



National Aeronautics and Space
Administration

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Interlaminar Fracture and Fatigue Characterization of Laminated Composites

Ms. Gretchen B. Murri
Aerospace Engineer
Durability, Damage Tolerance, and Reliability Branch
NASA Langley Research Center



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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



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

APPROACH



Collaborative research between NASA and U.S. rotorcraft companies with 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

Durability and Damage Tolerance Validation Testing

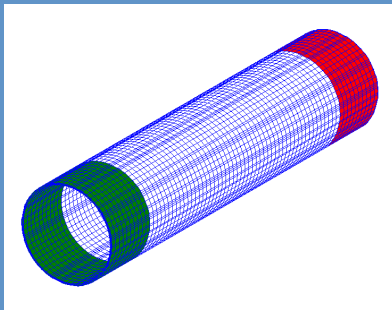


Representative
Geometry

Representative
Loading

Potential Application
Area

Composite Tube

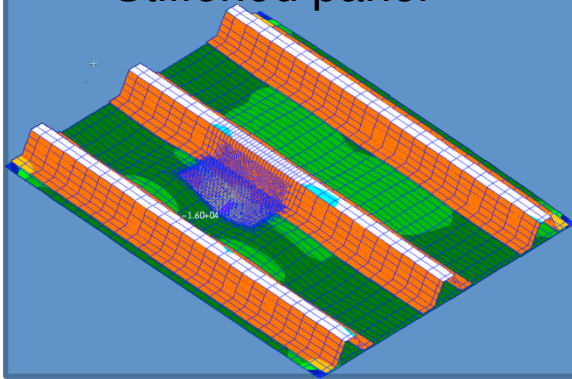


Torsion Fatigue Loading

Helicopter Rotor Blade Spar



Stiffened panel



Compression Fatigue
Loading (Post Impact)

Tilt Rotor Wing

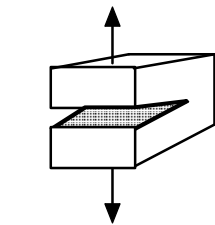


Background - Delamination Characterization

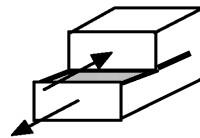


Energy Release Rate

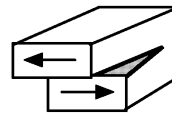
$$G = \frac{P^2}{2B} \frac{dC}{da}$$



opening
Mode I



in-plane shear
Mode II

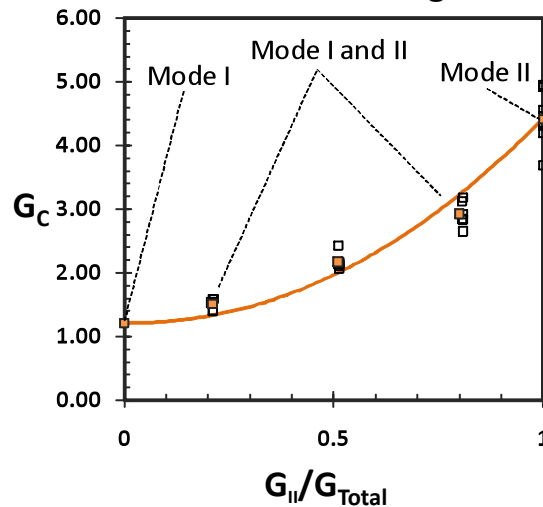


tearing
Mode III

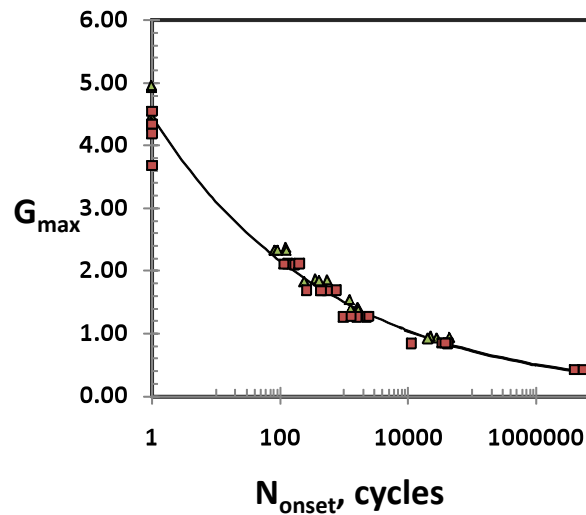
Needed Properties

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

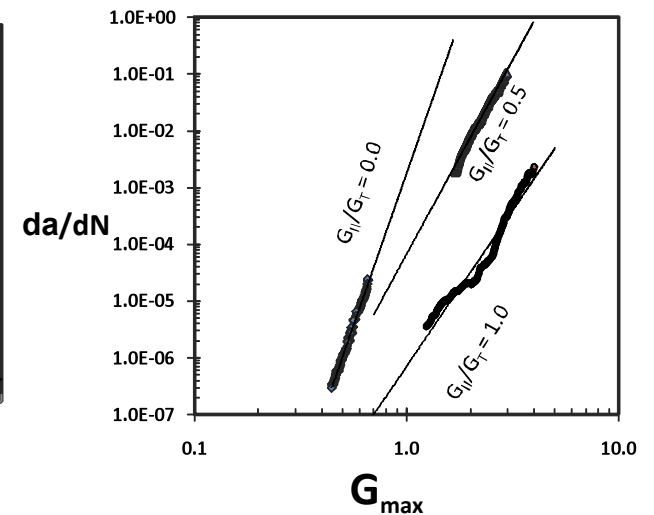
Mode I, II, I&II
Static Fracture Toughness



