Delamination/Disbond Arrest Features in Aircraft Composite Structures

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AMTAS Fall Meeting

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Sponsored Project Information

- **Principal Investigator:**
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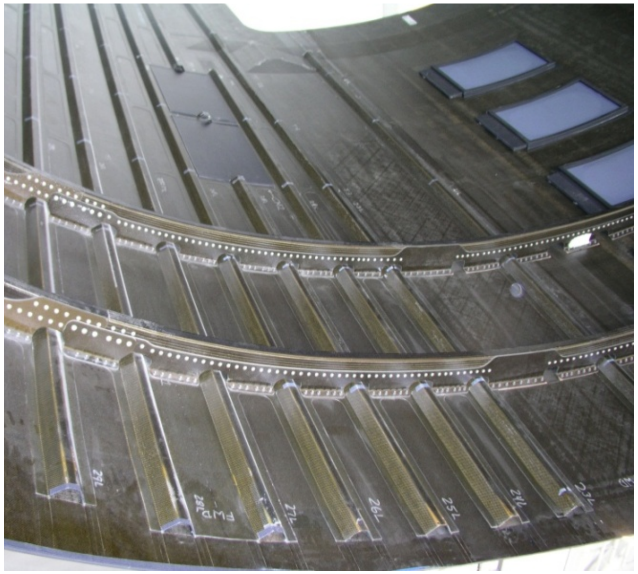
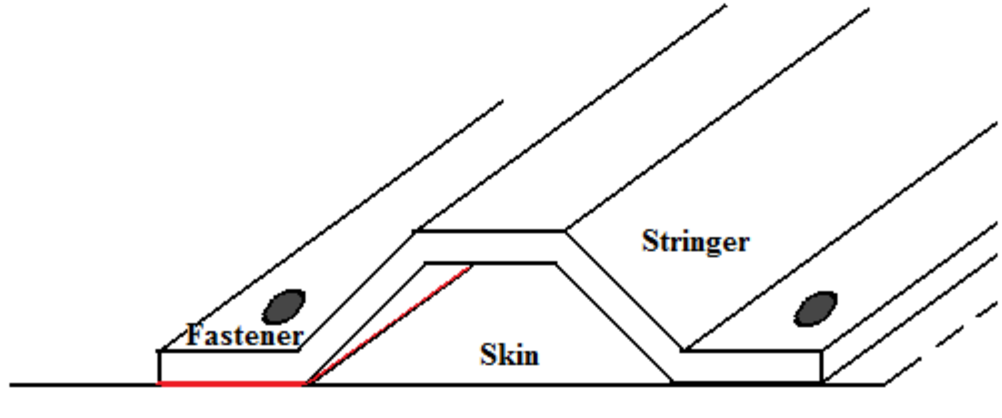
- **FAA Technical Monitor:** Lynn Pham
- **Other FAA Personnel:** Curtis Davies, Larry Ilcewicz
- **Industry Participants:**
  - **Boeing**: Marc Piehl, Gerald Mabson, Eric Cregger, Matthew Dilligan, Caihua Cao, Eric Sager
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Masahiro Hashimoto, Felix Nguyen
- **Industry Sponsors: Toray and Boeing**

