macroscopic delamination

Mode I and Mode II Delamination Onset

Test Matrix

- Initial loading at G_{max} = 50%, 40%, 30%, and 20% of G_c
- Tested specimens from 2 different manufacturers
- f=5 Hertz





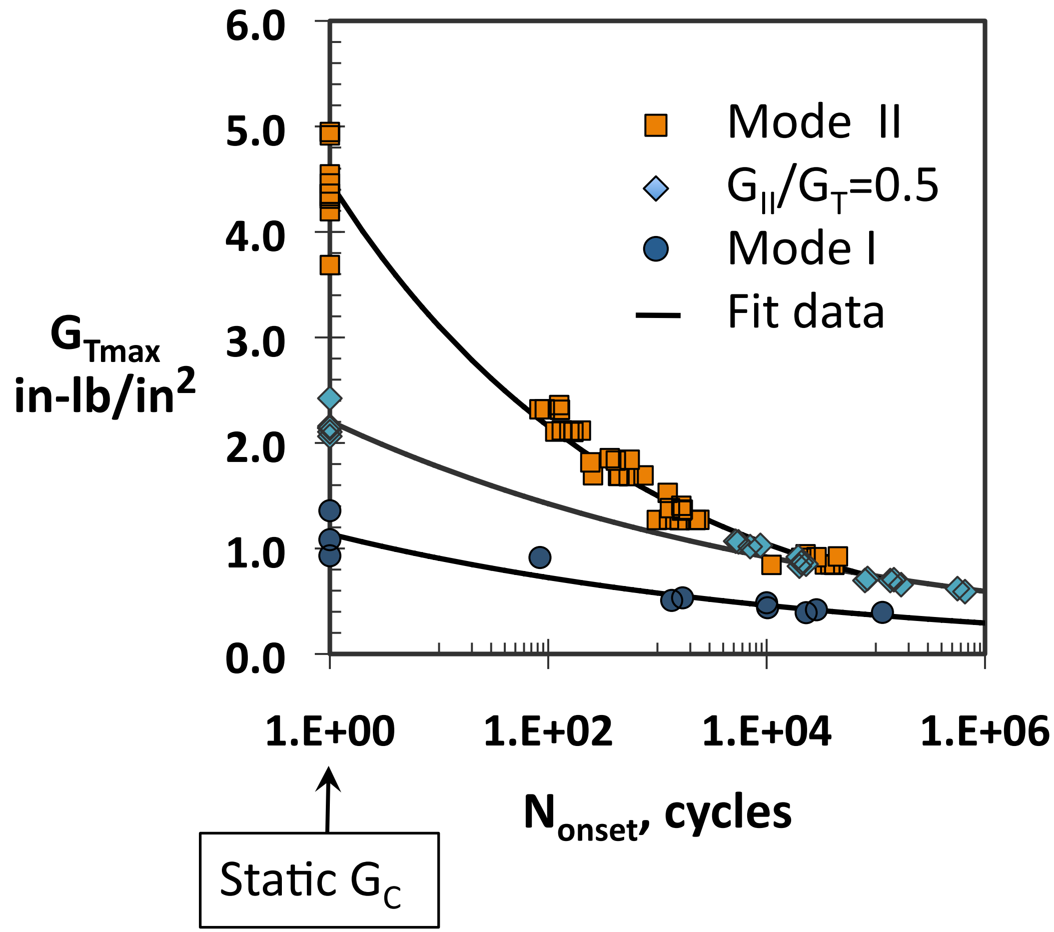
Results

- Data from both sources follow same trend for both Mode I and Mode II
- Earlier onset in precracked Mode II specimens compared to tests from insert