Fatigue Onset



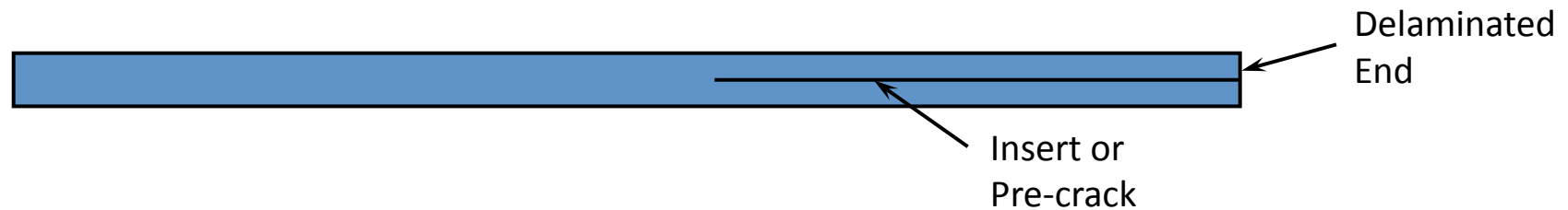
Fatigue Delamination Growth



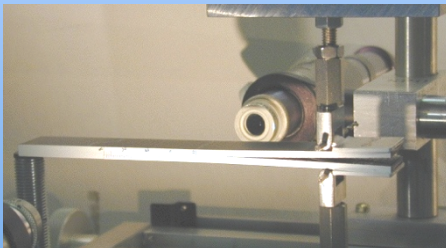
Specimens and Interlaminar Test Methods



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



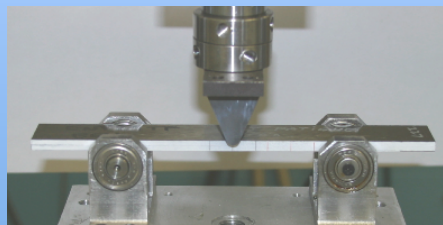
Mode I



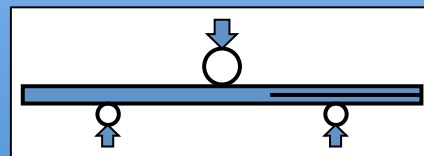
Double Cantilever Beam
(DCB)



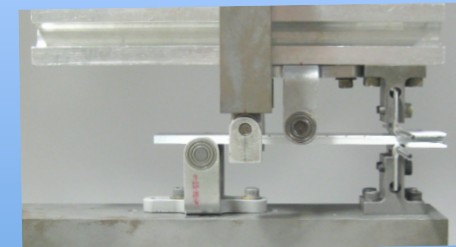
Mode II



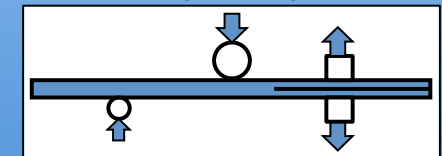
End Notch Flexure (ENF)
3 Point Bend



Mixed Mode I/II



Mixed Mode Bending
(MMB)



Interlaminar Test Standards



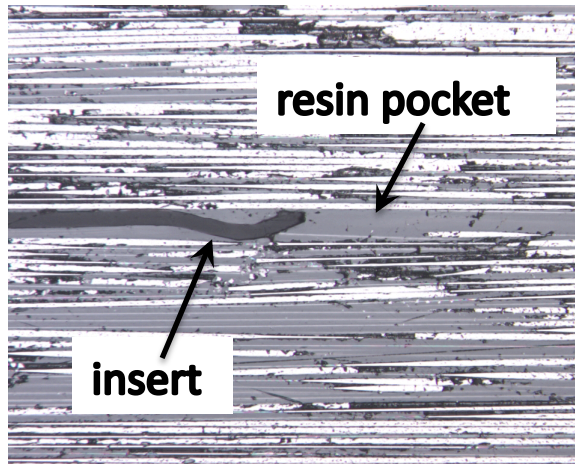
Characterization Methods

- *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

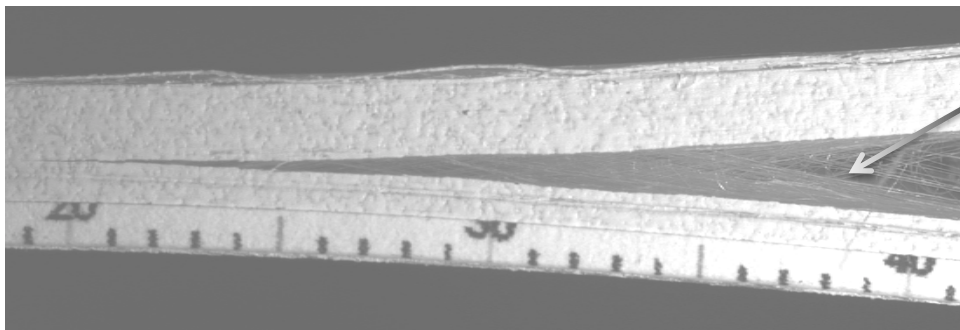
* Currently participating in Round Robin testing through ASTM committee D30.06