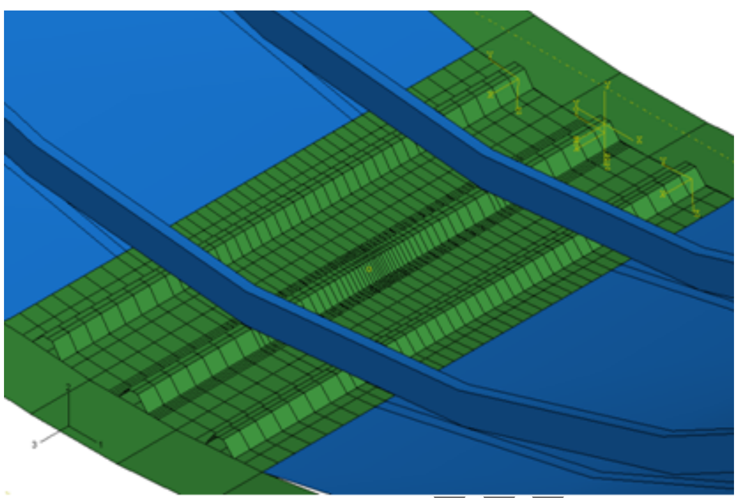
Research Objectives

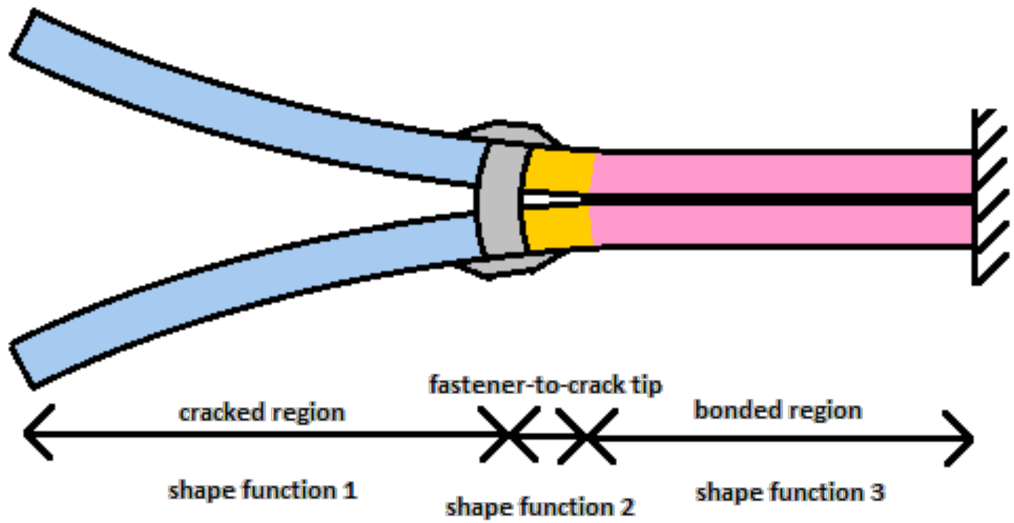
- Enhance accuracy of crack arrest capability predictions for varying laminate and fastener configurations
  - Develop understanding of crack propagation and arrest by multiple fasteners under static and fatigue loading
  - Develop knowledge of how crack propagation varies with different laminate configurations

Crack Arrest Mechanism by Fastener









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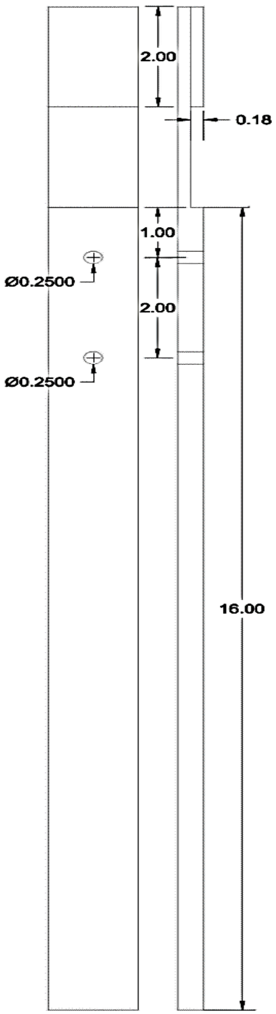
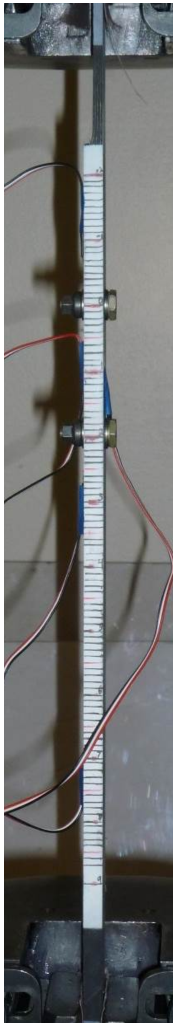
Background

