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Delamination/Disbond Arrest Features in Aircraft Composite Structures

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JAMS Technical Review

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Sponsored Project Information

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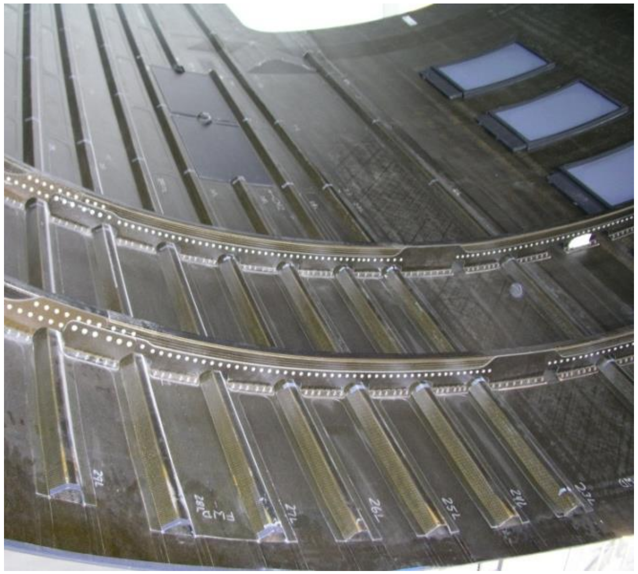
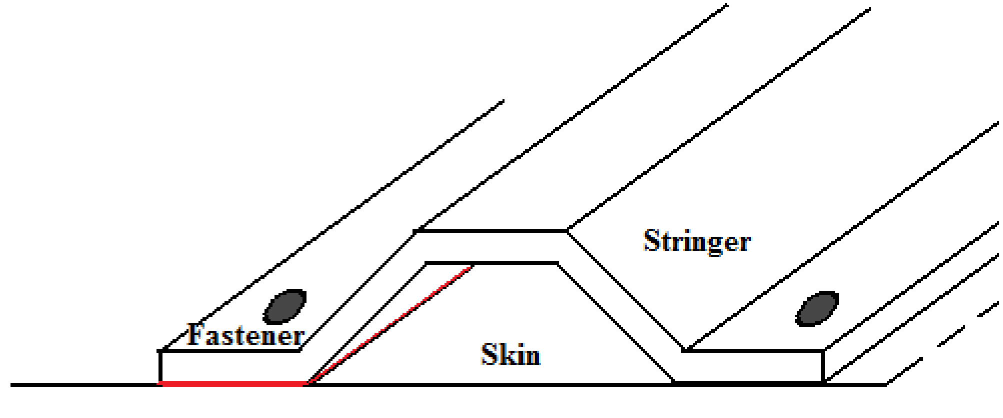
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Masahiro Hashimoto, Felix Nguyen
- **Industry Sponsors: Toray and Boeing**

