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Delamination/Disbond Arrest Features in Aircraft Composite Structures

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JAMS 2014 Technical Review
March 25-26, 2014

Sponsored Project Information

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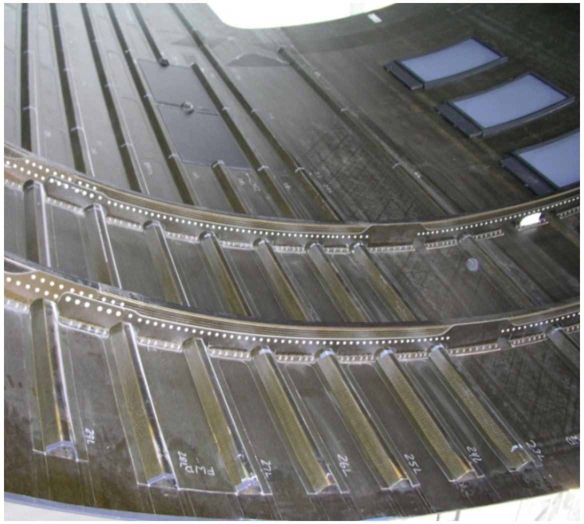
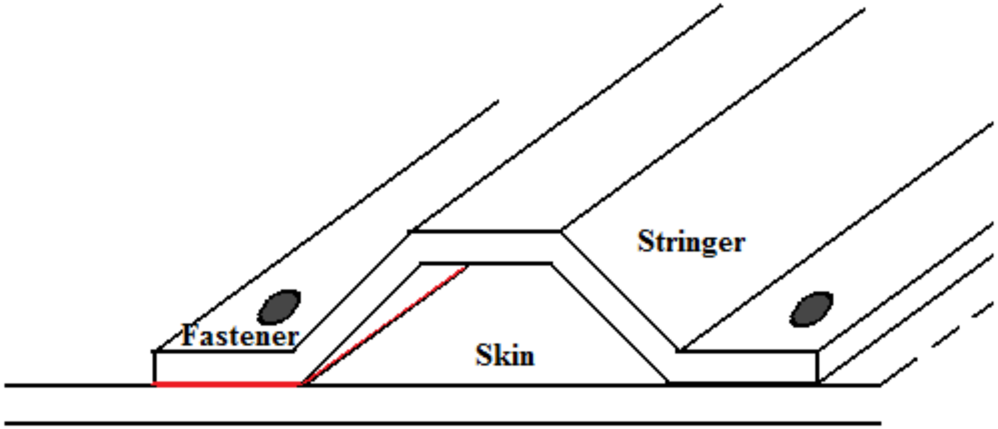
- **FAA Technical Monitor:** Lynn Pham
- **Other FAA Personnel:** Curtis Davies, Larry Ilcewicz
- **Industry Participants:**
  - **Boeing**: Marc Piehl, Gerald Mabson, Eric Cregger, Matthew Dilligan, Steve Precup
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Masahiro Hashimoto, Felix Nguyen
- **Industry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