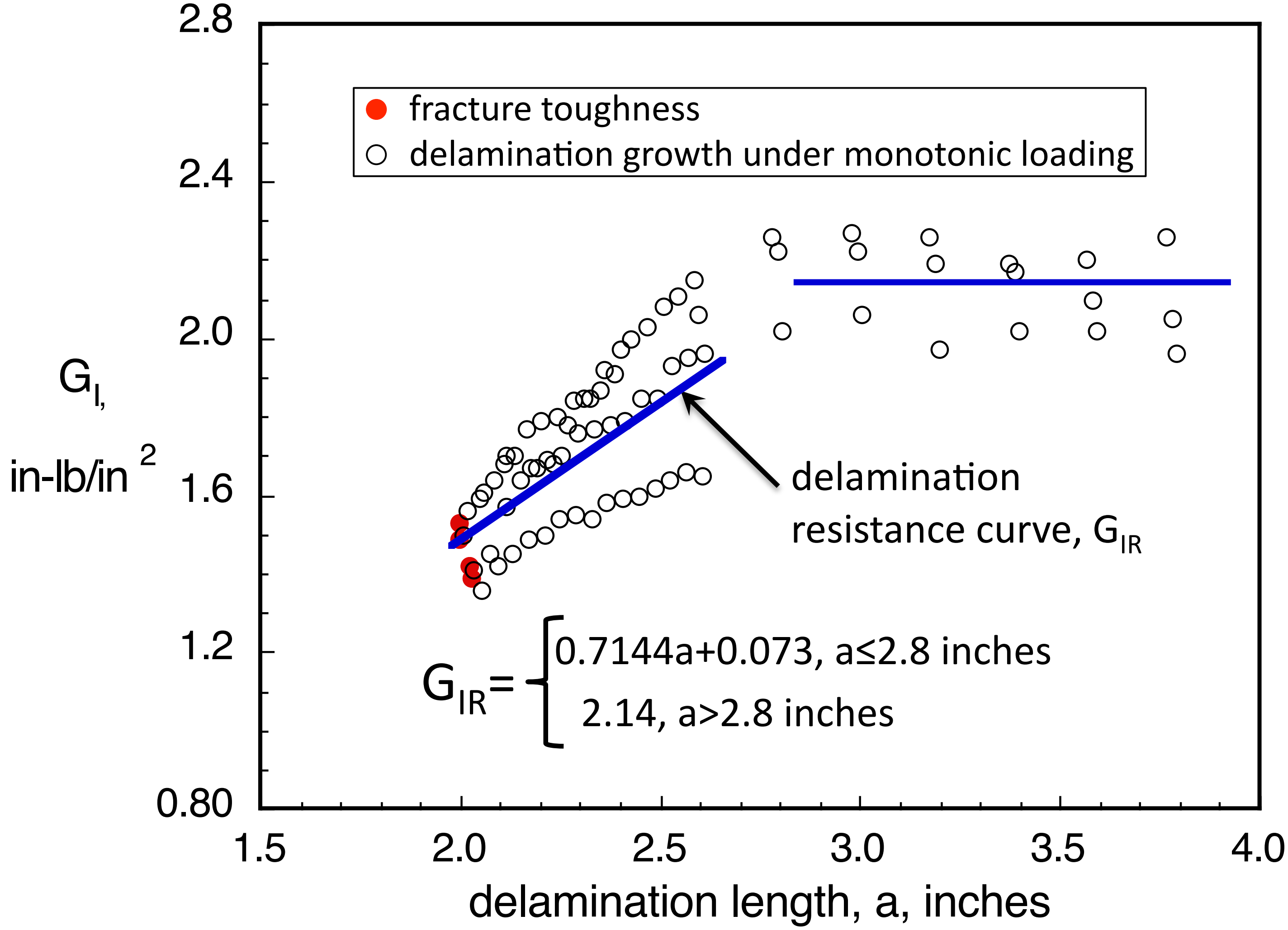
Mixed Mode I/II Delamination Onset

Test Matrix

- Tested at 3 mode ratios G_{II}/G_C = 0.2, 0.5, 0.8
- Tested at initial loading for G_{max} = 50%, 40%, 30% and 20% of G_c
- Tests from insert
- Tested specimens from Source 1 only
- f=2 Hertz