- Motivation and Key Issues
  - Delamination is a critical damage type for laminated and bonded composite structures
  - Bolted joint design methodology is inefficient
- Objective
  - To understand the arrest process of delamination/disbond arrest features, particularly in novel configurations
  - To develop analysis tools for design and optimization
- Approach
  - Perform FEM analyses in ABAQUS with VCCT
  - Conduct sensitivity studies on fastener effectiveness
  - Conduct coupon-level experiments using novel specimens

Two Fastener Experimental Work

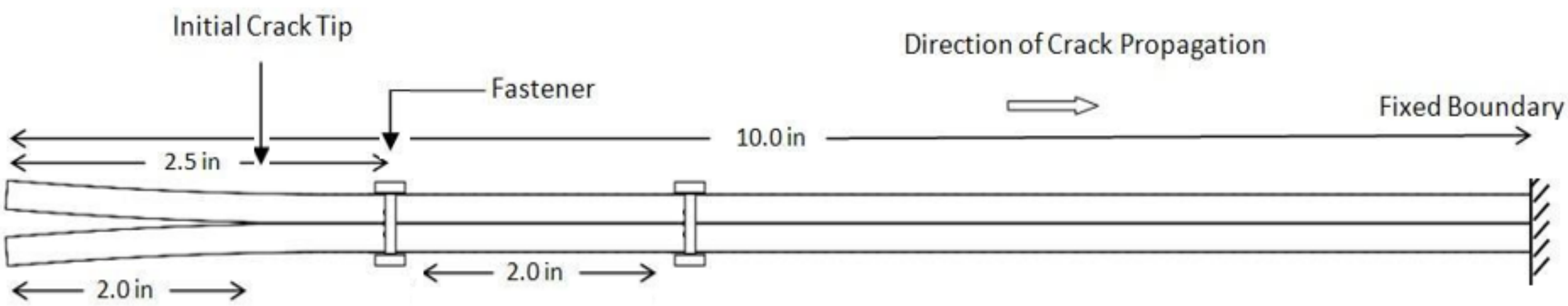




- T800S/3900-2B unidirectional pre-preg tape
- BMS 9-17 surplus unidirectional pre-preg tape
- 0.25 Inch titanium fasteners
- $(0/45/90/-45)_{3S}$
- Load rate 0.1 mm/min
- Crack tip tracked visually
- 0.1 in Scale

2-Plate Two-Fastener Finite Element Model

- Fastener flexibility (H. Huth, 1986) $C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1E_1} + \frac{1}{nt_2E_2} + \frac{1}{2t_1E_3} + \frac{1}{2nt_2E_3}\right)$
  - Thickness $t_1=t_2=0.18$ in., diameter d=0.25 in., E_x= laminate stiffness
  - Single Lap, bolted graphite/epoxy joint, constants taken as; a=2/3, b=4.2, n=1
- Fastener joint stiffness $k_{slide} = \frac{1}{C}$, Fastener tensile stiffness $k_{clamp} = \frac{AE}{(t_1 + t_2)}$
- Fracture parameters, G_{IC}=1.6 lb/in, Nominal $G_{IIC}=G_{IIIC}$=14 lb/in
  Measured: 12 lb/in (BMS 8-276) 10 BMS 9-17)
- Power Law fracture criterion $\left(\frac{G_I}{G_{IC}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIC}}\right)^\beta + \left(\frac{G_{III}}{G_{IIIC}}\right)^\delta \leq 1$
  $\alpha = \beta = \delta = 1$ linear mode mixture assumed
- Fixed boundary condition similar to test; grips not modeled
- Friction coefficient assumed to be fixed value or zero