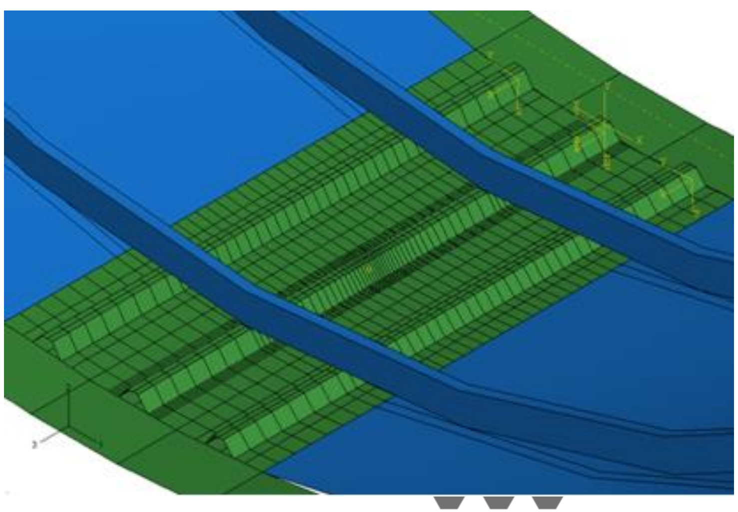
Background

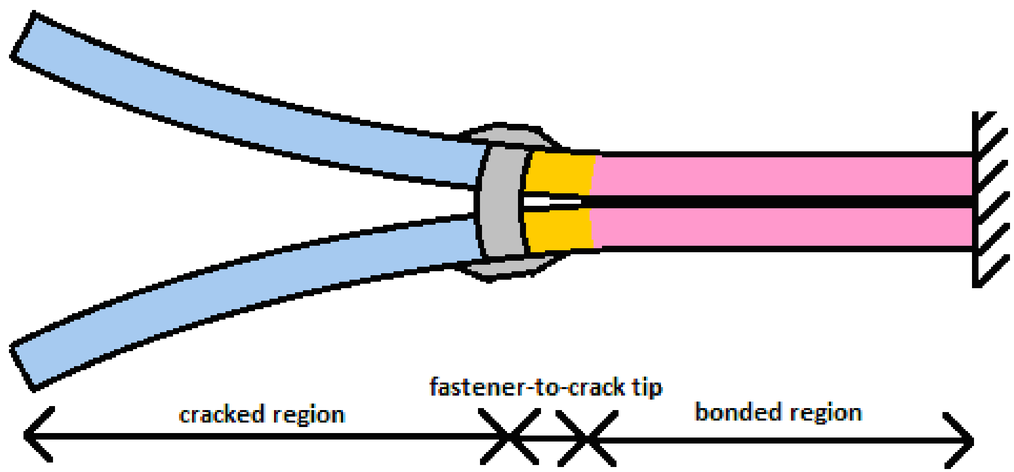
- Motivation and Key Issues
  - Delamination is a critical damage type for laminated and bonded composite structures
  - Bolted joint and point testing design is inefficient
- Objectives
  - Understand the arrest process of a delamination/disbond
  - Develop analysis tools/techniques for design and optimization
  - Verify general applicability of design tools/techniques
- Approach
  - Perform FEM analyses in ABAQUS with VCCT
  - Develop custom models for design and optimization
  - Conduct coupon-level experiments

Crack Arrest Mechanism by Fastener









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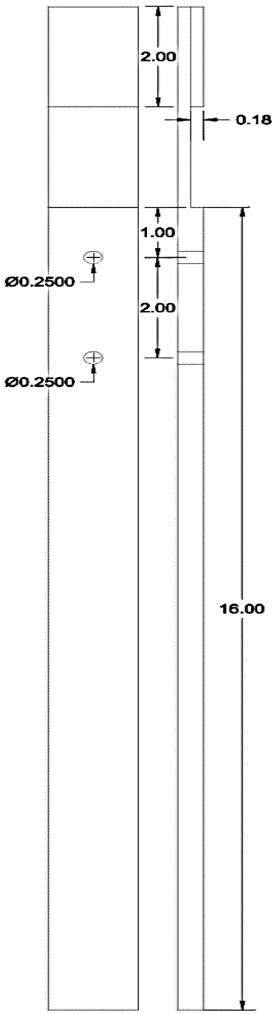
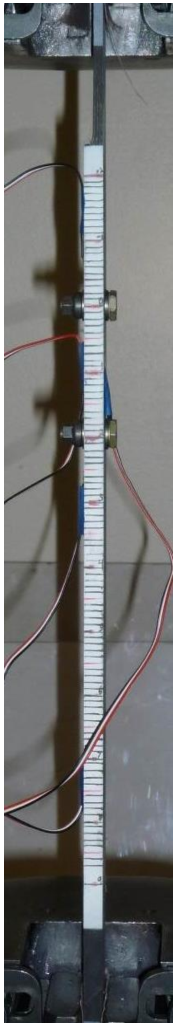
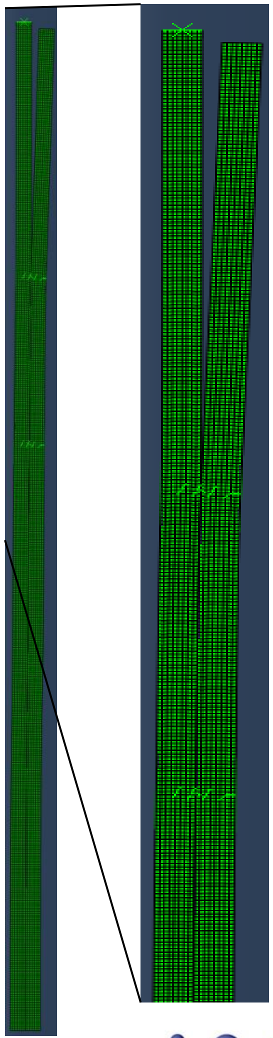
Research Objectives

- Accurately predict crack arrest capability for varying laminate and fastener configurations
  - Understand driving parameters of crack propagation and arrest by multiple fasteners under static and fatigue loading
  - Develop modeling techniques which can be employed for design, certification and optimization