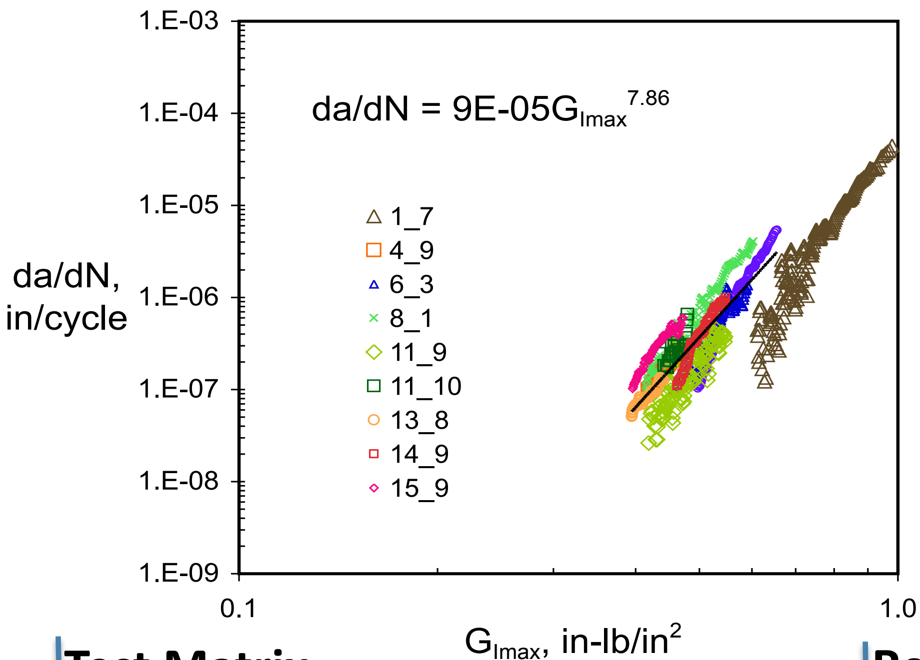


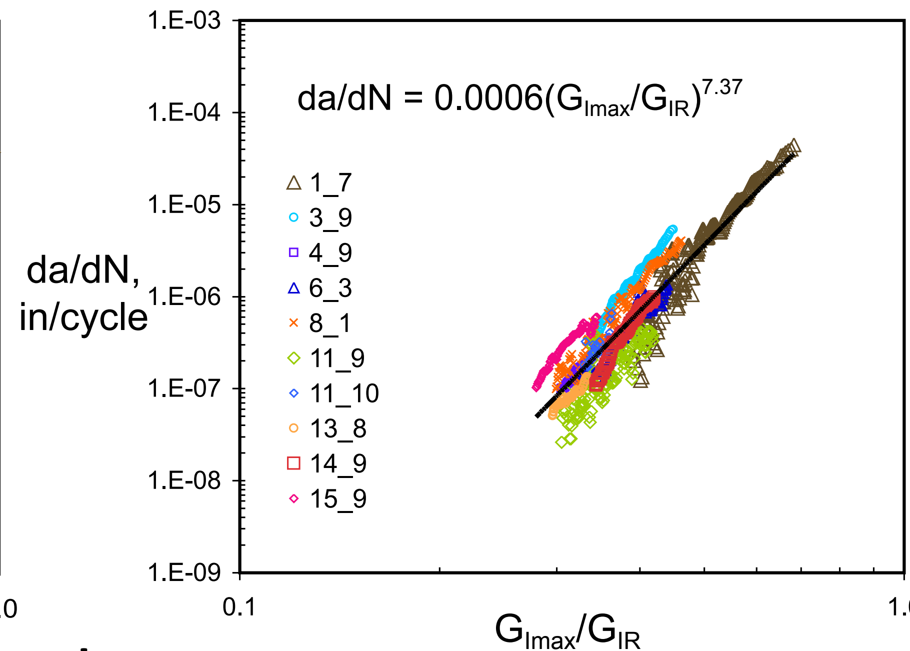
Delamination Resistance Curve for Mode I