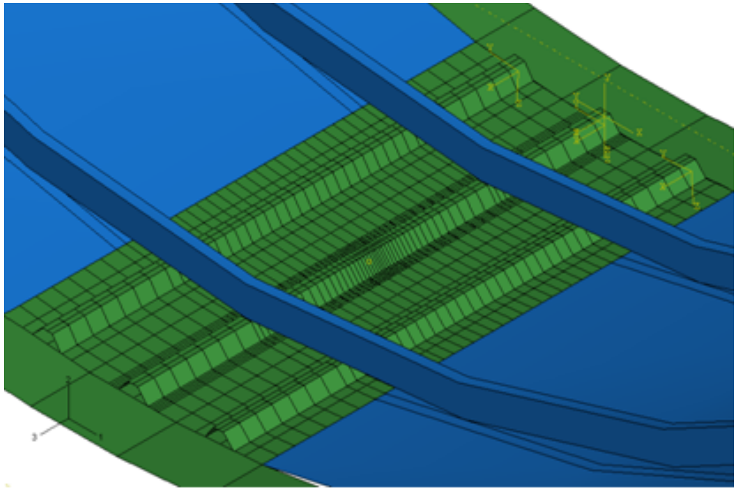
Research Objectives

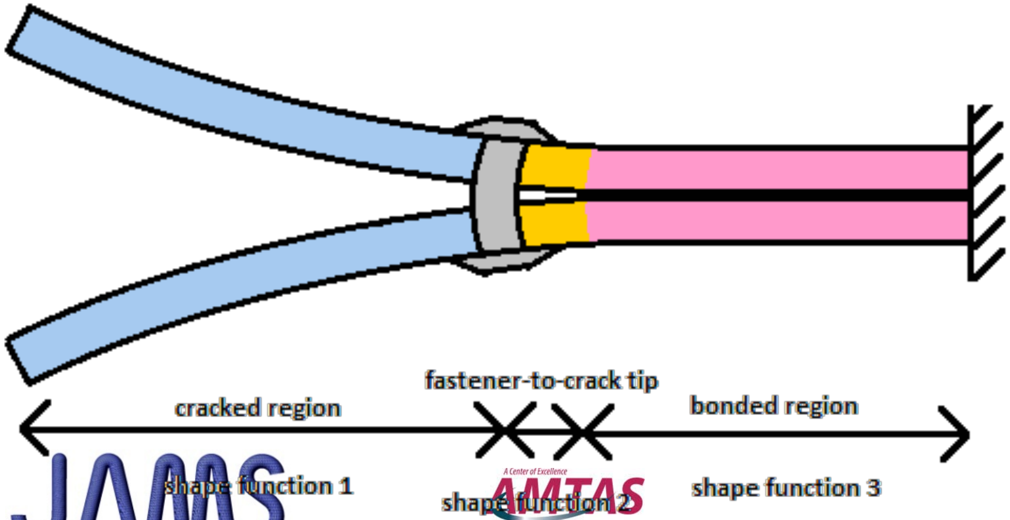
- Enhance accuracy of crack arrest capability predictions for varying laminate and fastener configurations
  - Develop understanding of crack propagation and arrest by multiple fasteners
  - Develop knowledge of crack propagation variations under different laminate configurations

Crack Arrest Mechanism by Fastener





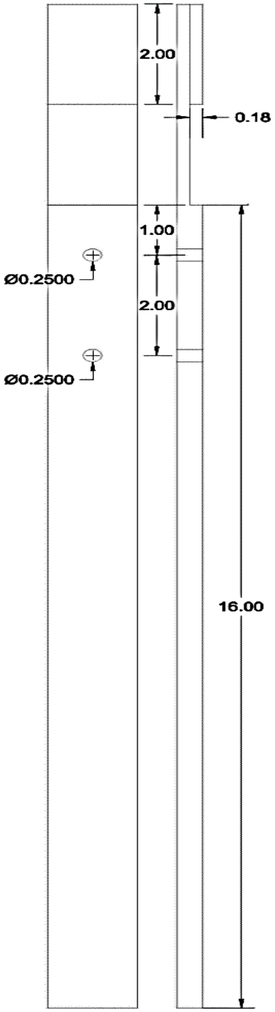


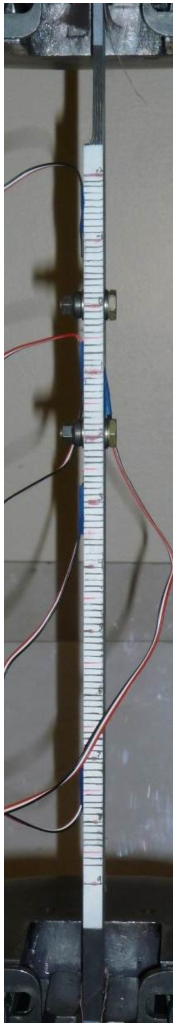


Background

- Motivation and Key Issues
  - Delamination is critical damage for laminated and bonded composite structures
  - An isolated fastener is unable to fully arrest delamination
- Objective
  - To understand the effectiveness of delamination/disbond arrest features
  - 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