Two Fastener Experimental Work



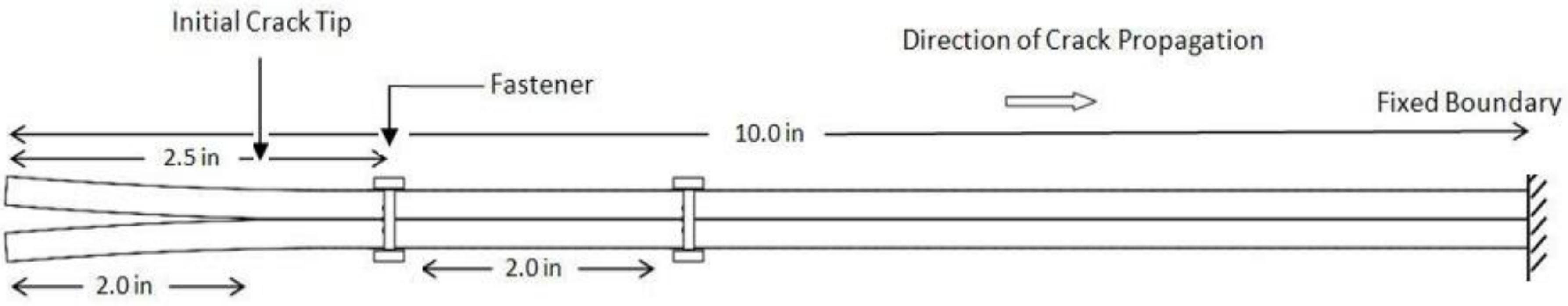




- T800S/3900-2B unidirectional pre-preg tape
- BMS 9-17 surplus unidirectional pre-preg tape
- 0.25 Inch titanium fasteners
- $(0/45/90/-45)_{3S}$ and 50% 0
- Load rate 0.1 mm/min
- Crack tip tracked visually
- 0.1 in Scale

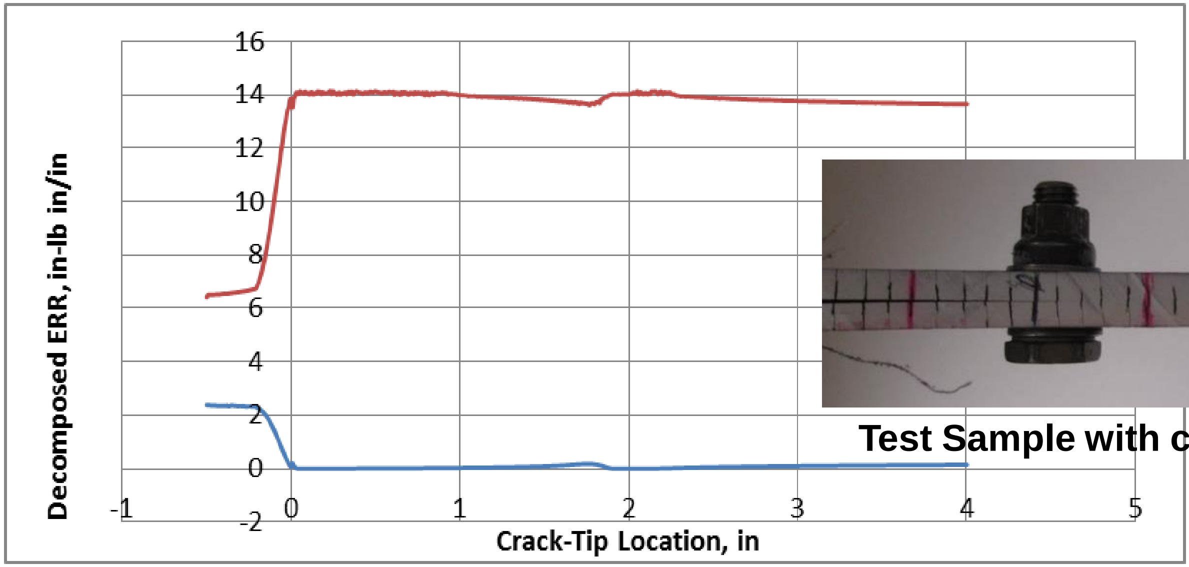
2-Plate Two-Fastener Finite Element Model

- 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 $\left(\frac{G_I}{G_{IC}}\right)^\alpha+\left(\frac{G_{II}}{G_{IIC}}\right)^\beta+\left(\frac{G_{III}}{G_{IIIC}}\right)^\delta \leq 1$
- Fixed boundary condition similar to test; grips not modeled
- Friction coefficient assumed to be fixed value or zero



Mode I Suppression

- First fastener effectively suppresses Mode I
  - Mode I suppression regardless of clearance value
    - Propagation load increases as $G_{IIC} > G_{IC}$
  - Fastener size excessive for Mode I suppression
    - 6-32 fasteners (D=0.1380) found to suppress mode I