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



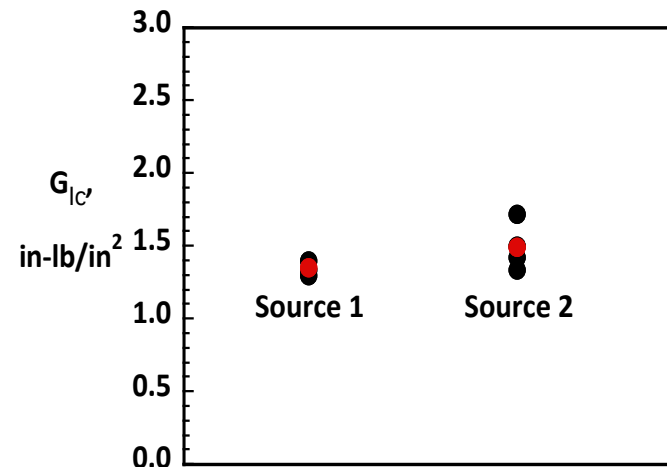
Test Matrix

- 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

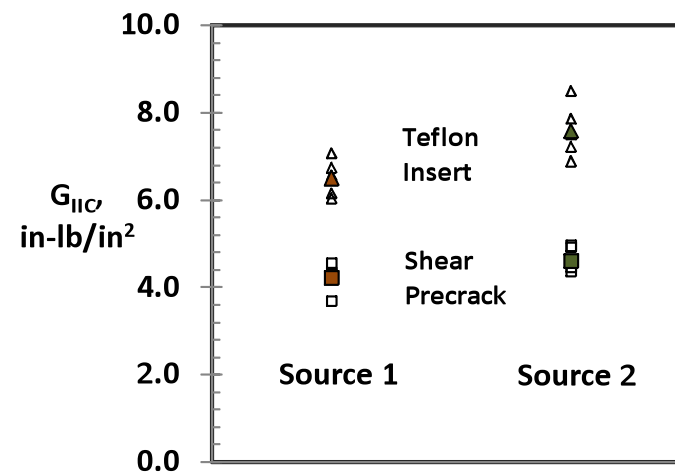
Results

- 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

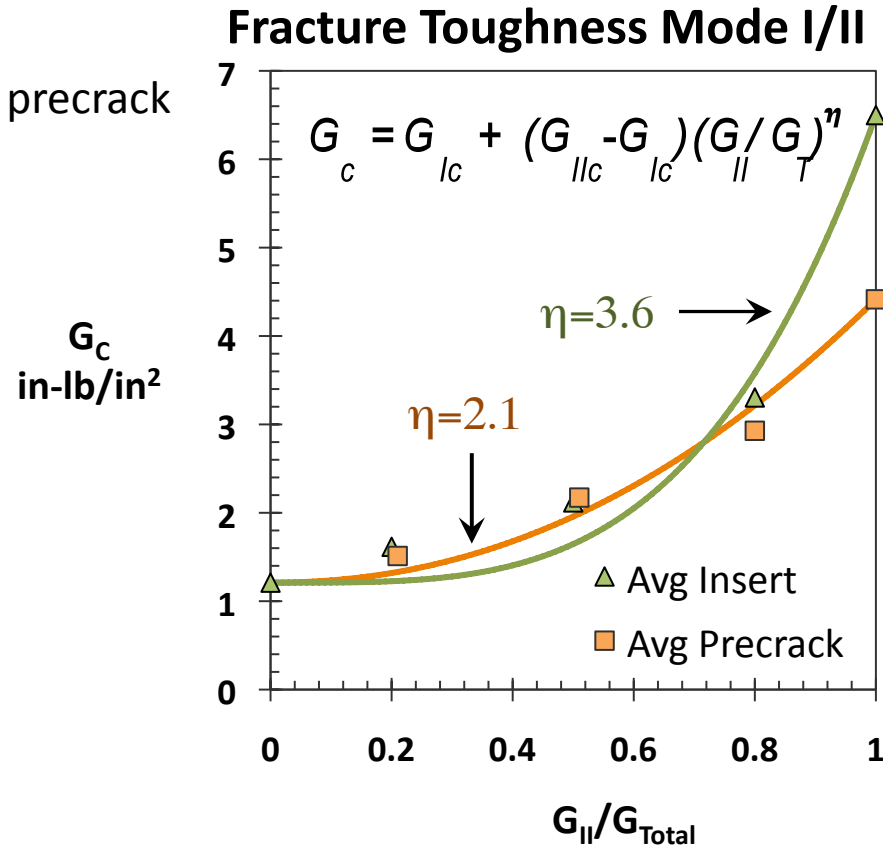


Test Matrix

- 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

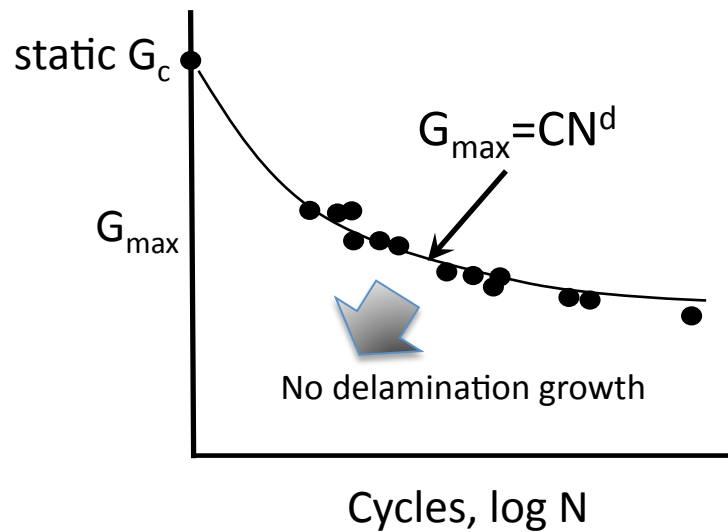
- Tests from inserts and precracks were similar for tests at 20% and 50% mode II