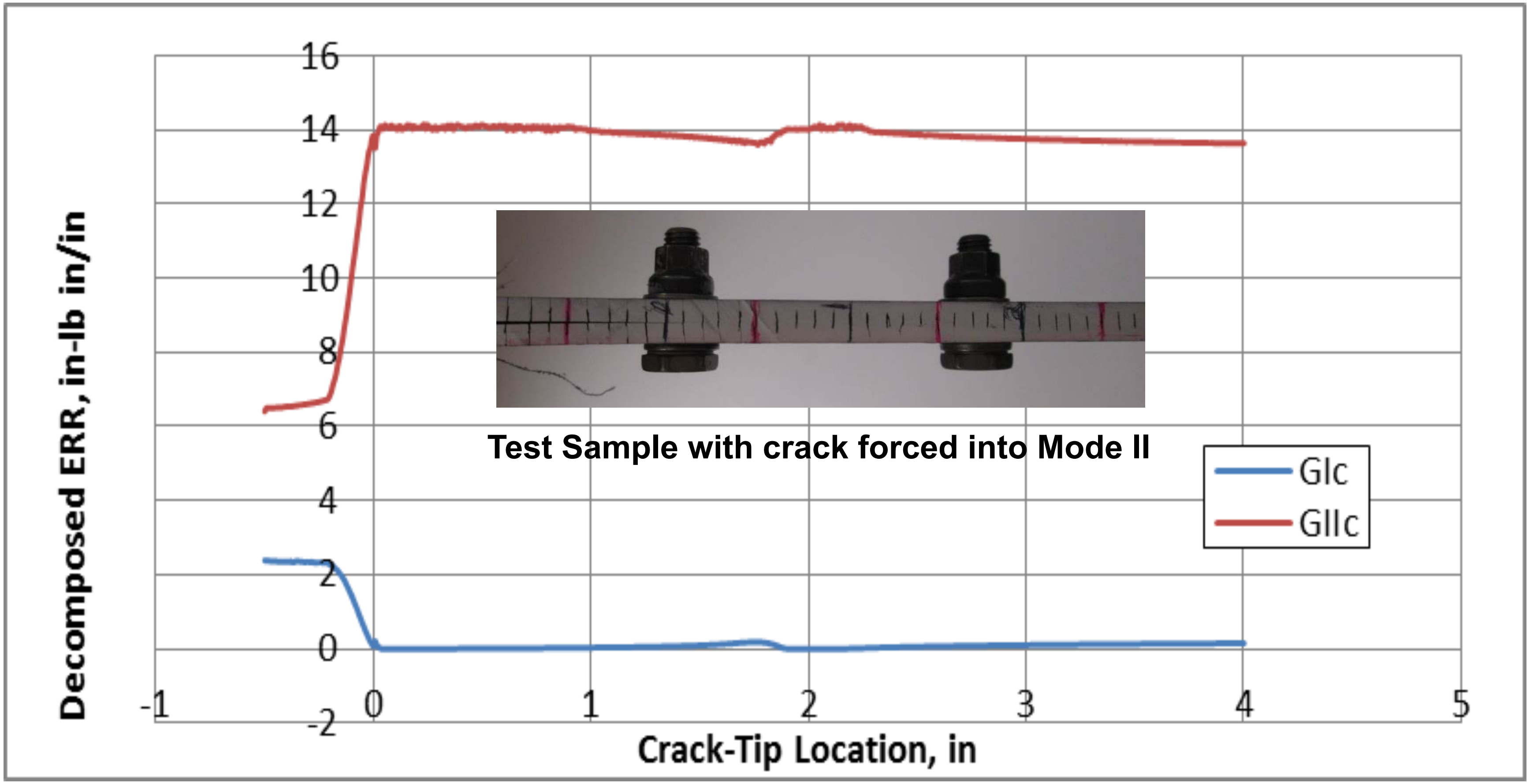
Clearance

- Typical ¼ inch bolt clearance 0.007-0.016 in.
  - Previous single and multiple fastener research utilized zero clearance (tight fitting hole)
- Bolt clearance and fracture toughness varied
  - Fastener stiffness set as zero over ±0.007-0.016 inch span
  - Fracture toughness varied from 5 to 14 lb/in to capture two different material systems

