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"Delamination/Disbond Arrest Features in Aircraft Composite Structures"

JAMS Technical Review

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October 27, 2016

Sponsored Project Information

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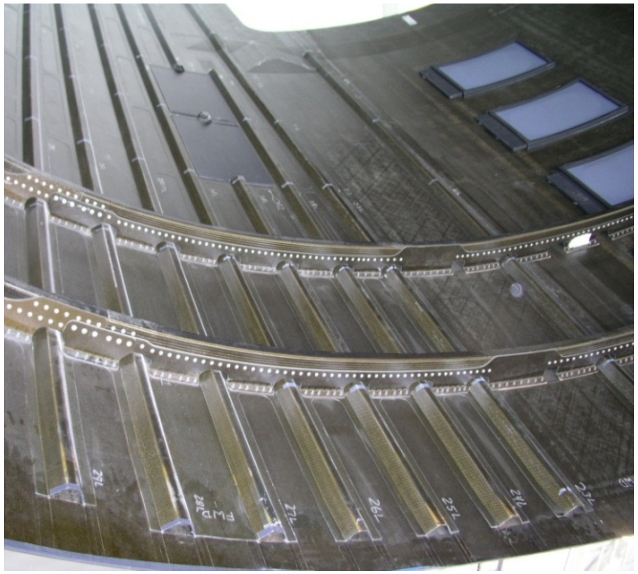
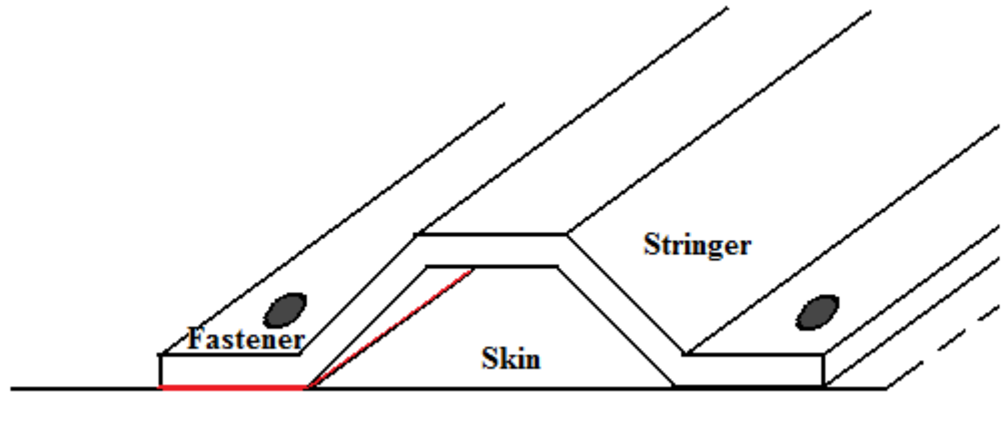
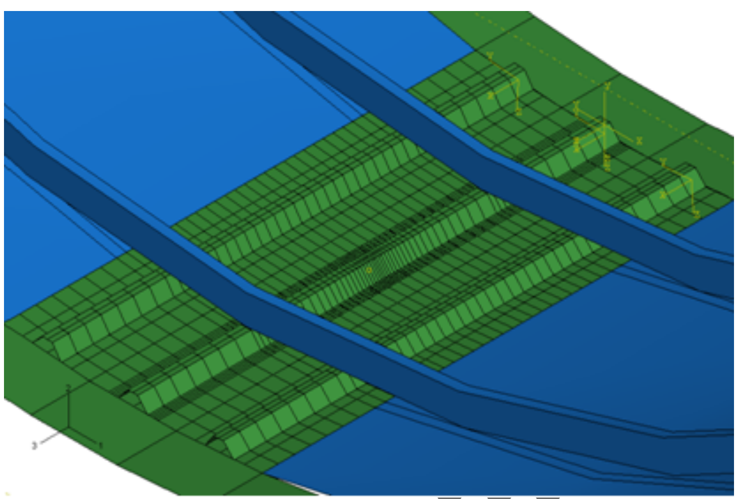
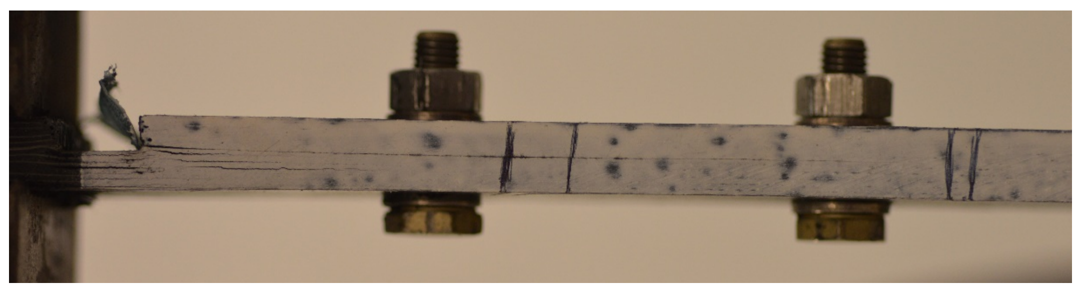
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Masahiro Hashimoto, Felix Nguyen
- **Industry Sponsors: Toray and Boeing**