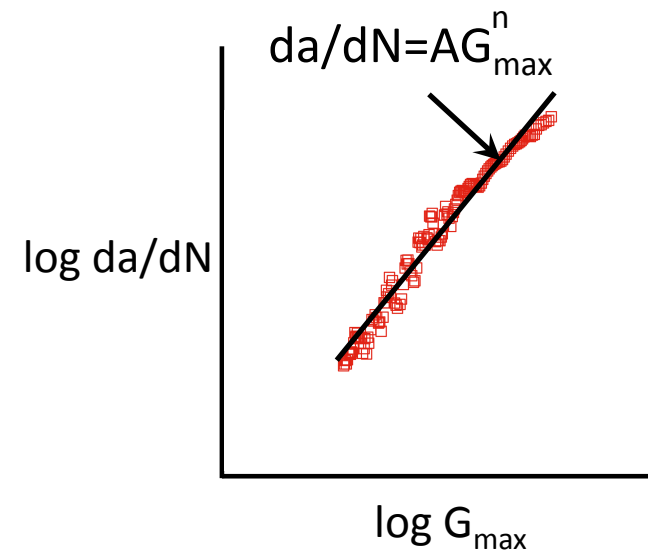
Composite Fatigue Delamination Testing



Delamination Onset Testing



Delamination Growth Testing

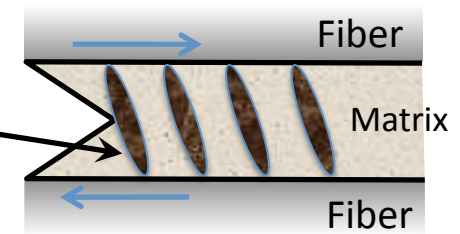
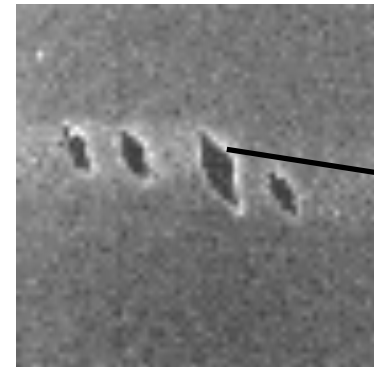
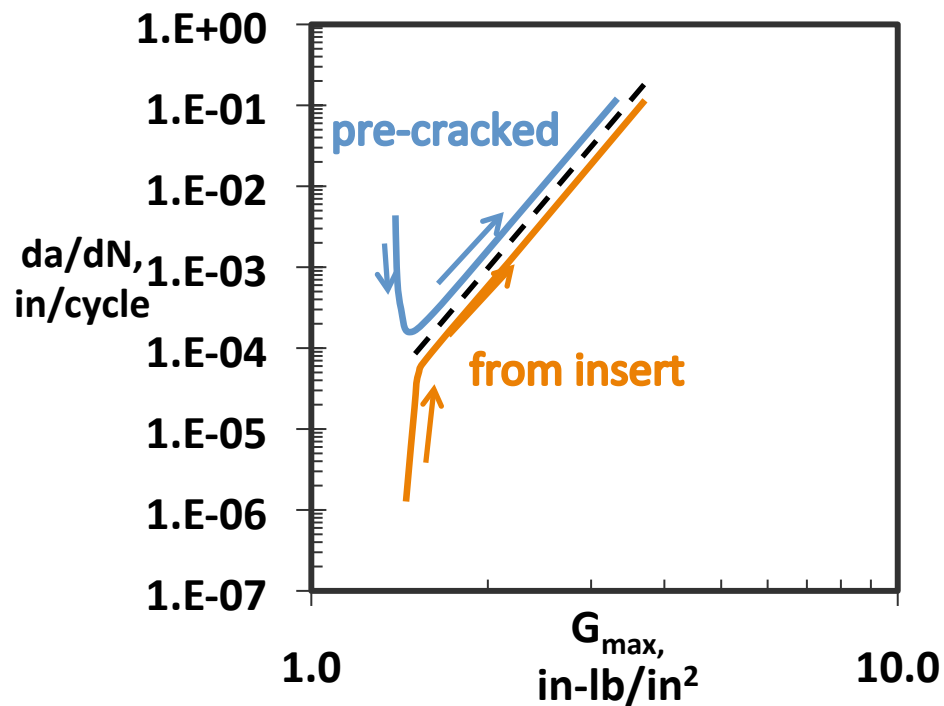


- One specimen used for both types of data
- Load levels chosen as percentage of G_c
- Typically define onset as percentage increase in compliance