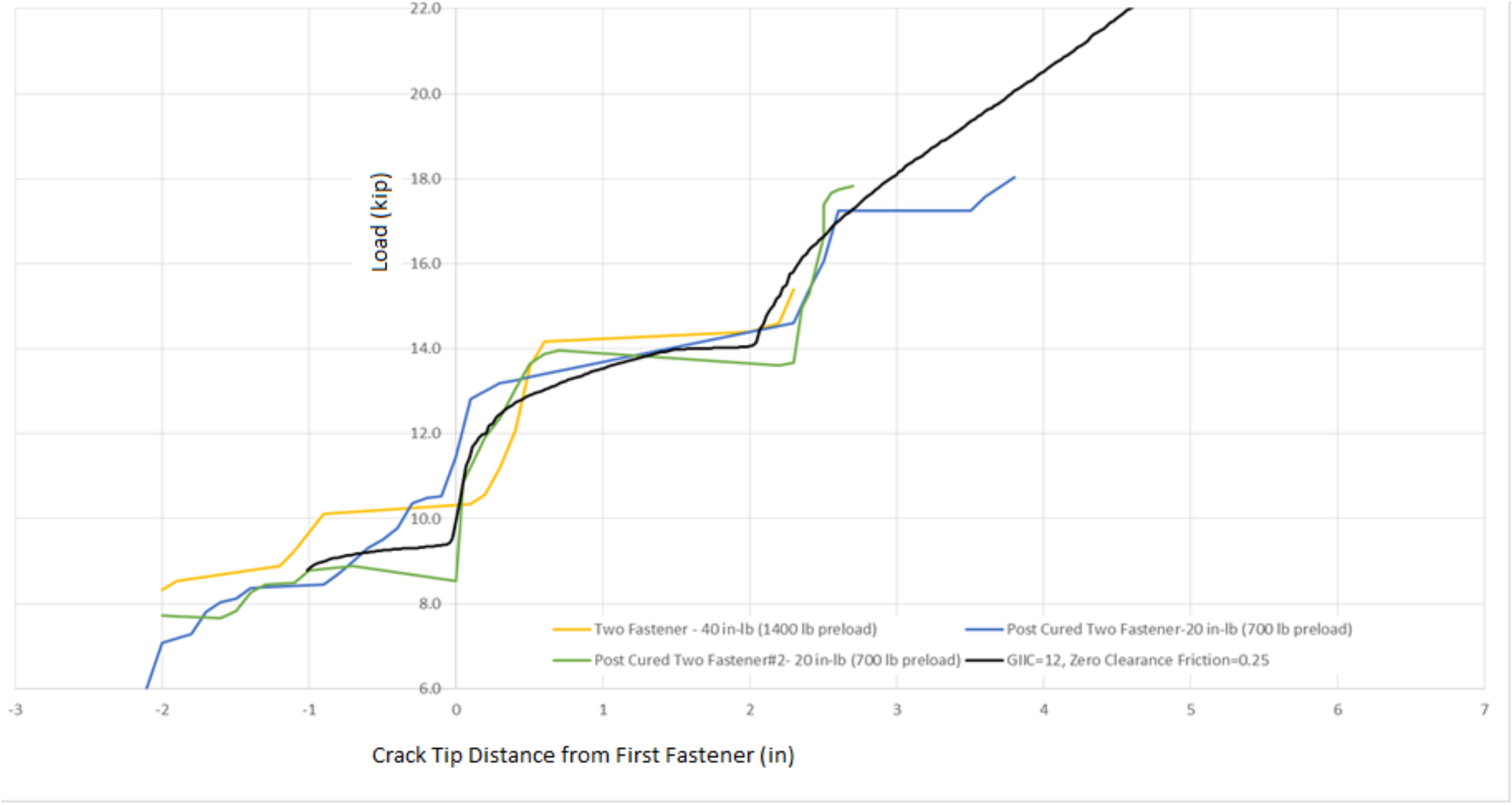
Results

- Delamination Arrest Mechanism
  - Mode I suppression
    - Propagation load increases as $G_{IIC} > G_{IC}$
  - Fastener flexibility is a major driver of arrest
  - Clearance greatly influences arrest capability by delaying fastener engagement
  - Crack-face friction slows propagation
- Limitations
  - Delamination can steer around the fastener's grip
  - Friction is poorly understood