Crack Arrest Mechanism by Fastener





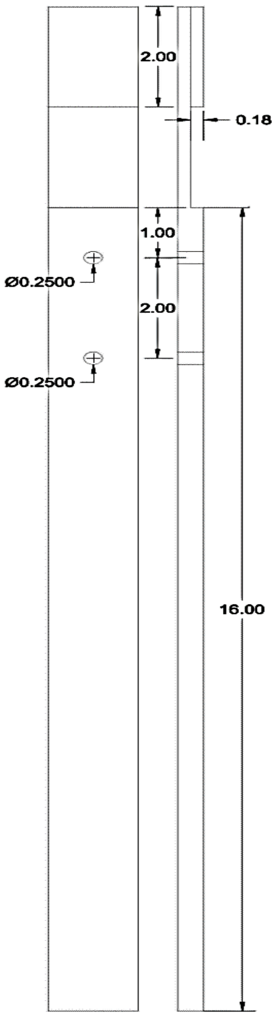


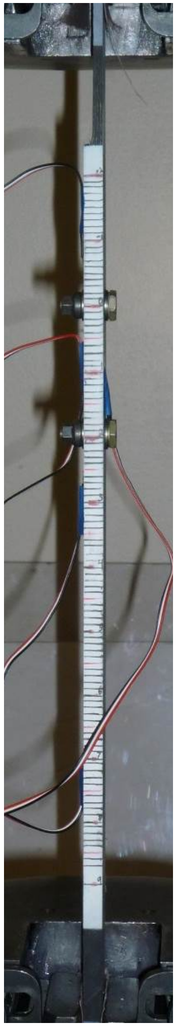


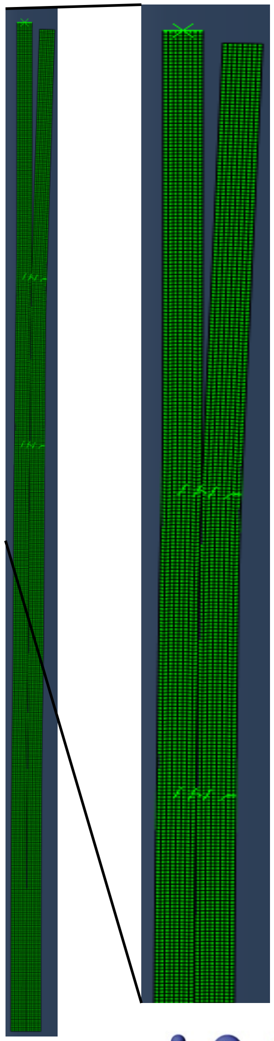
Research Objectives

- 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
- 0.25 inch fasteners (Titanium and Stainless)
- $(0/45/90/-45)_{3S}$ and 50% 0
- Load rate 0.1 mm/min (Static)
- 10 Hz or less (Fatigue)
- Crack tip tracked visually
- Crack tip via stiffness drop (fatigue)

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2-Plate Two-Fastener Finite Element Model

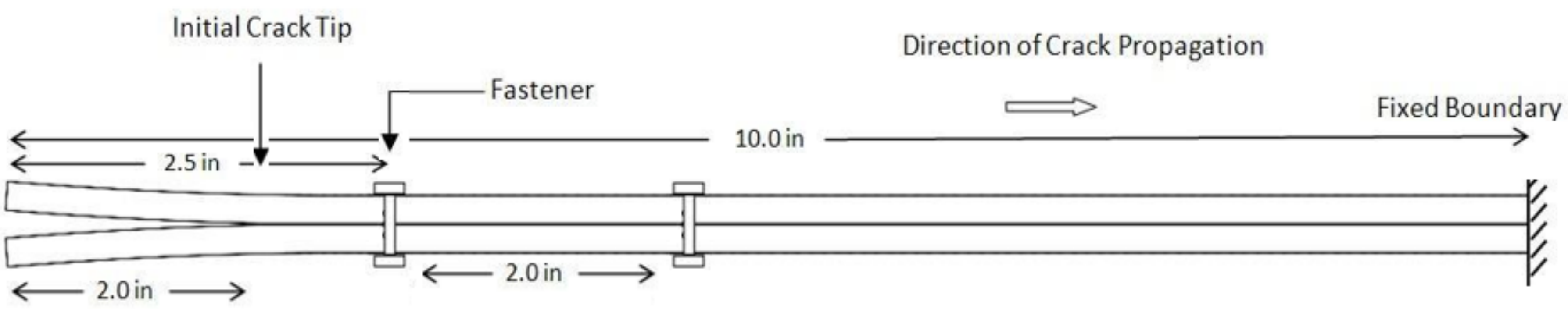
- Virtual Crack Closure Technique (VCCT) used for crack propagation
- Fracture parameters, G_{IC}=1.6 lb/in, Nominal G_{IIC}=G_{IIIC}=14 lb/in
  Measured G_{IIC}: 12 lb/in (BMS 8-276)
- Fixed boundary conditions, test figure not modeled
- Two Dimensional
  - Plane strain representing crack growth along centerline
  - Lamina properties utilized in the model
- One Dimensional
  - Plates represented as beam/bar segments
  - Laminate properties derived from CLT
- Fatigue
  - Paris law utilized for crack growth vs. number of cycles
  - Damage beyond delamination not considered