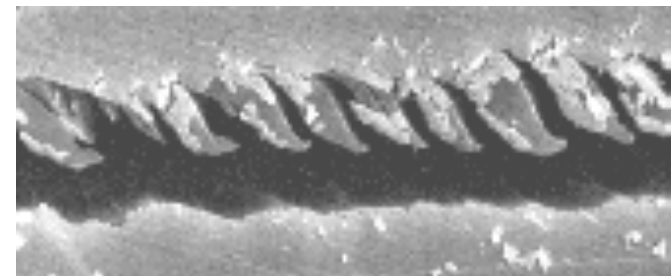
Fatigue Onset Response of ENF Specimens



Mode II Fatigue Growth



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



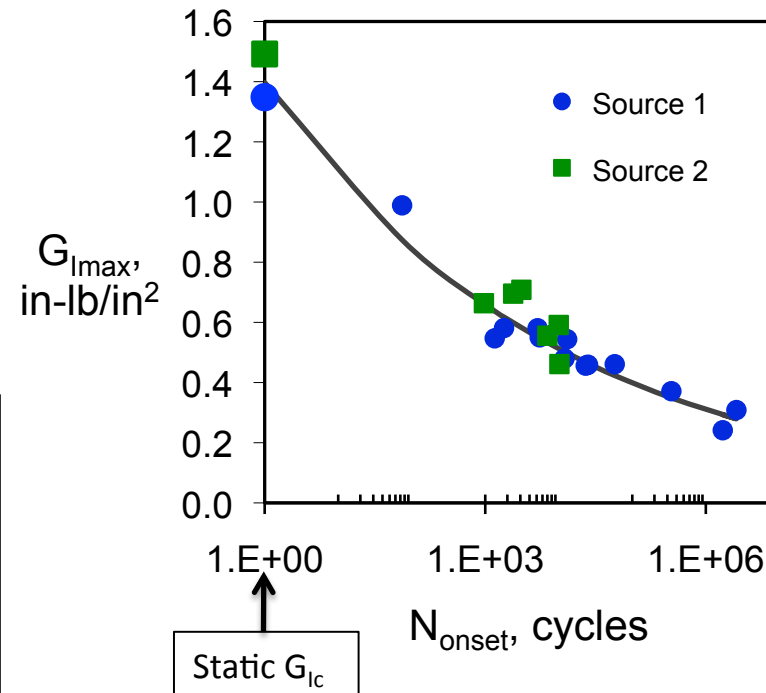
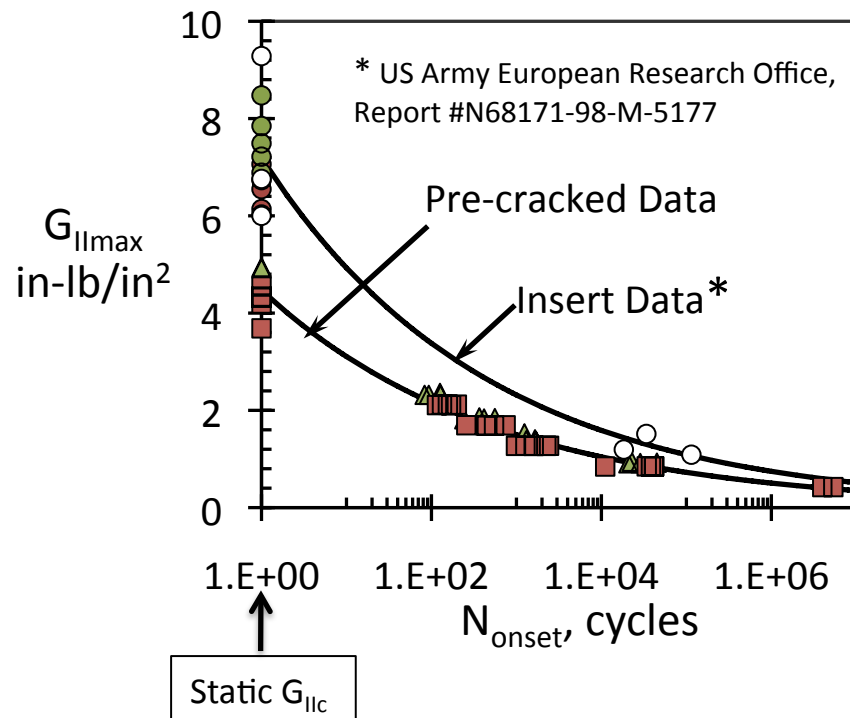
Micro-cracks coalesce to form the macroscopic delamination