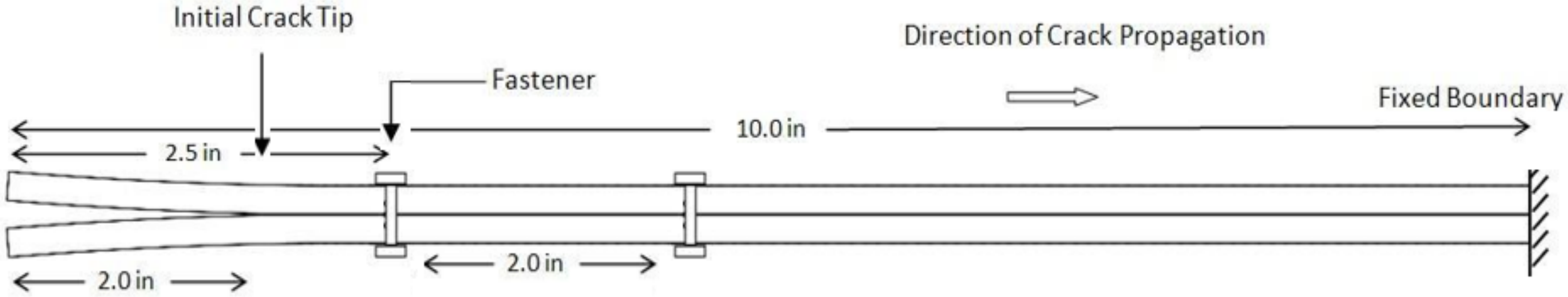


- T800S/3900-2B surplus unidirectional pre-preg tape
- BMS 8-308 peel ply
- 0.25 Inch titanium fasteners
- $(0/45/90/-45)_{3S}$
- Load rate 0.1 mm/min
- Crack tip tracked visually
- 0.1 in Scale

2-Plate Two-Fastener Finite Element Model

- Fastener flexibility (H. Huth, 1986) $C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{2 t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$
  - 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, G_{IIC}=G_{IIC}=14 lb/in.
- 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