2-Plate Two-Fastener Finite Element Model

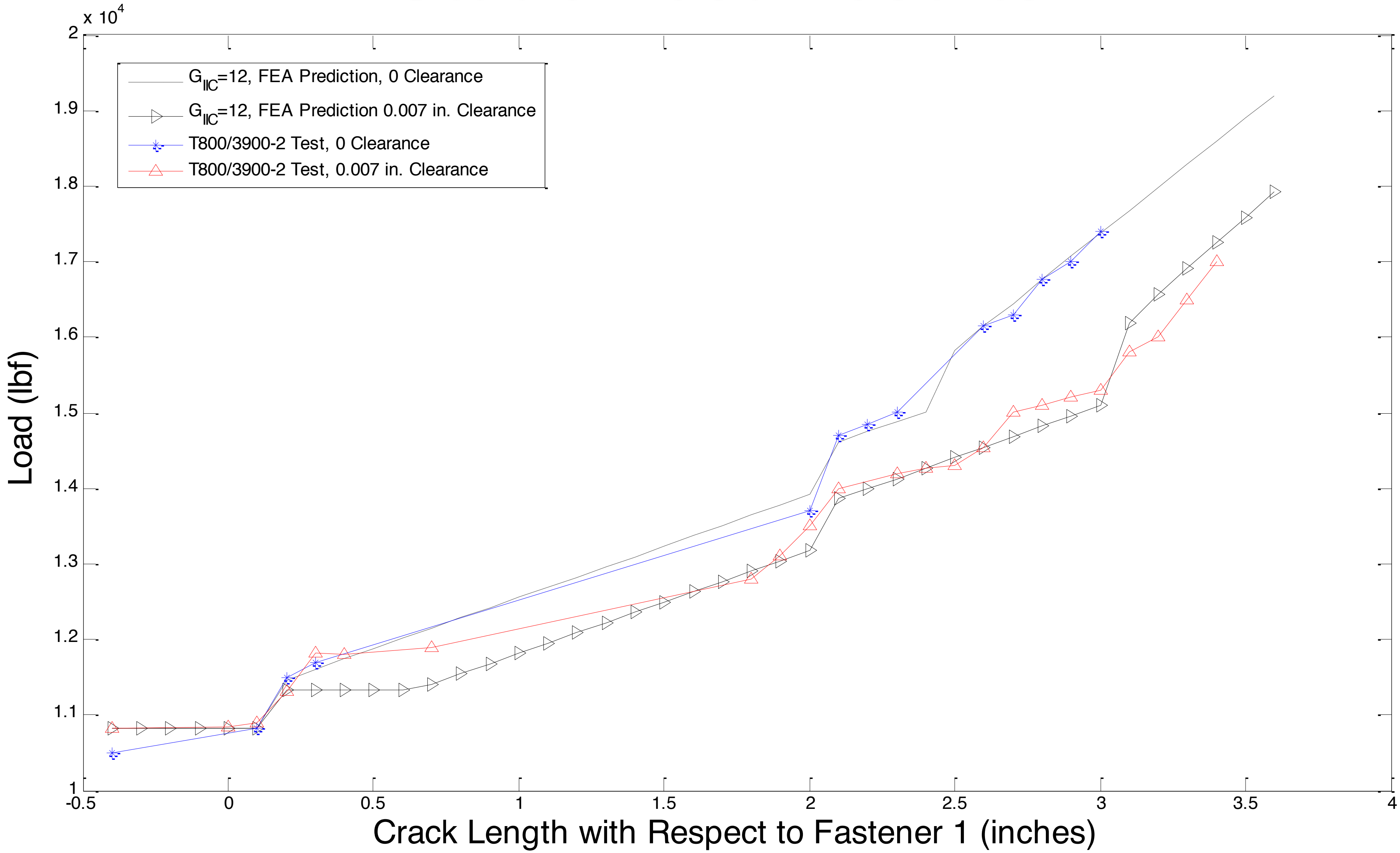
- Fastener flexibility (H. Huth, 1986) $C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1E_1} + \frac{1}{nt_2E_2} + \frac{1}{2t_1E_3} + \frac{1}{2nt_2E_3}\right)$
  - Thickness t_1=t_2=0.18 in., diameter d=0.25 in., E_x= laminate stiffness
  - Single Lap, bolted graphite/epoxy joint, constants taken as; a=2/3, b=4.2, n=1
- Fastener joint stiffness $k_{slide} = \frac{1}{C}$, Fastener tensile stiffness $k_{clamp} = \frac{AE}{(t_1 + t_2)}$

$$\left(\frac{G_I}{G_{IC}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIC}}\right)^{\beta} + \left(\frac{G_{III}}{G_{IIIC}}\right)^{\delta} \leq 1$$

- Power Law fracture criterion
- Fixed boundary condition similar to test; grips not modeled
- Friction coefficient assumed to be fixed value or zero