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

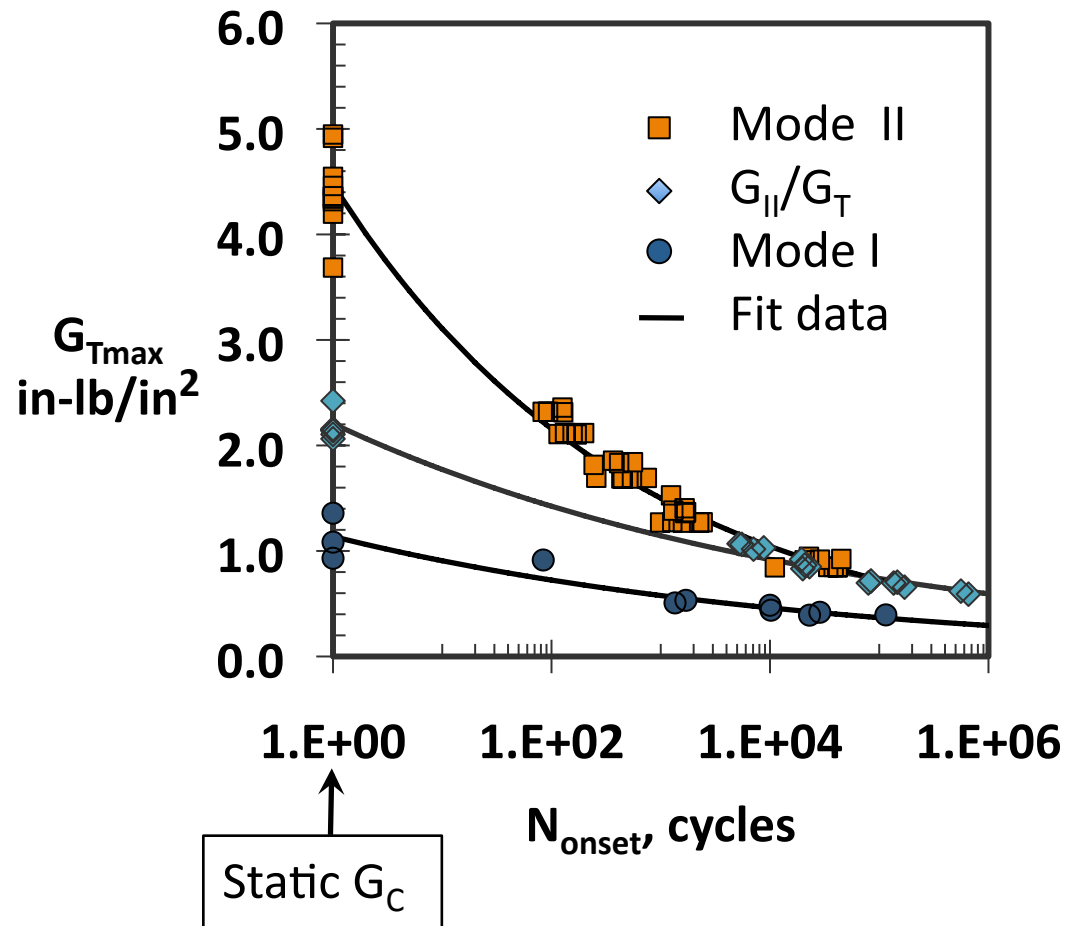
- Data from both sources follow same trend for both Mode I and Mode II
- Earlier onset in precracked Mode II specimens compared to tests from insert