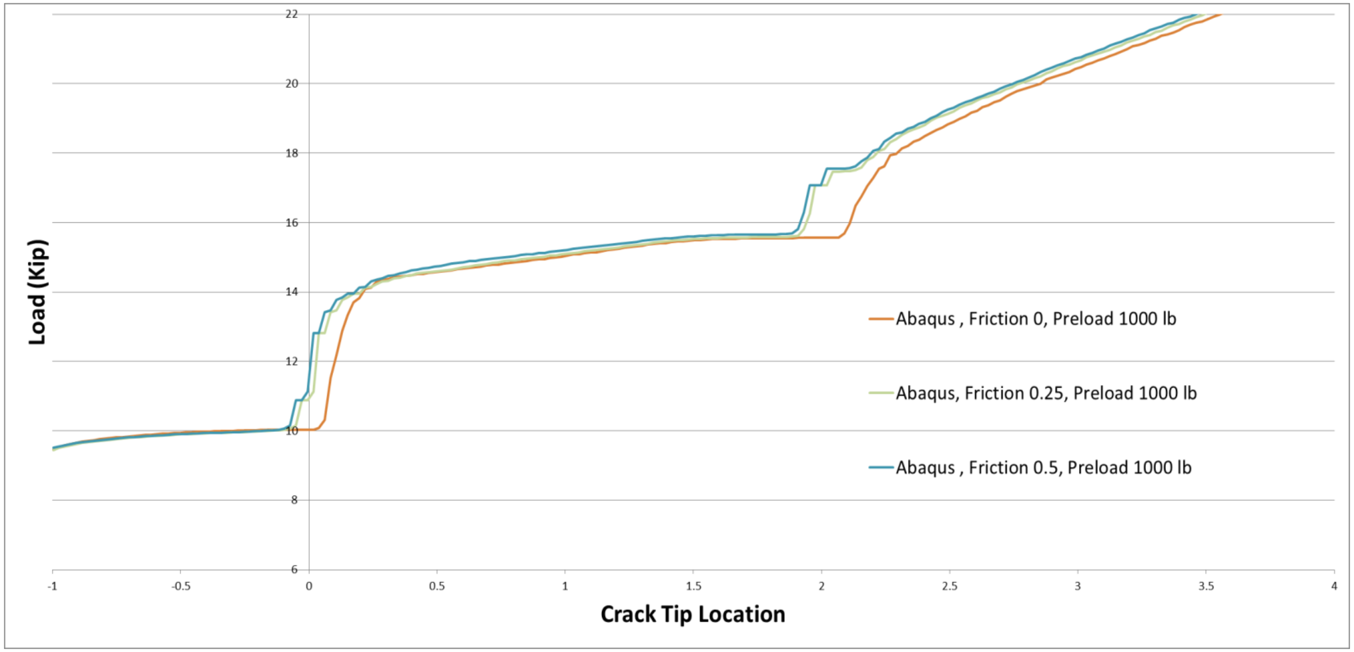


Results

- Delamination Arrest Mechanism
  - Mode I suppression
    - Propagation load increases as $G_{IIC}>G_{IC}$
  - Fastener flexibility is a major driver of arrest
  - Crack-face friction slows propagation
    - Crack Arrest fastener becomes effective before crack passes bolt
- Limitations
  - Crack-face friction is poorly understood and rarely studied, difficult to model
  - Delamination could steer around the fastener's grip
  - Crack front advances faster at sample edges
    - Results in offset of experimental vs. FEM results

Arrest Effectiveness vs. Friction Modeling

- Inclusion of friction increases arrest capability by 10% for constant coefficient of 0.5, preload of 1000 lbs (40 in-lb installation torque)
- Reduction of friction to 0.25 reduces arrest capability by 3%, 300 lbs of load for a 1.25 inch specimen
- Increase in friction coefficient provides diminishing returns