Static Test Results



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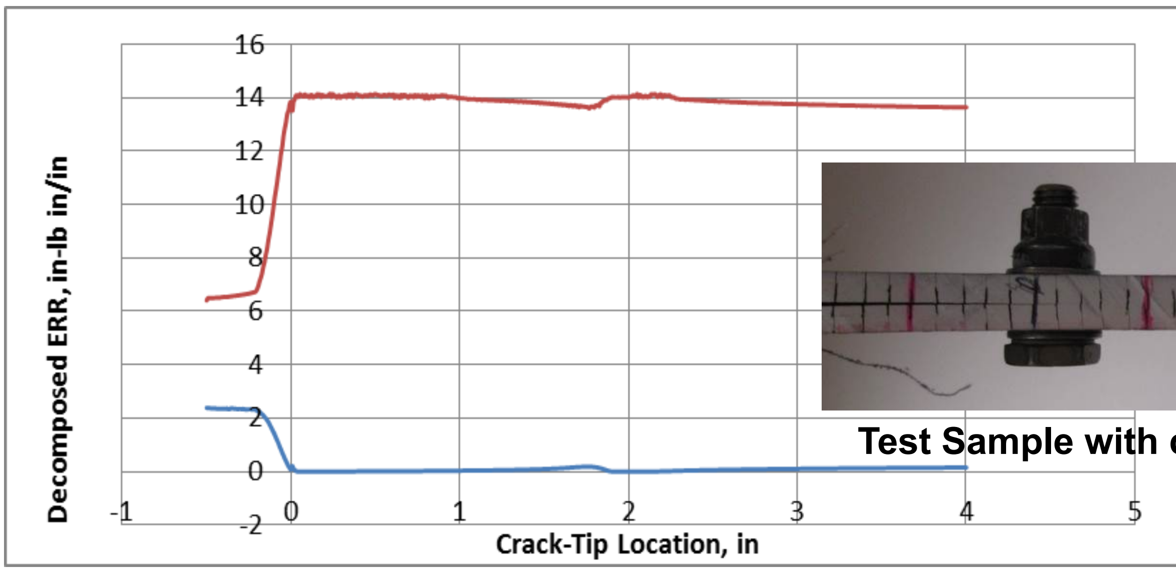
Mode I Suppression

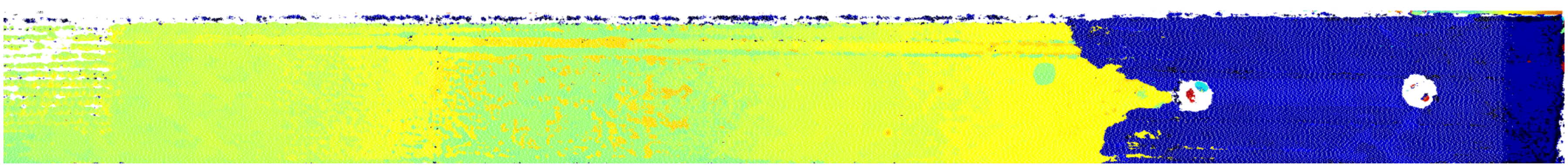
- First fastener effectively suppresses Mode I
  - Mode I suppression regardless of clearance value
    - Propagation load increases as $G_{IIC}>G_{IC}$
  - Fastener size excessive for Mode I suppression
    - 6-32 fasteners (D=0.1380) found to suppress mode I