Test Sample with crack forced into Mode II

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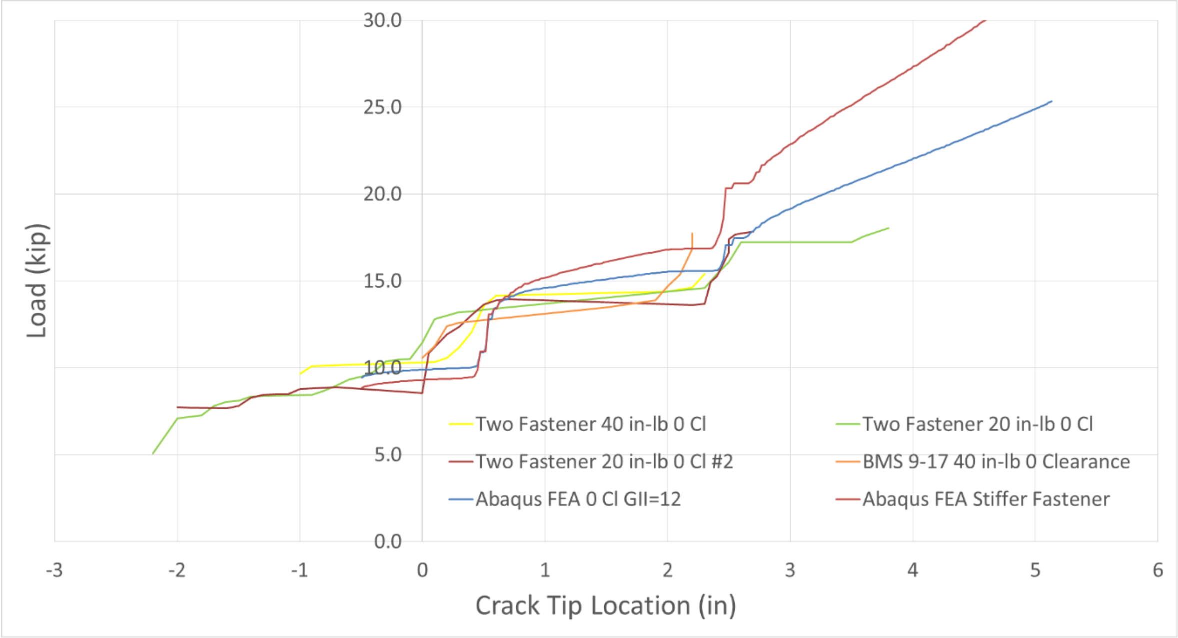
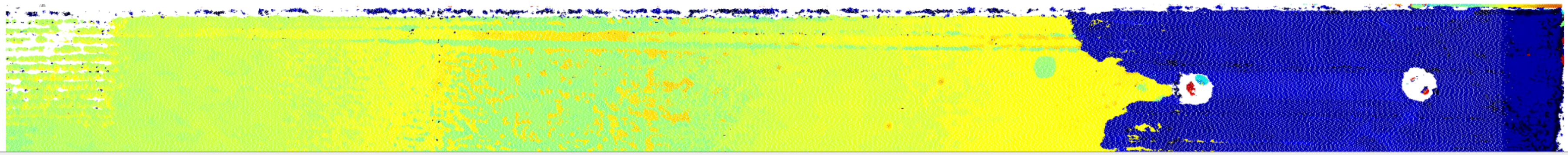
0 Clearance Results

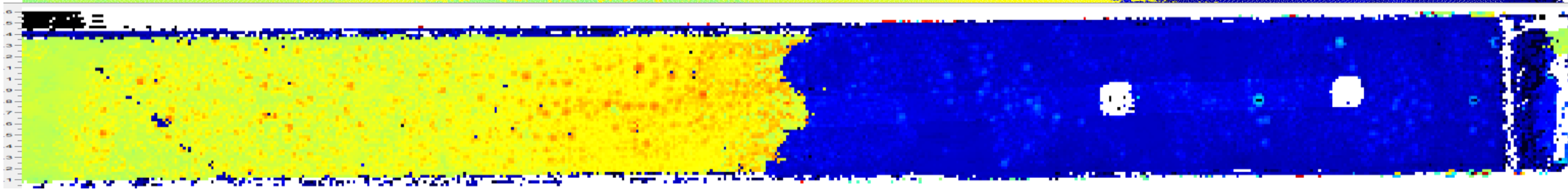
- Fastener Flexibility is major driver of Mode II arrest
  - Slope of load vs. crack length curve driven by fastener flexibility
  - Mode II shear propagation is resisted primarily through load transfer via the fastener in shear