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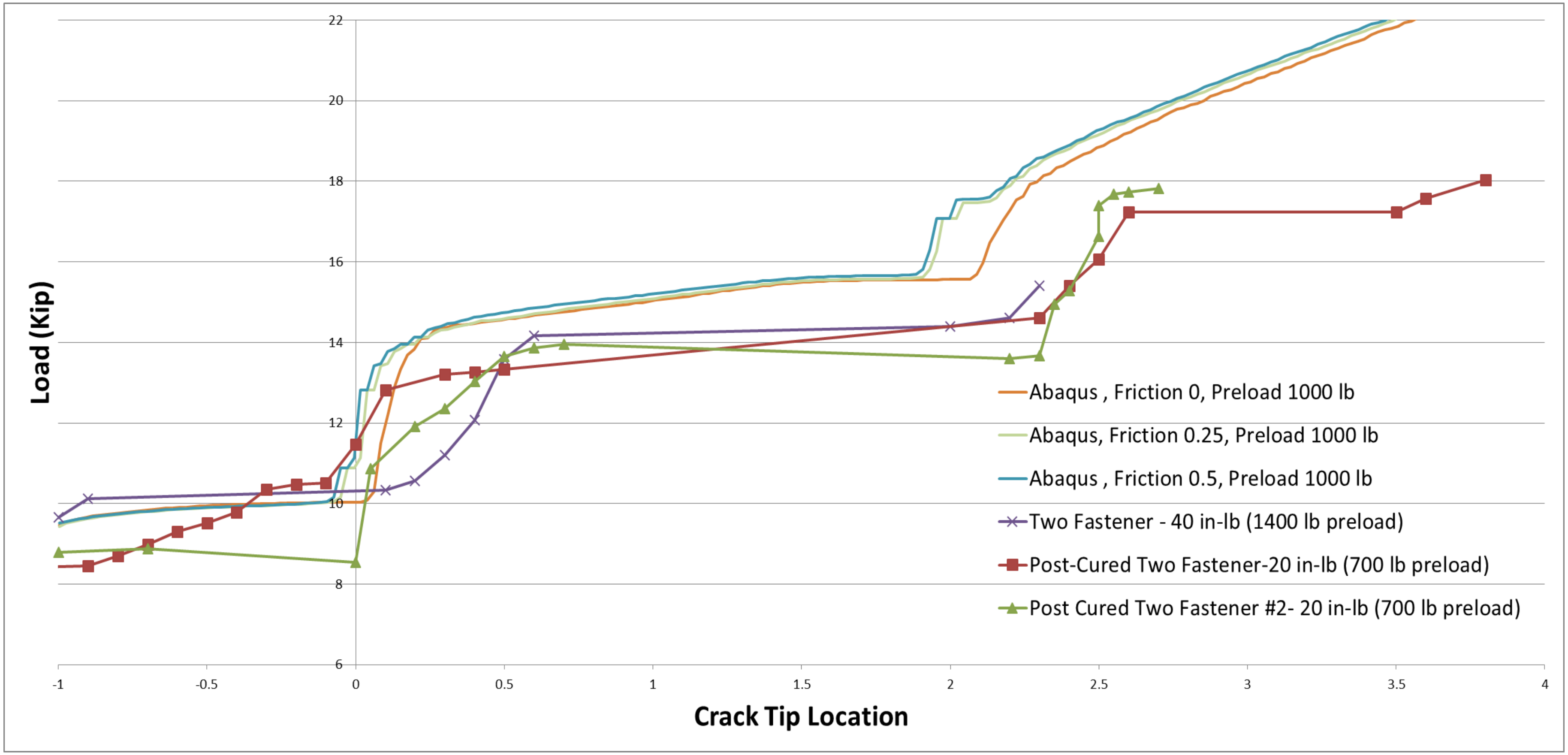
Experimental vs. Analytical Results