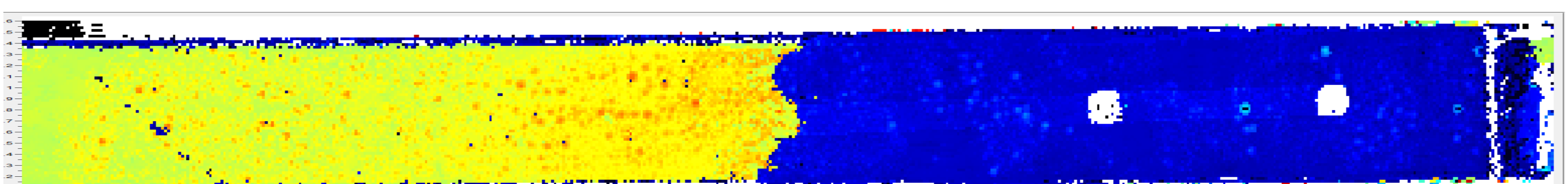


Test Sample with crack forced into Mode II

Friction and Crack Curvature

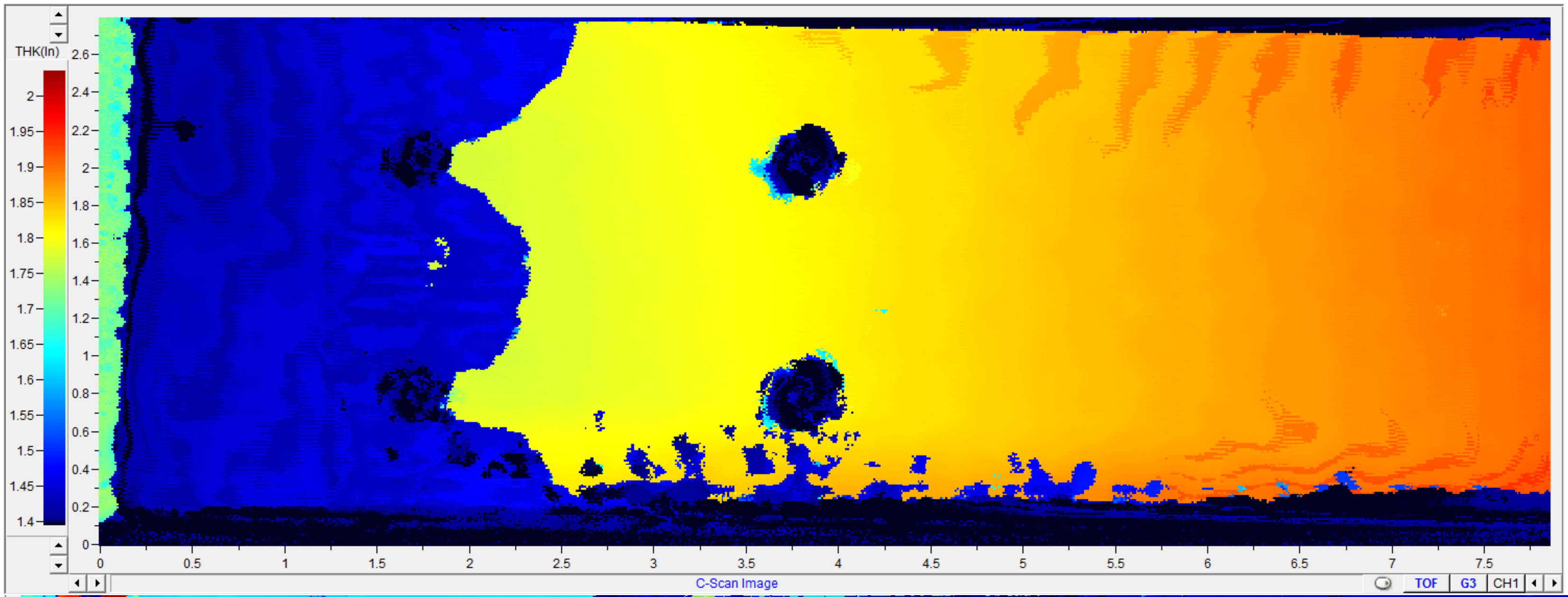
- 0/0 interface has minimum tested coefficient of static friction: 0.25
- Load transfer through friction is small compared to through fastener for static loading
  - 1000 lb preload results in 250 lb load transfer
  - Load transfer plays key role in fatigue loading
- Crack Curvature is extensive near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

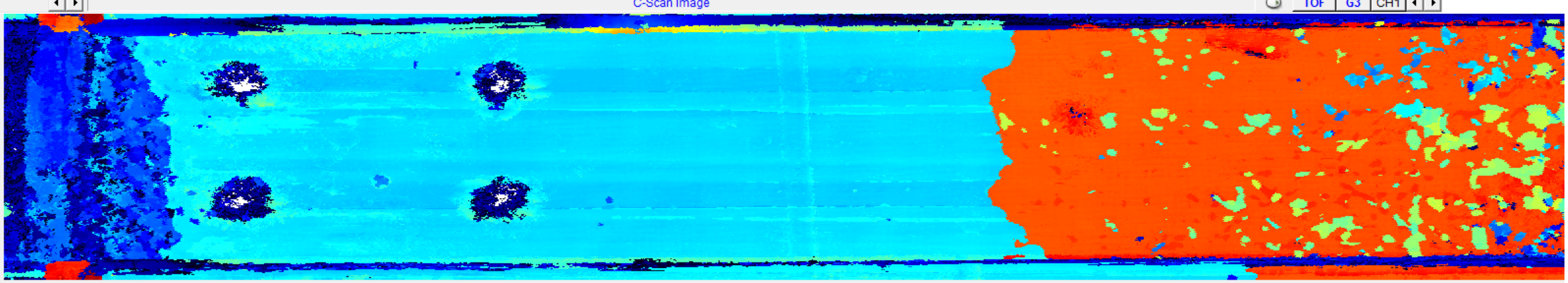




Strip Model Verification

- Testing double width specimens supports the assumption that strip modeling is accurate