Clearance and Fracture Toughness

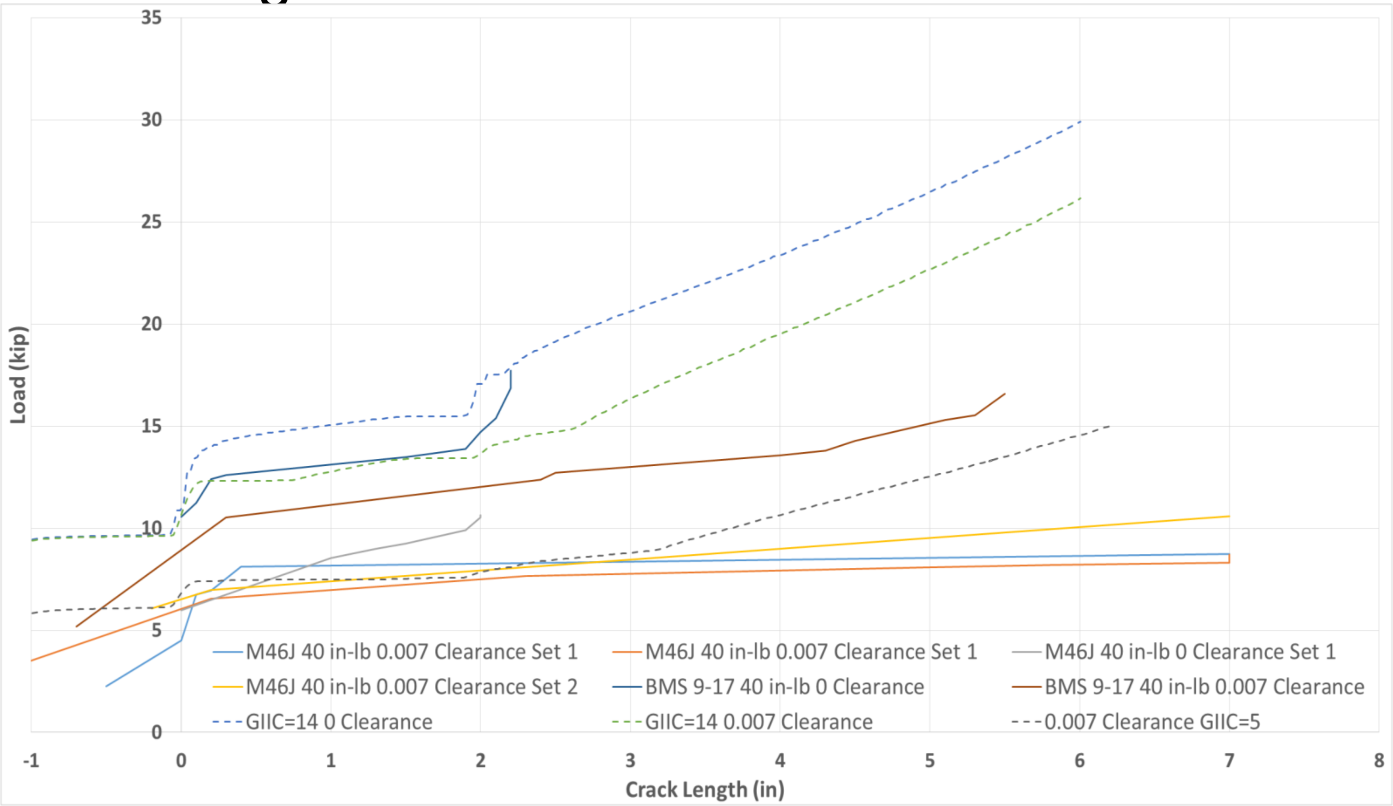
- Typical ¼ inch bolt clearance 0.007-0.016 in.
  - Previous single and multiple fastener research utilized zero clearance (tight fitting hole)
- Bolt clearance and fracture toughness varied
  - Fastener stiffness set as zero over ±0.0035-0.008inch span
  - Fracture toughness varied from 5 to 14 lb/in