Two-Fastener Analysis of SERR vs. Crack Tip Location



Experimental vs. Analytical Results 0 Clearance



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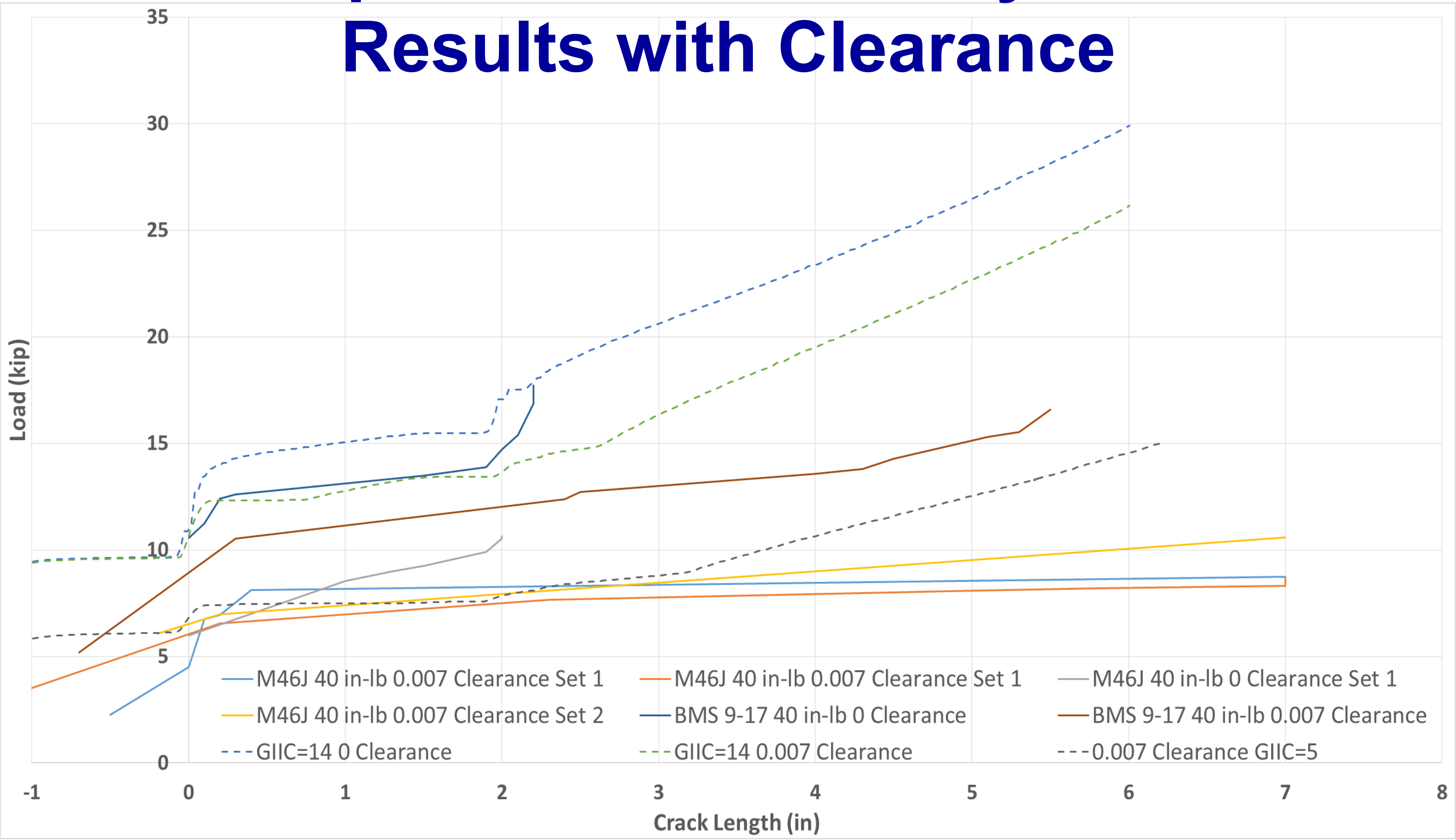
Experimental vs. Analytical Results with Clearance