•Use delamination resistance curve, G_{IR}, to normalize fatigue growth data in Mode I

Mode I Fatigue Delamination Growth
Source 1





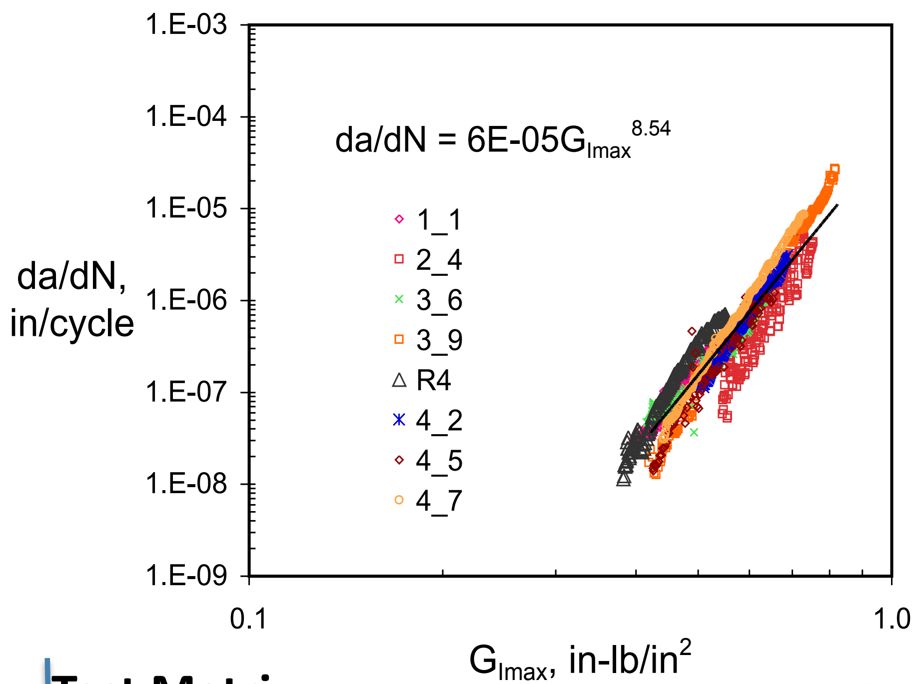
Test Matrix

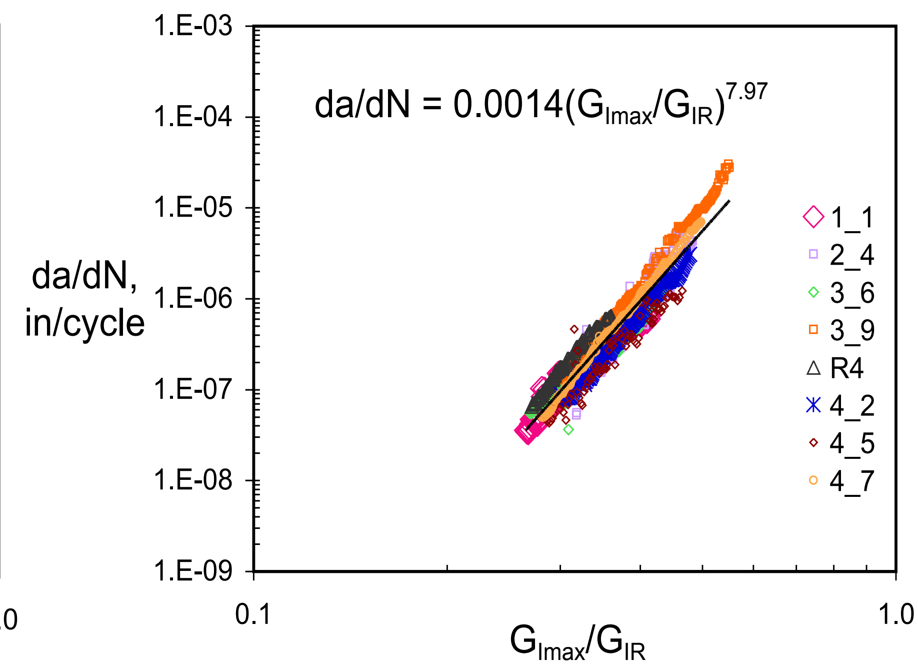
- Same specimens used for testing to onset
- Tested in displacement control
- Frequency=5 Hz