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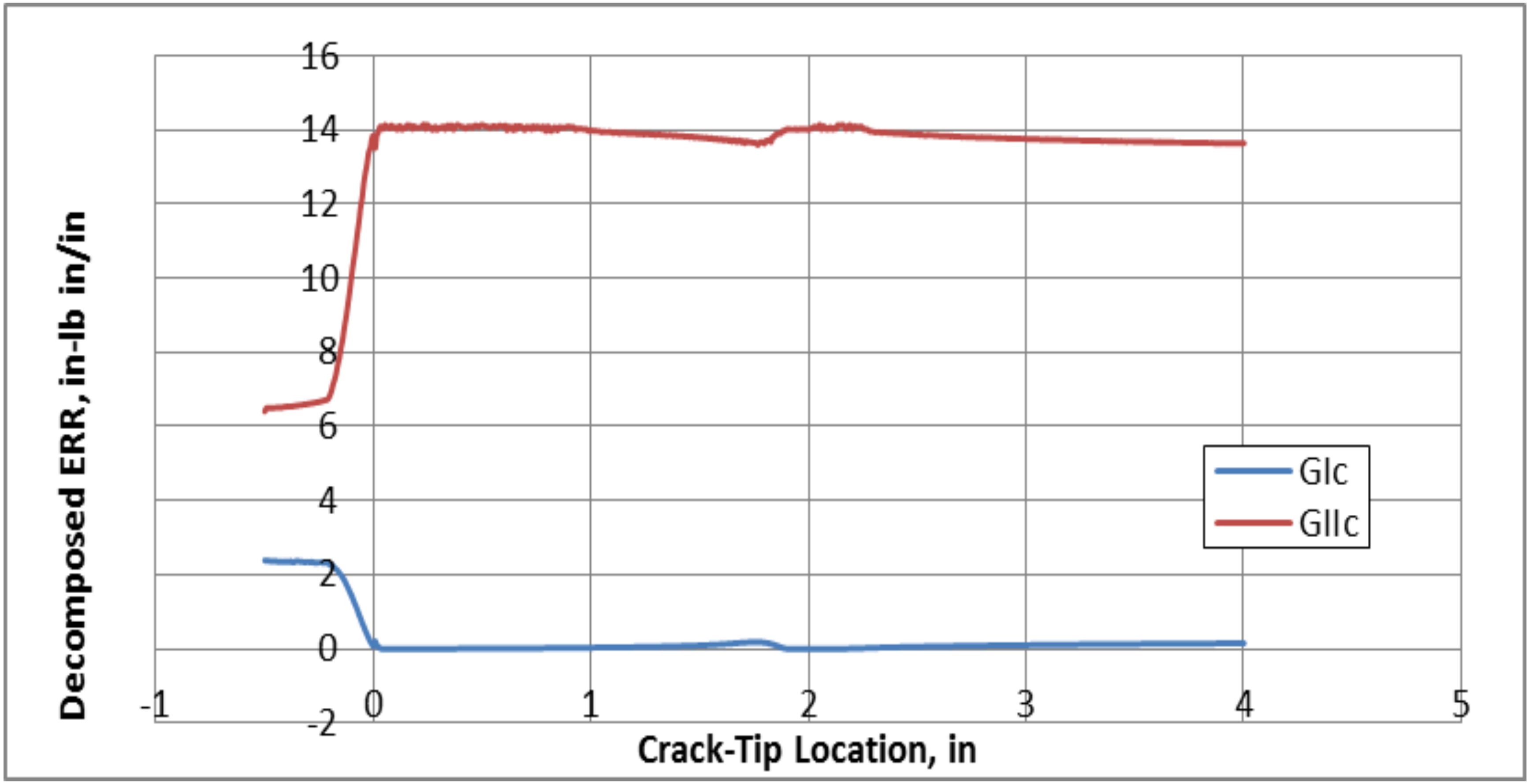
Two-Fastener Analysis of SERR vs. Crack Tip Location