Mode I/II Delamination Onset

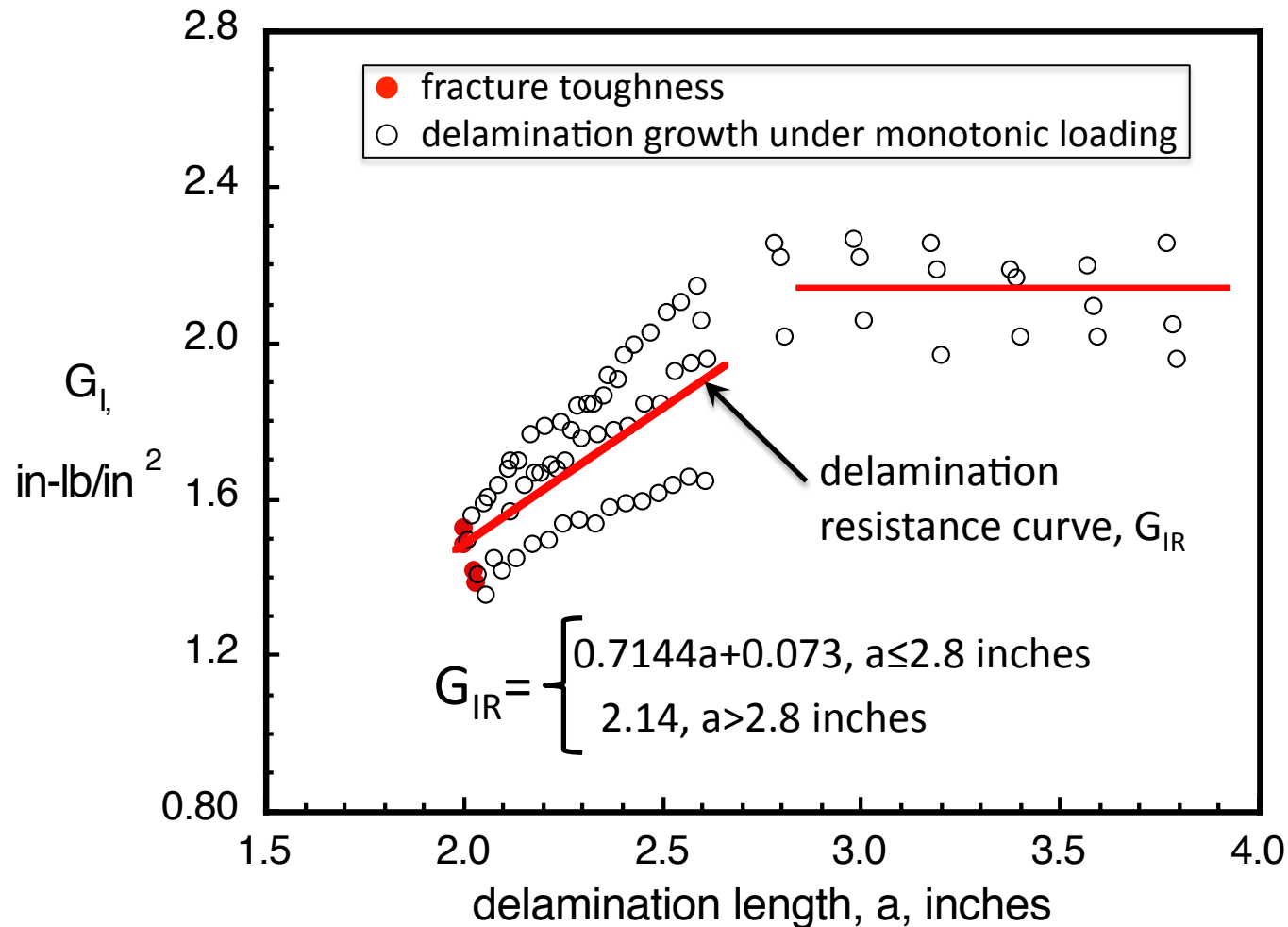


Test Matrix

- 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

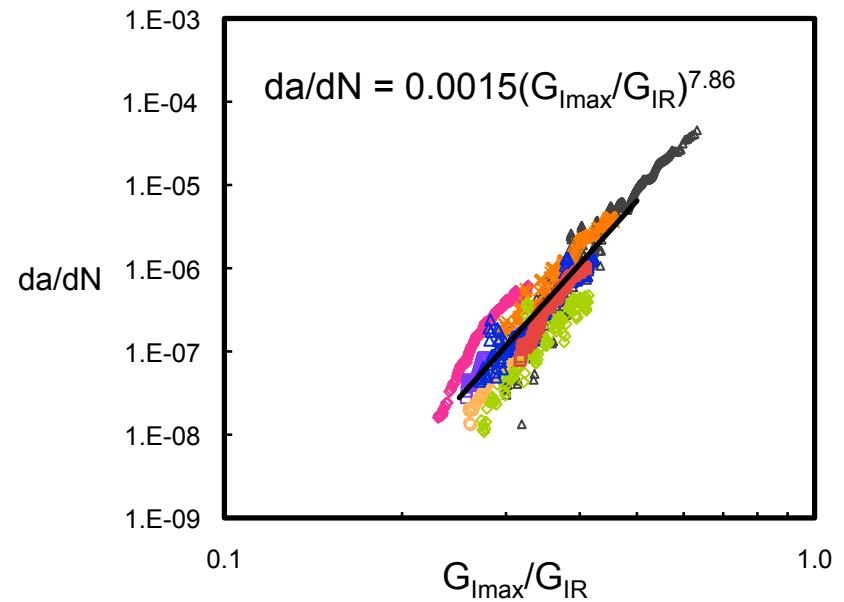
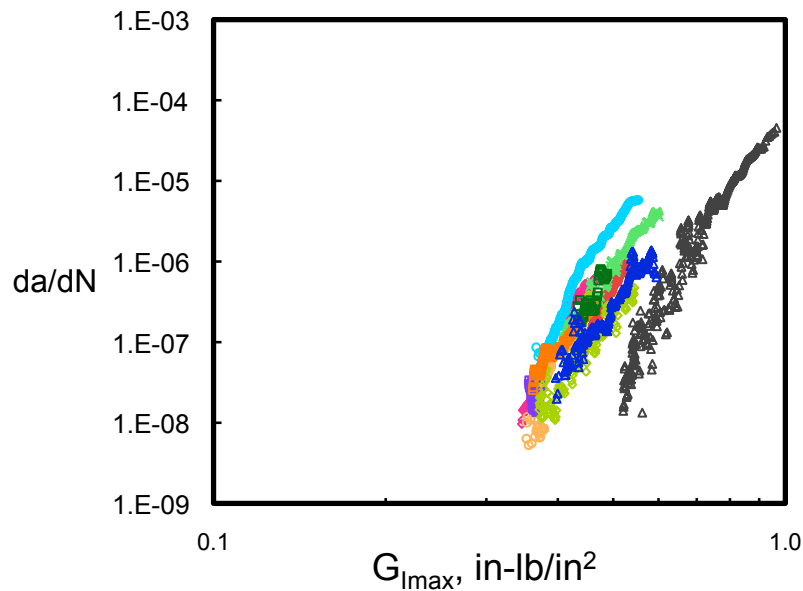


Delamination Resistance Curve for Mode I



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

Mode I Fatigue Delamination Growth



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 II Fatigue Delamination Growth