Fatigue Modeling

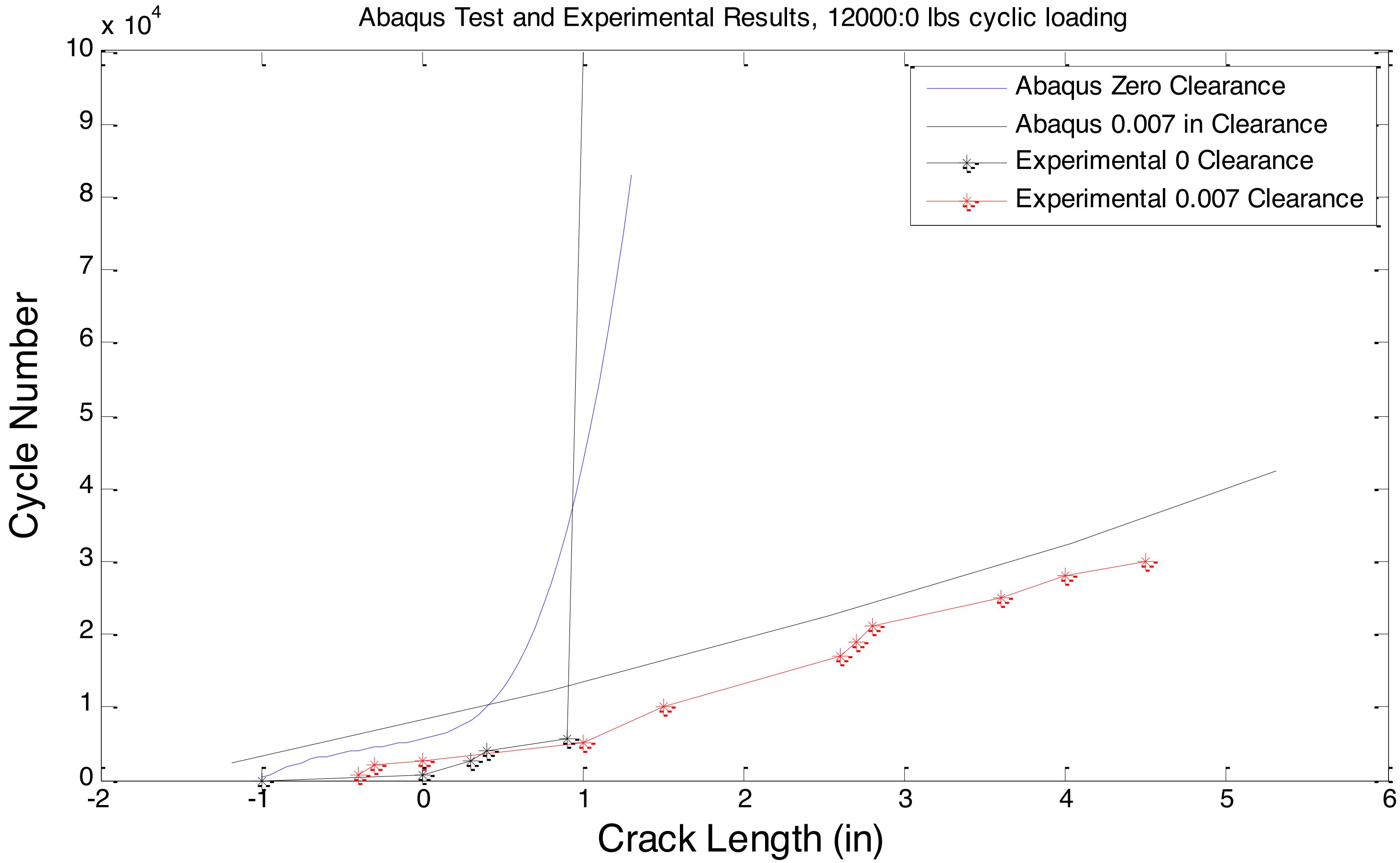
- Identical two and one dimensional models
  - Constant and Variable amplitude loading simulated
    - Paris Law and Miner’s rule assumed to apply
  - Zero and positive clearance simulated
- Interplay between frictional load transfer and clearance
  - Sufficient frictional load transfer reduces negative affects of clearance
  - With zero friction, even minimal clearance leads to significantly greater crack growth

Fatigue Testing

- Below fatigue threshold, fastener has no effect
- Fastener hole size has significant effect on low cycle fatigue
  - Crack arrest capability greatly reduced by the inclusion of clearance
- Loss of fastener clamping has arisen
  - Bending of specimen fatigues fastener head
- Fastener preload (install torque) is of critical importance
  - Loosely installed fasteners perform dramatically worse

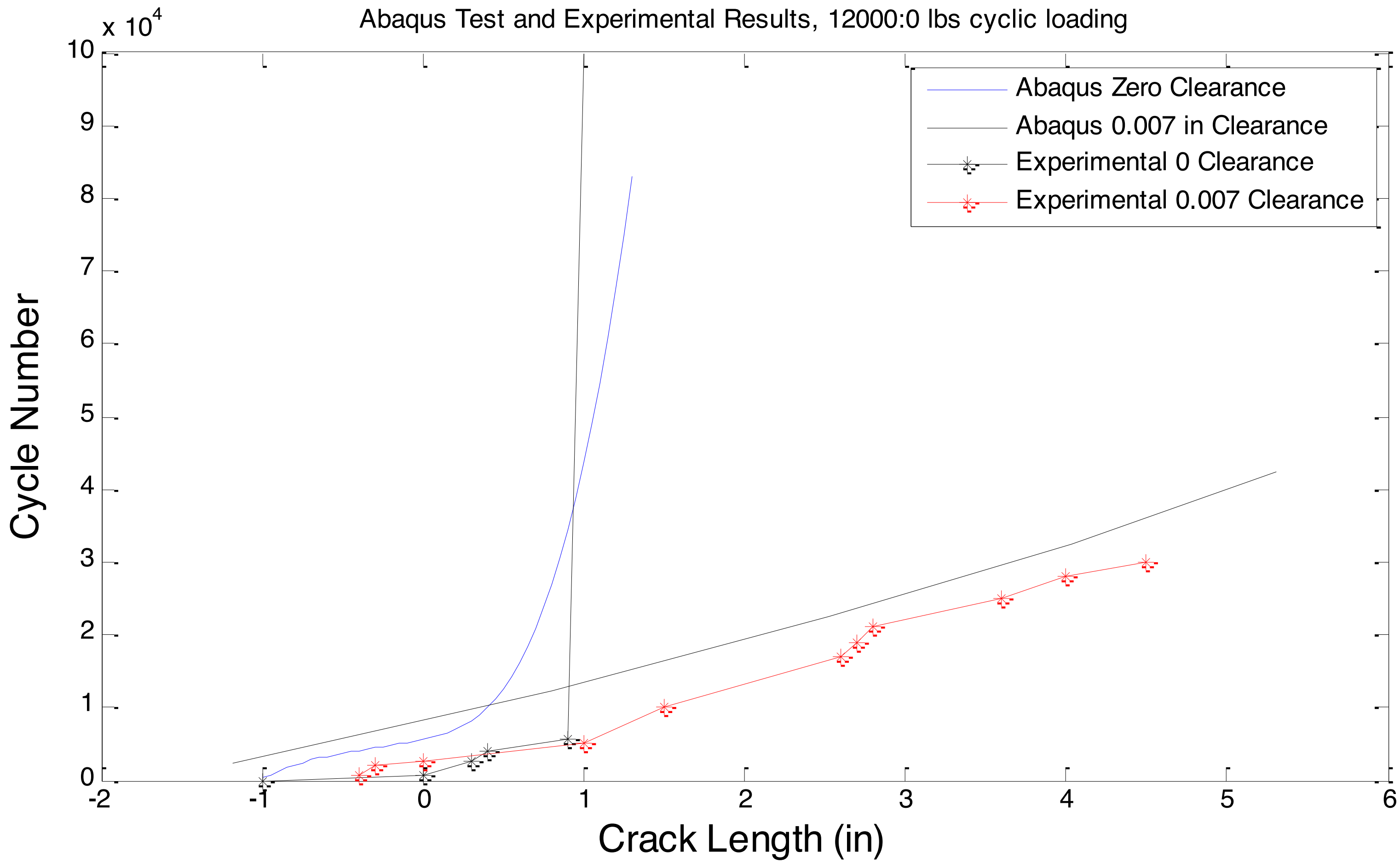
Fatigue Results (High Loading)