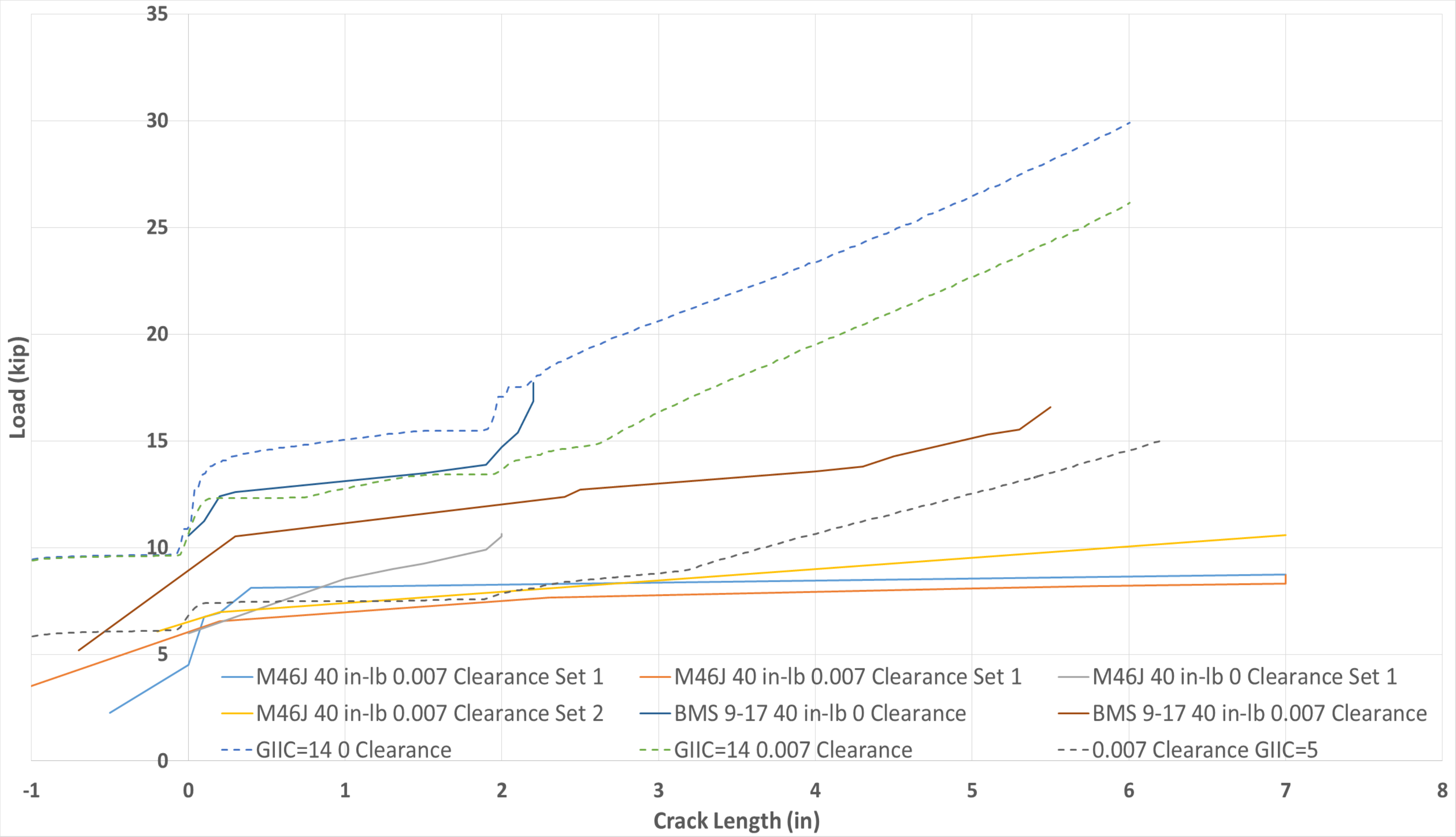
Clearance Testing

- Typical ¼ inch bolt clearance 0.007-0.016 in.
  - Previous single and multiple fastener research utilized zero clearance (tight fitting hole)
    - Preliminary sample set tested
      - 0.2500” hole, 0.2570” hole, 0.2660” hole,
      - $[(0/45/90/-45)_{3S}]_S$ and $[(0/45/90/-45)_{3S}/(0/45/0/-45/0/90)_{2S}]$
- Unstable crack propagation occurs in samples with clearance holes
  - Crack extends from first fastener to end of sample
  - Phenomena not fully captured in ABAQUS simulations

Clearance Modeling

- 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
- Stability of Crack propagation decreased
  - Crack is able to pass by fasteners prior to resistance
  - Clearance delays engagement of fastener in shear
  - Stiff laminates with a low fracture toughness experience most dramatic decrease in arrest capability