Results

- Normalized results show much better agreement compared to G_{Imax} results
- Power law fit to results for all load levels have similar slopes

Mode I Fatigue Delamination Growth-Source 2





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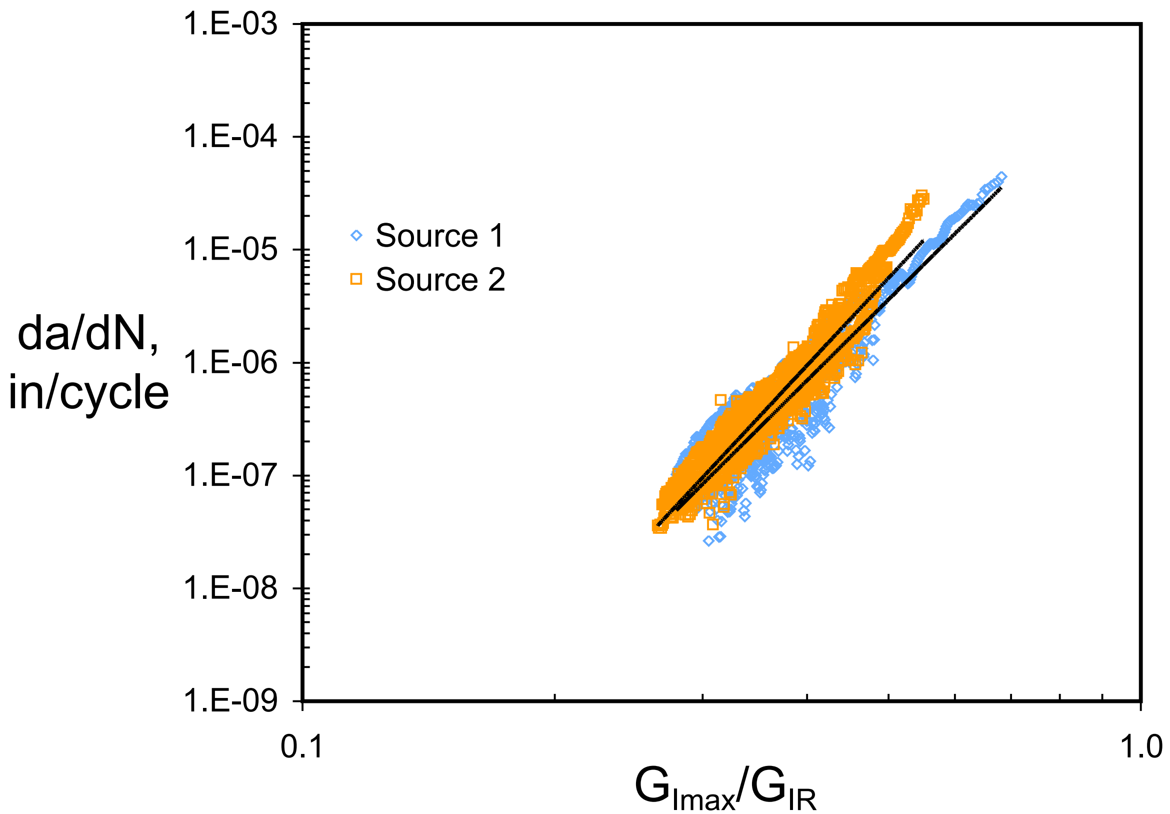
Fatigue Delamination Growth Rate Comparison