- Loads equal to or greater than static crack initiation load (9000 lbs)
- Distinct knee in zero-clearance hole
  - Fastener provides sufficient load alleviation so as to eliminate further crack propagation (below threshold)



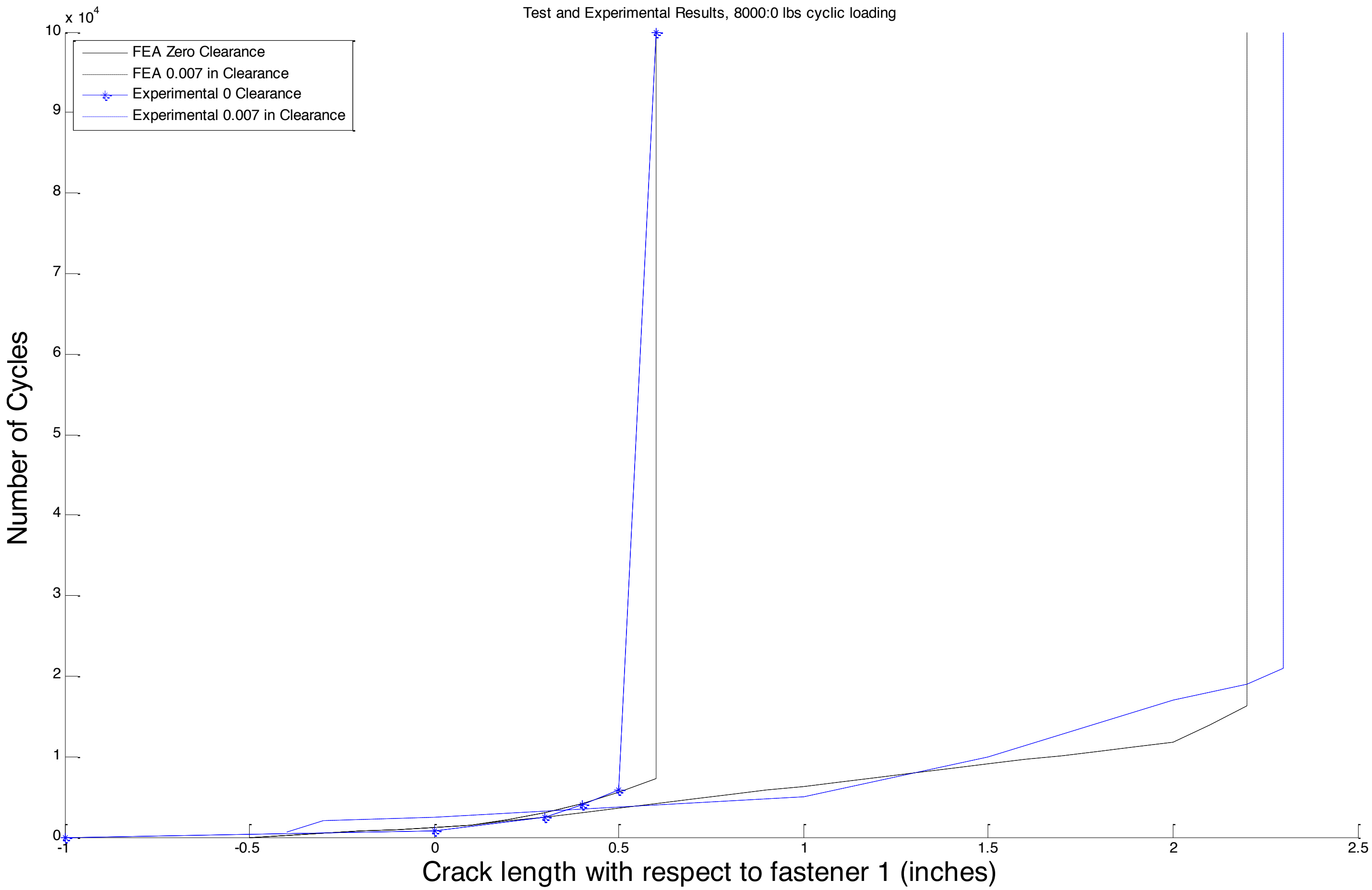
Fatigue Results (High Loading)