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Co-Cured Vs. Secondary Bonded

- All Test results shown are for cocured structures
  - Delamination resistance is governed by matrix properties
  - Structural adhesives typically have higher fracture toughness
- Previously delaminated samples re-bonded
  - Hysol EA9309 structural adhesive
    - Chosen for advertised shear properties
  - Secondary bonded structures failed prior to crack propagation
    - Crack driven off bondline and into laminate
    - Effective Mode II fracture toughness increased

Current Tasks

- Further Develop Analysis for Multiple Fasteners
  - Develop multi-dimensional modeling capability
    - Accurately model propagation with varying levels of detail
  - Conduct sensitivity studies
    - Fracture toughness shifts curve vertically
    - Optimize fastener pitch and pattern
- Fatigue Studies
  - Two fastener quasi-static modeling demonstrated
    - Fatigue predictions and performance unverified
  - Establish hybrid bolted/bonded joint performance in fatigue
    - Develop predictive capability based on pristine fatigue properties

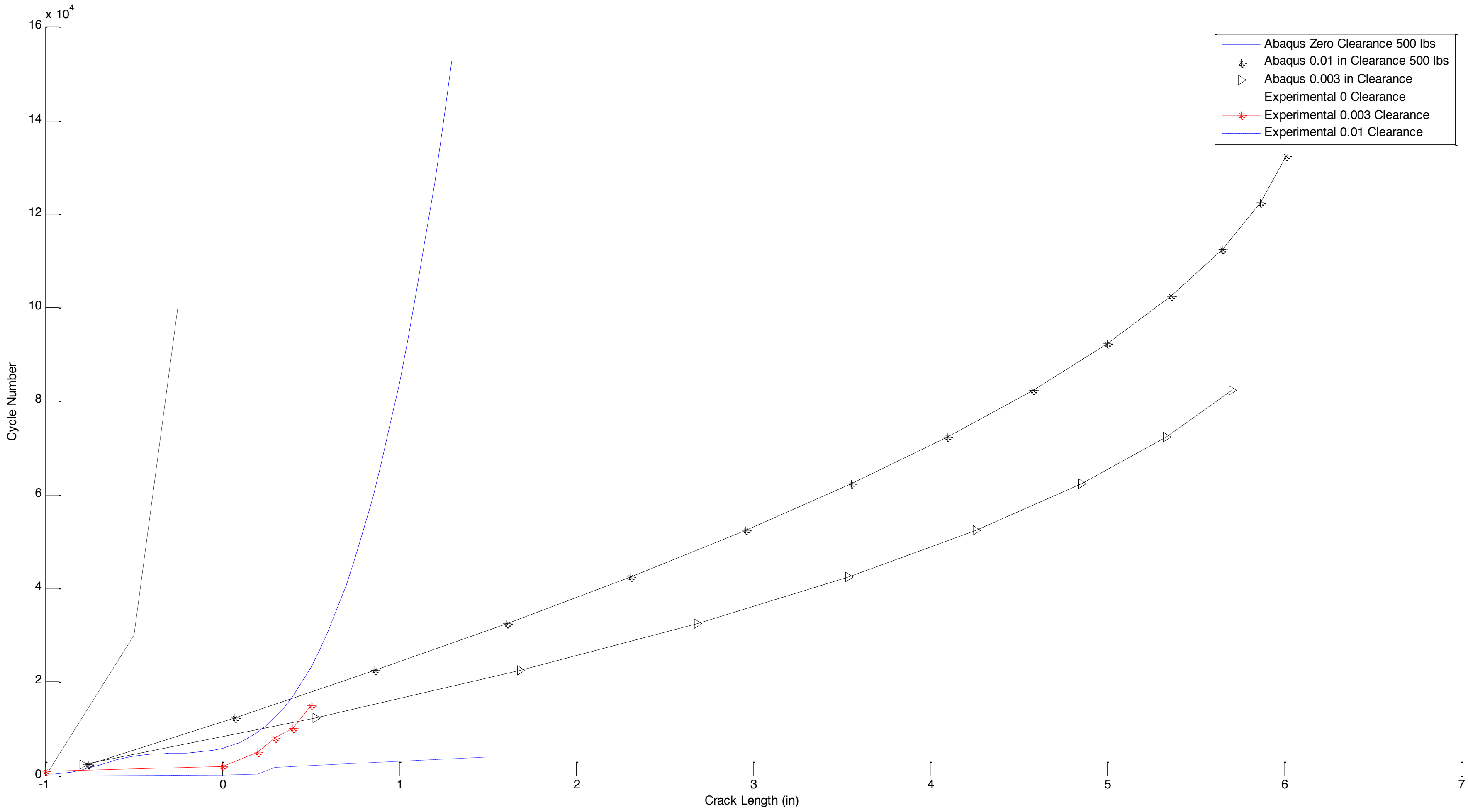
Fatigue Modeling

- Identical two dimensional model
  - Fatigue properties currently sourced from literature
  - Sinusoidal and triangular loading simulated
  - Zero and positive clearance simulated
  - Hole damage not currently modeled
- Dramatic fatigue life difference due to clearance
  - Consistent result both in tension-tension and tension-compression loading
- Hole damage may be critical factor
  - Even 0.001 in clearance results in lower fatigue life

Fatigue Testing

- Fastener has no effect on high cycle fatigue
  - No crack propagation to suppress
- Fastener hole treatment has significant effect on low cycle fatigue
  - Crack arrest capability greatly reduced by the inclusion of clearance
  - Poorly drilled clearance holes performed better than well drilled clearance holes
    - Effective clearance reduced
- Hole damage may be critical factor
  - Not visible on tested samples

Fatigue Results



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Work in Progress

- Evaluate fatigue performance