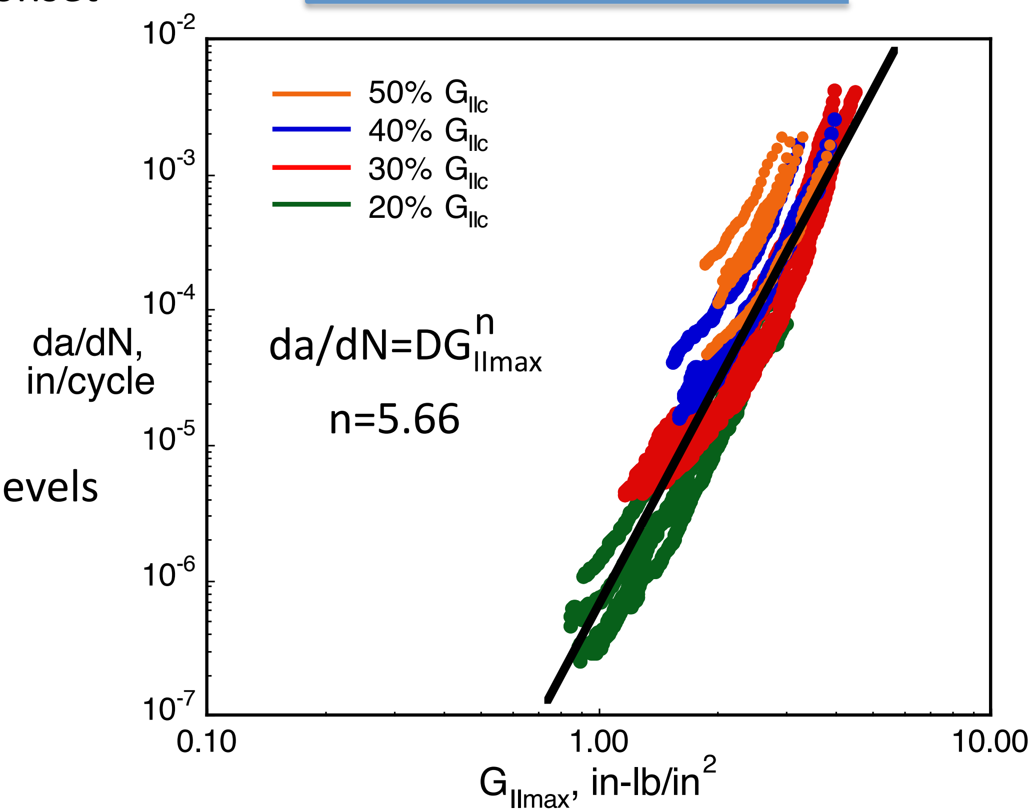
Delamination growth rates (da/dN) are similar for both source materials

Mode II Fatigue Delamination Growth

Test Matrix

- Same specimens used for testing to onset
- Tested in load control
- Frequency=5 Hertz