- Run-out (10^7 cycles) did not occur
- Clearance drilled hole did not experience arrest, crack propagation is only slowed



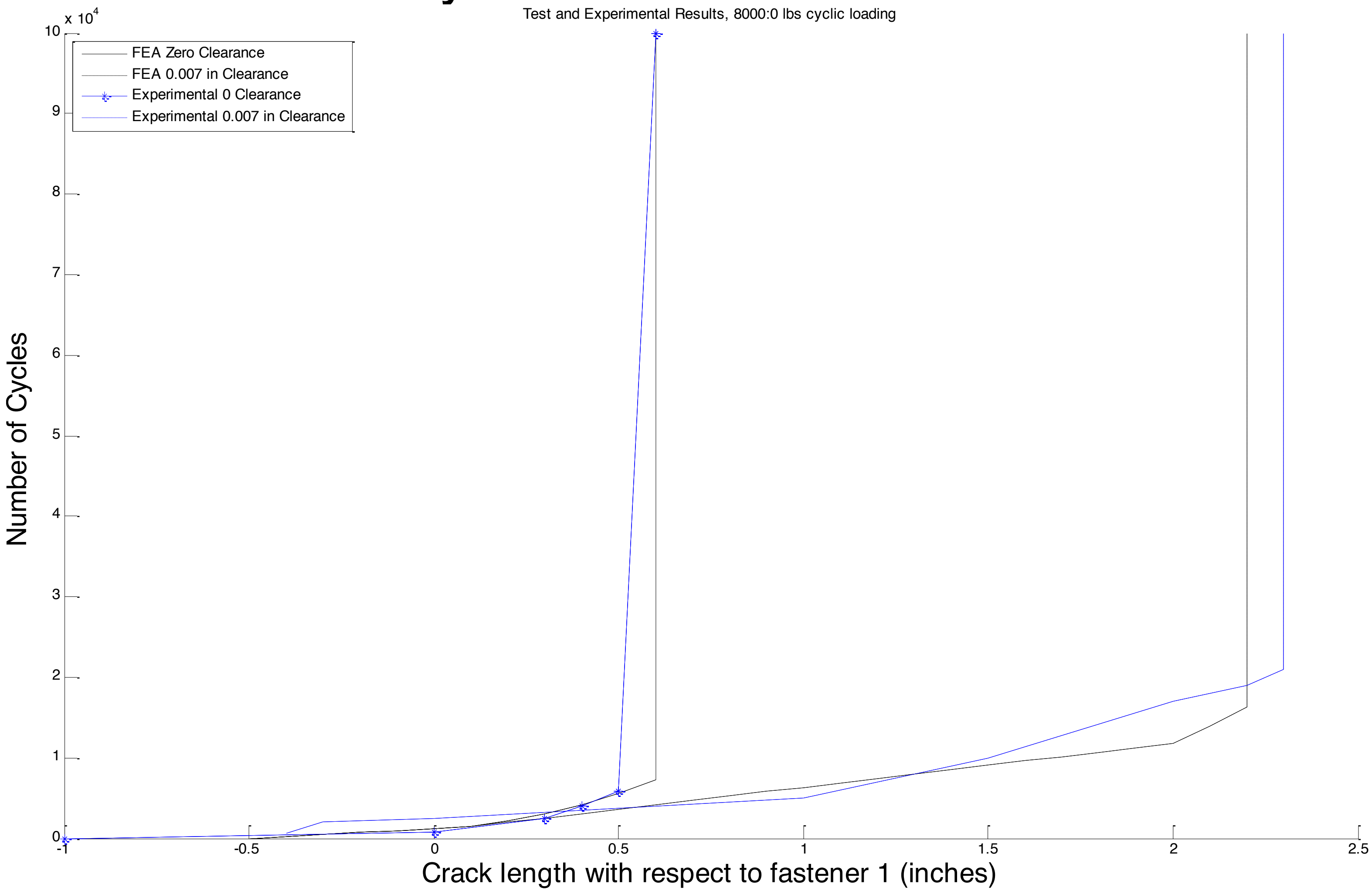
Fatigue Results (Low Loading)

- Loads equal to or less than crack initiation loading (9000 lbs)
- Fatigue threshold included in modeling to improve agreement



Fatigue Results (Low Loading)

- Test demonstrated importance of fastener friction
- Fastener Flexibility Critical



Fatigue Results Compression

- Anti Buckling fixturing utilized to stabilize specimen
- Strain gauges bonded to initial test to verify buckling suppression
- Lower (-8,000:0 and -8,000:8,000) showed reasonable agreement with tension results
  - Results have not been plotted yet
- High loading showed less agreement with tension specimens
  - Higher performance linked to extra clamping provided by anti-buckling fixture
  - Additional clamping provided additional frictional load transfer

Future Work

- Determine Critical Load Conditions
  - Establish scenarios where fastener is least effective
  - Determine conditions where hole damage affects propagation
- Continued Model development
  - Simulating N fasteners
  - Simulation of varying configurations
- R Ratio
  - Current work has been at an R ratio of 0 or -1
  - Can the R ratio correction method used for metals be applied to composite delamination?

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 better establish parameters
  - 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?

Thank you.

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