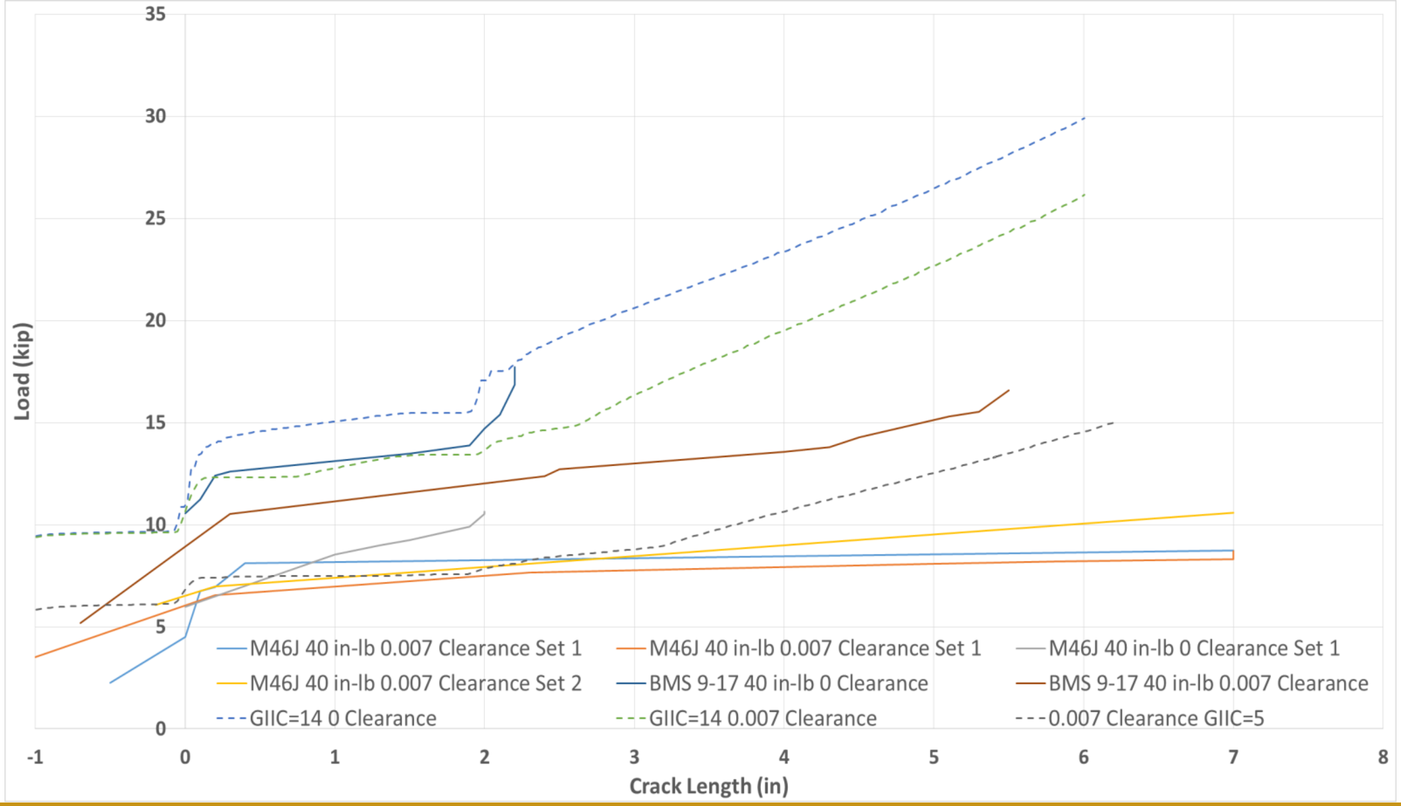
Fracture Toughness

- Fracture toughness varied from 0-14 lb/in
  - Mode II fracture toughness found to have linear relationship with propagation loads
  - Increasing mode I had little affect due to fastener eliminating this mode



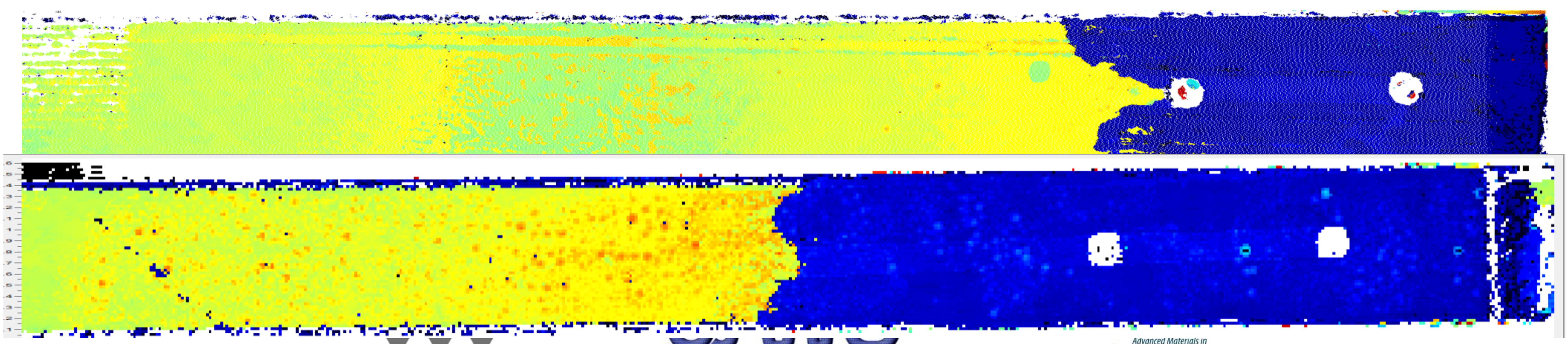
Clearance

- Bolt clearance varied
  - Increasing clearance reduced arrest capability
  - Fastener engagement in shear is delayed by clearance
    - Maximum crack length then determines clearance



Friction and Crack Curvature

- 0/0 interface has minimum coefficient of static friction: 0.25
- Load transfer through friction is small compared to through fastener
  - 1000 lb preload results in 250 lb load transfer
  - Load transfer may be non-negligible in fatigue loading
- Crack Curvature is extensive near fasteners but minimal outside the influenced zone



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
- Samples secondary bonded
  - Secondary bonded structures failed prior to crack propagation
    - Crack driven off bondline and into laminate
    - Crack propagation was minimized
  - Driving crack off of 0/0 interface can improve crack arrest effectiveness

Current Tasks

- Further Develop Analysis for Multiple Fasteners
  - Test modeling techniques on array
    - Does crack curvature change when propagating through an array
  - Improve methodology for modeling the system
    - Using beam/bar for optimization methods
  - Test novel configurations
    - Improve arrest effectiveness through non-traditional configurations
- Fatigue Studies
  - Establish hybrid bolted/bonded joint performance in fatigue
    - Develop predictive capability based on pristine fatigue properties