  - Establish Da/Dn curves of unfastened structure
  - Establish relation between unfastened and fastened performance
- Establish boundaries of arrest capability
  - Asymmetric laminates experience greater crack growth
  - Can non-uniform fastener patterns be more efficient
- Investigate alternative or supplementary arrest features
  - Fastener tensile strength is excessive for configuration
  - Clearance minimization is key
  - Secondary or co-bonding may increase effective fracture toughness

Future Work

- Predict fatigue performance
  - Develop predictive abilities based on fatigue performance of coupon testing
  - Understand critical differences between static and fatigue performance of bolted bonded/joints
    - Hole damage not visible in quasi-static testing
  - Use knowledge developed from quasi-static work to predict fatigue performance of varying layup
- Predict limitations of fastener arrest
  - Analytically determine damage scenarios where multi-fastener arrest features are insufficient for full crack arrest

Future Work

- Establish security of bond assisted joints
  - Demonstrate sufficient fastener quantity for debonds to be considered arrested
  - Reduce structural weight with load transfer through bondline as well as fasteners
- Develop alternative/supplementary arrest features
  - Can crack arrest fasteners be modified for improved arrest at lower weight?
  - Reduce/eliminate hole clearance without sacrificing manufacturability

Looking Forward

- Benefit to Aviation
  - Tackle a crucial weakness of laminate composite structures
  - Reduce risks (analysis, schedule/cost, re-design, etc.) associated with delamination/disbond mode of failure in large integrated structures
  - Enhance structural safety by building a methodology for designing fail-safe co-cured/bonded structures
- Future needs
  - Further fatigue testing to establish parameters
  - Initiation investigation of crack propagation through fastener arrays
  - Industry/regulatory agency inputs related to the application, design, and certification of this type of crack arrest feature

Question and comments are strongly encouraged.

Thank you.

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