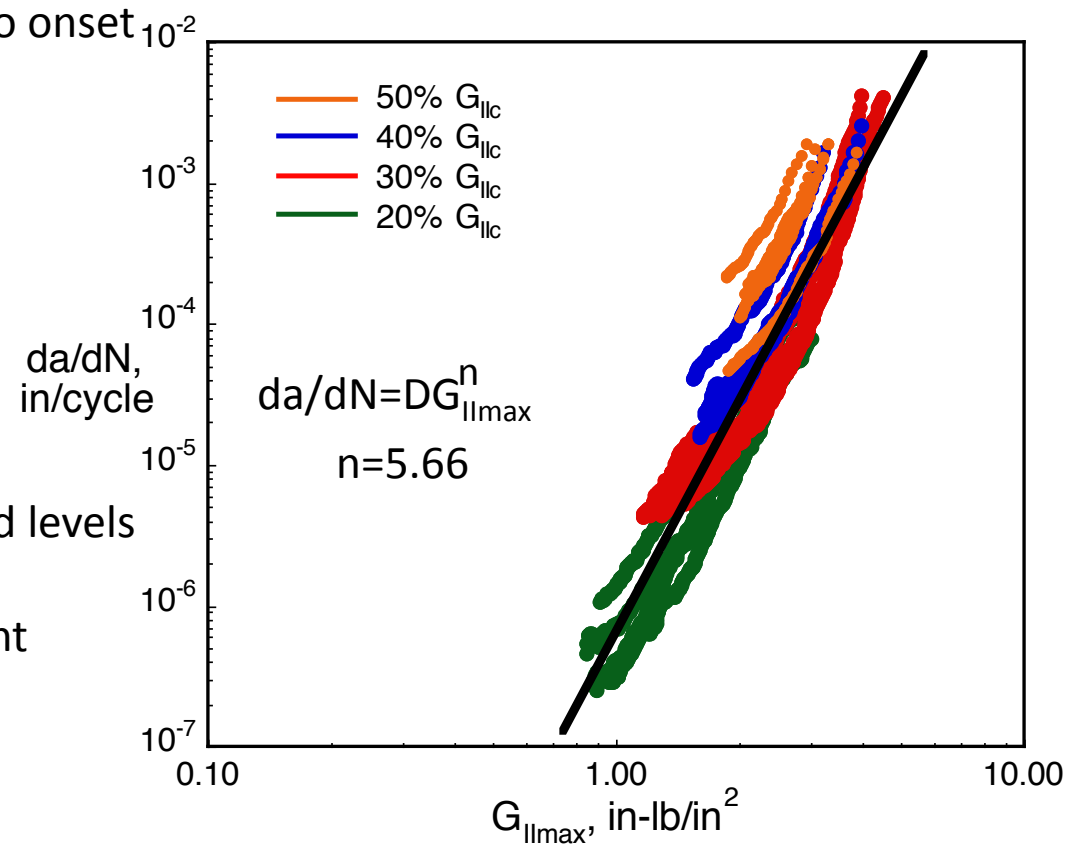
Test Matrix

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

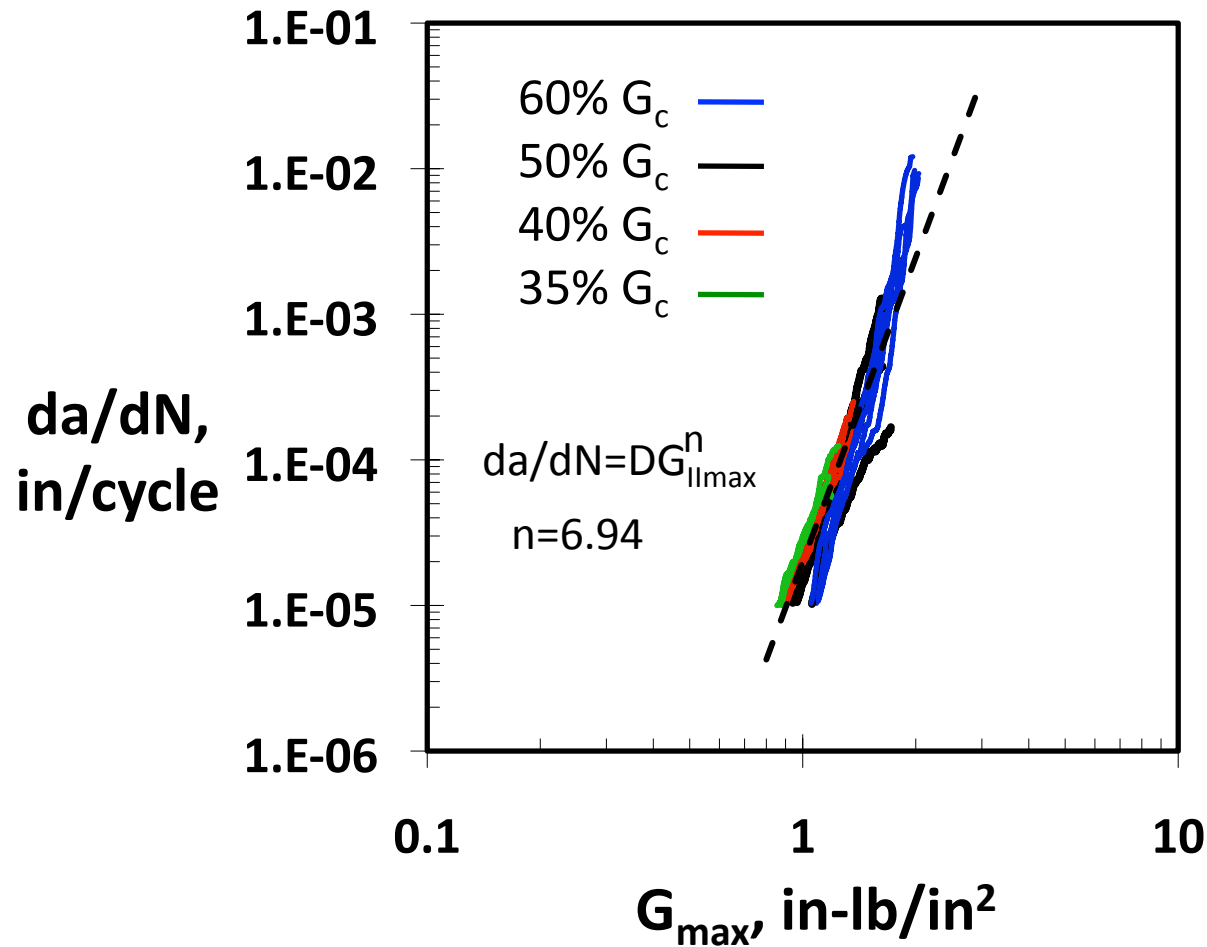
Results

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

Fatigue Growth Mode II



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