Fatigue Modeling

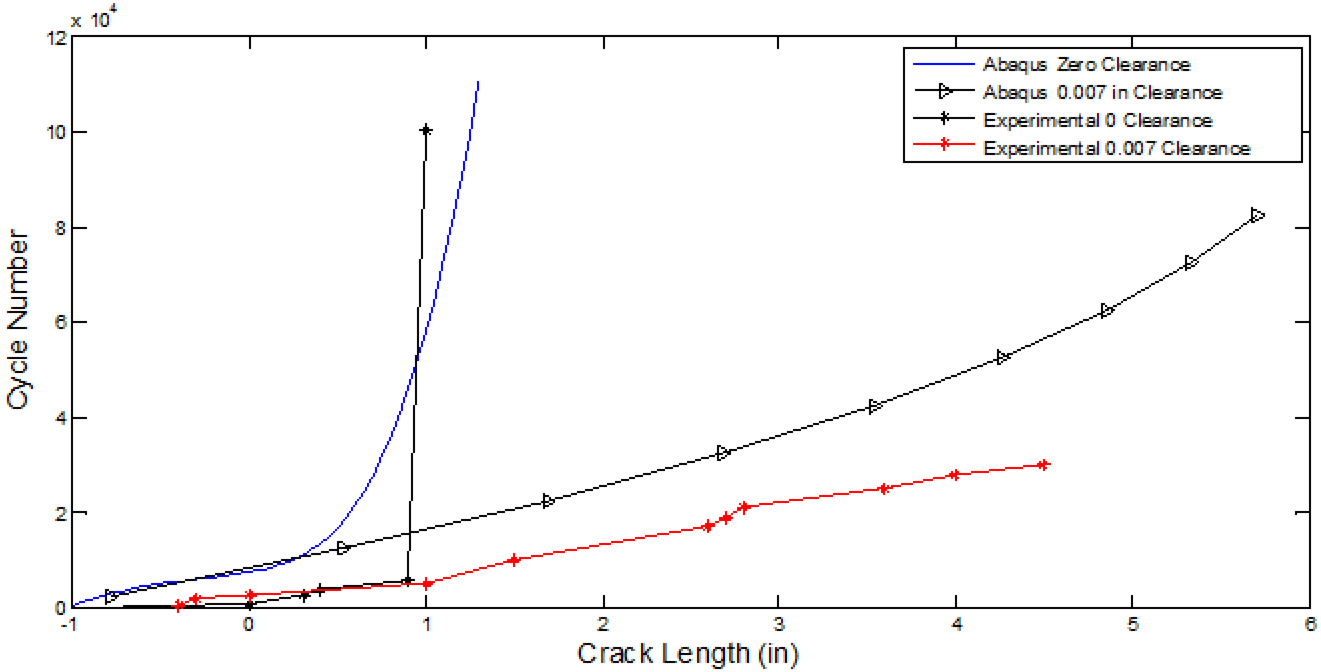
- Identical two and one dimensional models
  - Fatigue properties derived from initial testing and sourced from literature
  - Constant amplitude loading simulated
  - Zero and positive clearance simulated
  - Hole damage not currently modeled
- Dramatic fatigue life difference due to clearance
  - Consistent 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
- Loss of fastener clamping has arisen
- Hole damage may be critical factor
  - Not always visible on tested samples

Fatigue Results

- Fatigue model and test results agree reasonably well
  - Da/DN curves generated using $(0/90/0/\text{Crack})_3$ mode II test specimen
- Fatigue testing not run to establish runout of arrested crack
  - Further testing will be extended to establish this