Clearance Testing



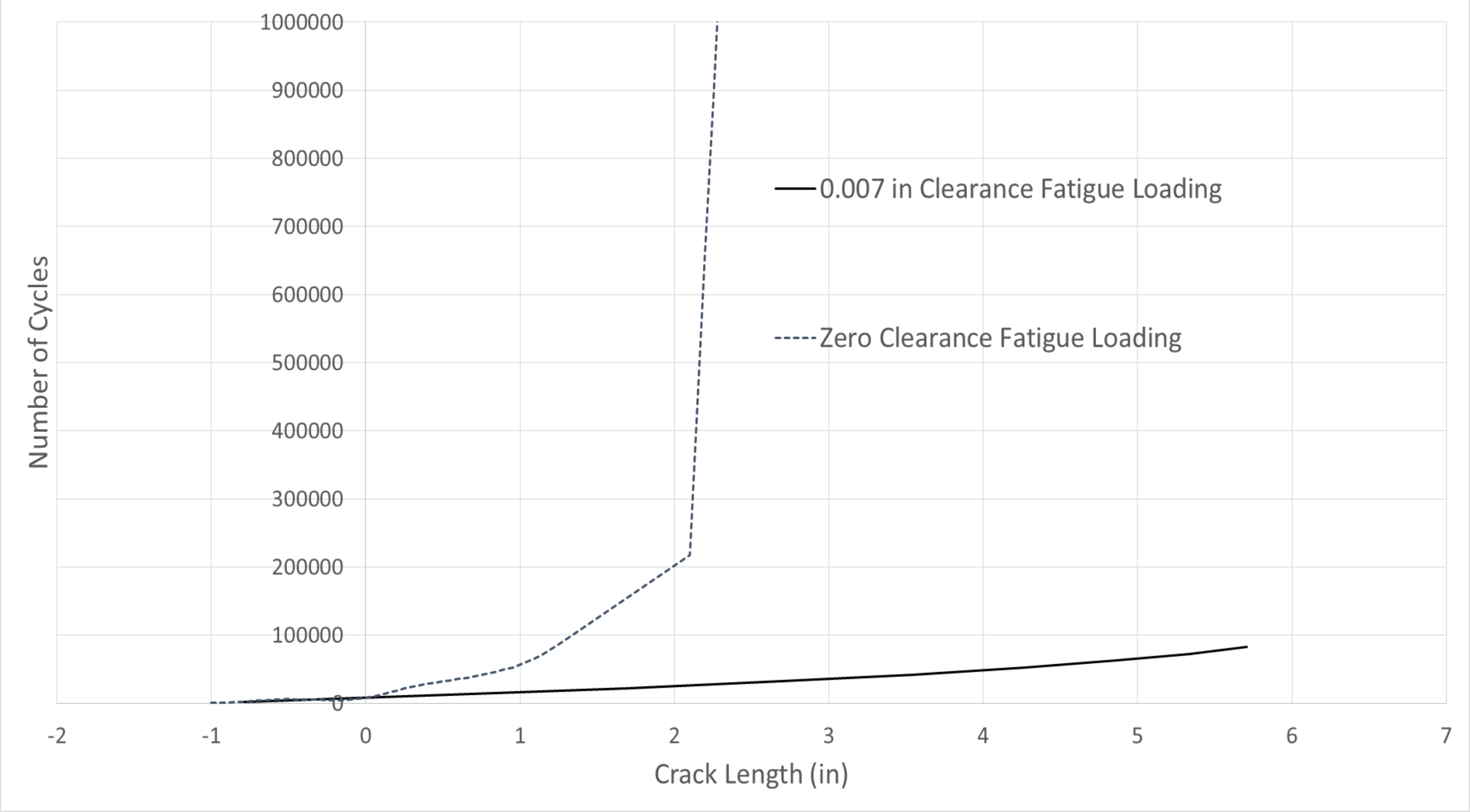
Current Tasks

- Further Develop Analysis for Multiple Fasteners
  - Expand modeling capability
    - Accurately model propagation of varied configurations
  - Understand possible sources of modeling error
    - Model sensitive to shear spring placement
    - Hole damage not modeled
- 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
  - Damage accumulation not currently modeled
- Dramatic fatigue life difference due to clearance
  - Consistent result both in tension-tension and tension-compression loading

Fatigue Modeling



Work in Progress

- Evaluate fatigue performance
  - Crack propagation expected to occur at subcritical loads
  - Samples fabricated and being tested
  - Develop predictive abilities based on fatigue performance of coupon testing
- Verify effectiveness of fasteners in series
  - Determine scenarios where two fasteners in series may be insufficient
  - Test varied configurations to ensure model capacity

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
  - Initiate research areas core to the interlaminar mode of failure, e.g. friction, fastener clamp-up
  - 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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