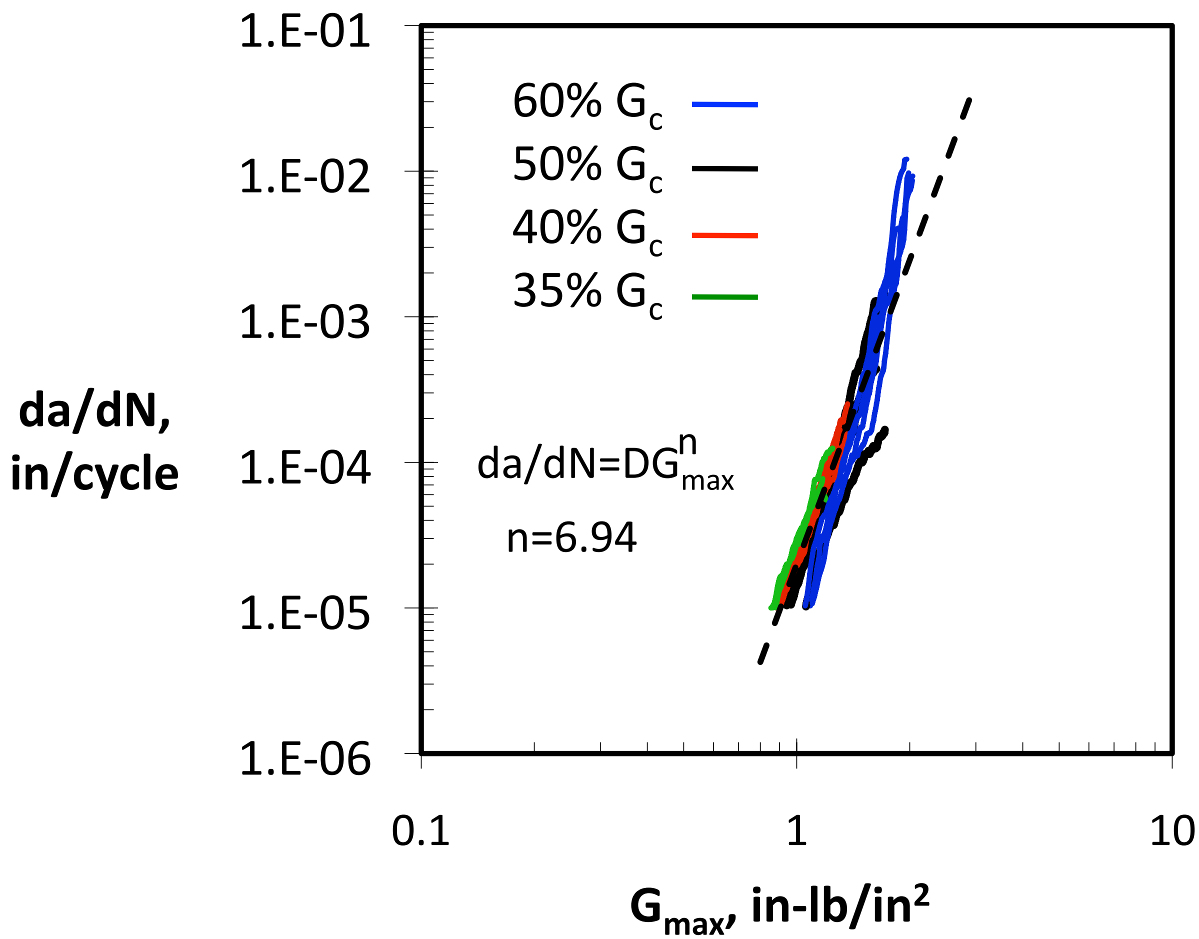
Fatigue Growth Mode II



Results

- Power law fit to results for all load levels have similar slopes
- Similar behavior between different manufacturers

Mixed Mode I/II Fatigue Delamination Growth



Fatigue Growth Mode I/II

- G_{II}/G_T=0.5
- Linear region of Paris law is consistent for all load levels

Summary

- Developed fatigue test methods and data reduction procedures for Mode II and Mixed Mode I/II testing
- Investigated the effects of a Teflon insert on Mode II delamination
- Mode I, Mode II and Mixed Mode I/II fracture toughness and fatigue characterization data for validation models

Future Work

- Mode II and Mixed Mode I/II fatigue delamination growth test standards will be drafted for ASTM
- Material properties will be used for input to validate delamination fatigue life prediction methodology on rotor spar and stiffened wing skin components

NASA