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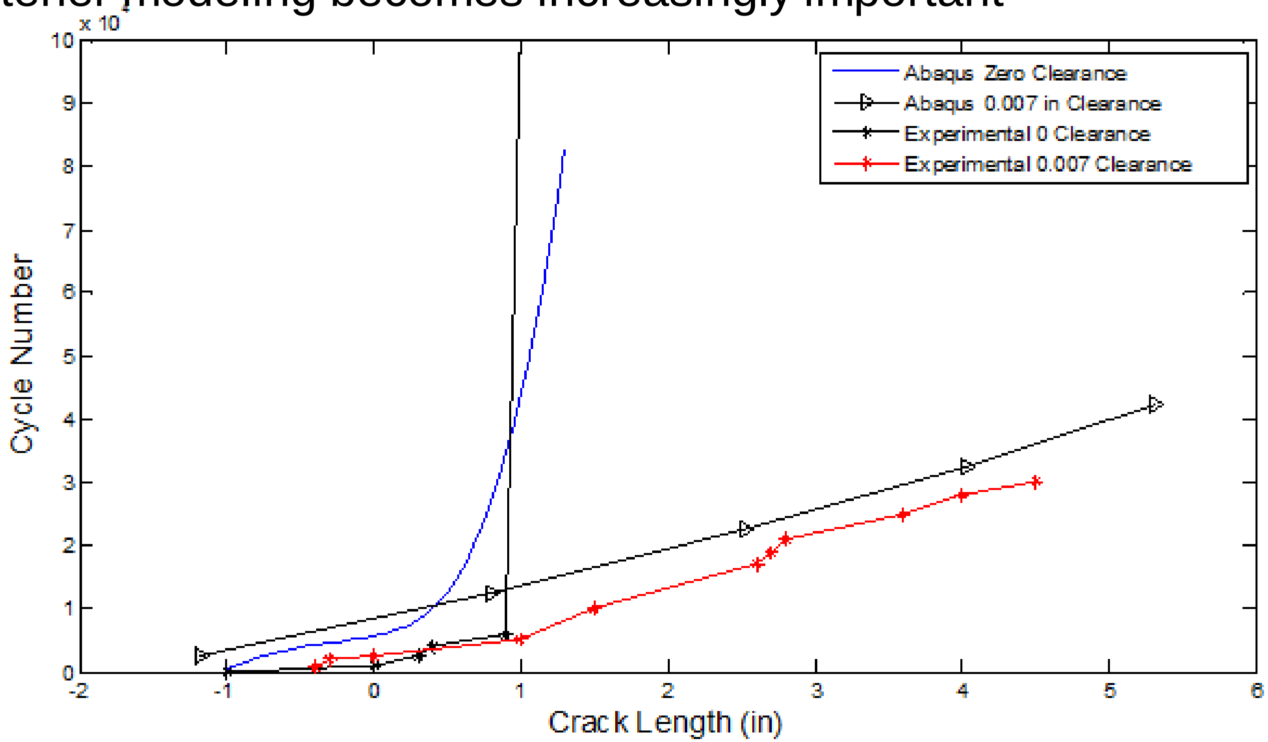
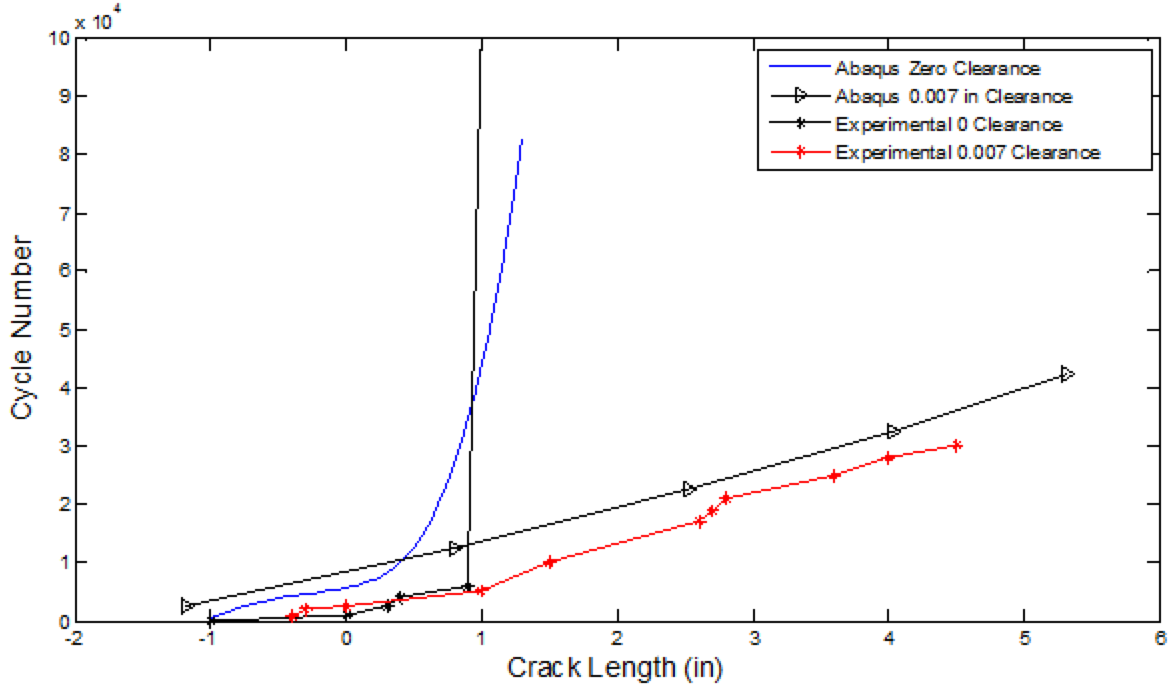
Fatigue Results

- Fatigue model and test results agree better when identical (quasi-isotropic) layup used for fatigue properties
  - Da/DN curves generated using $(0/45/90/\text{-}45/\text{crack})_3$ mode II test specimen with matching ΔG_{max} and ΔG_{min}
- 1D modeling provided better agreement
  - Fastener modeling becomes increasingly important



Fatigue Results

- Distinct knee in zero-clearance hole
  - Fastener provides sufficient load alleviation so as to eliminate further crack propagation (below threshold)
  - Run out (10^7+ cycles) did not occur
- Clearance drilled hole did not experience this, crack propagation is only slowed



2015-2016 Work Plan

- Evaluate fatigue performance
  - Determine variation in Da/Dn curves of unfastened structure due to layup; quasi-isotropic vs. 67% 0
  - Relate unfastened and fastened performance
  - R-ratio effects
    - Fully reversed load may result in greater hole damage
- Predict fatigue performance
  - Use un-fastened fatigue properties to predict fastened performance of different laminate/fastener configurations
  - Spectrum loading
- Establish boundaries of arrest capability
  - Asymmetric and harder laminates experience greater crack growth
  - Can non-standard configurations be more efficient

Looking Forward

- Benefit to Aviation
  - Tackle a crucial weakness of laminate composite structures
  - Improve analysis to prevent changes in schedule/cost due to a re-design associated with the 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
  - Testing to establish fastener flexibility for delamination configuration
  - Initiate 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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