“Delamination/Disbond Arrest Features in Aircraft Composite Structures”

JAMS Technical Review

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Sponsored Project Information

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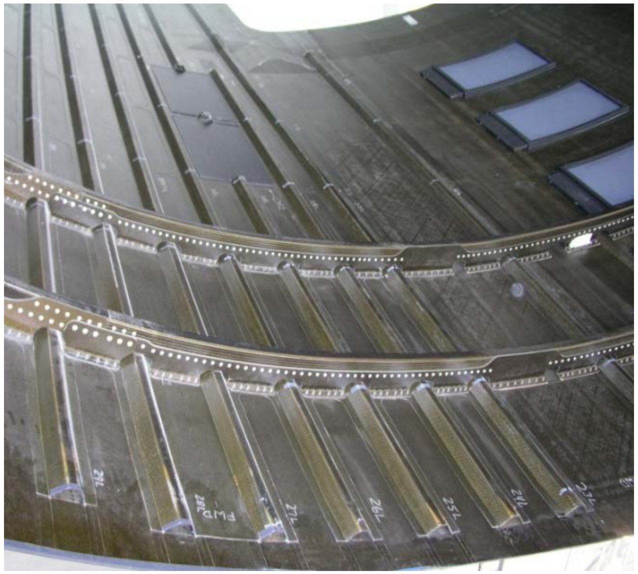
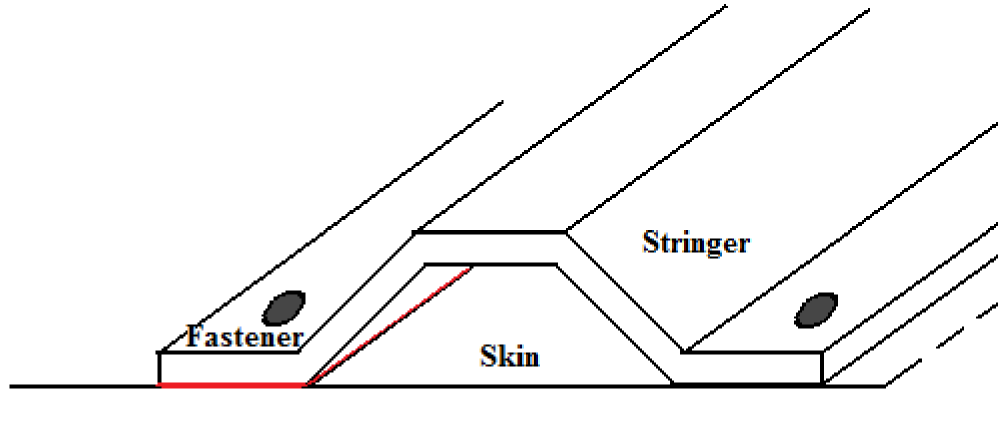
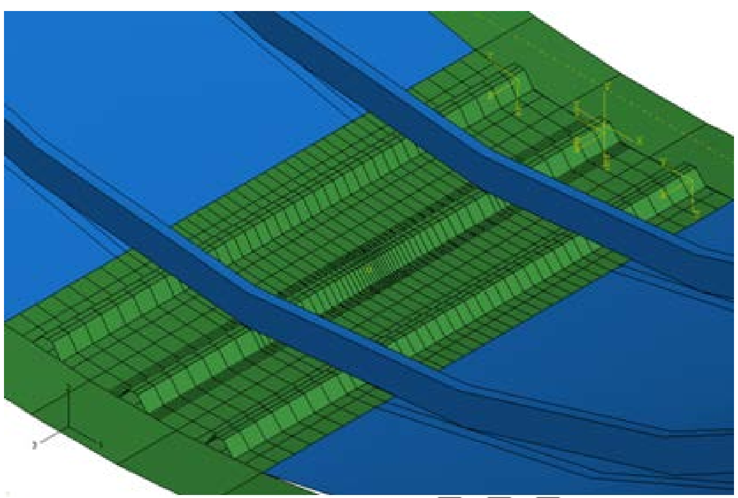
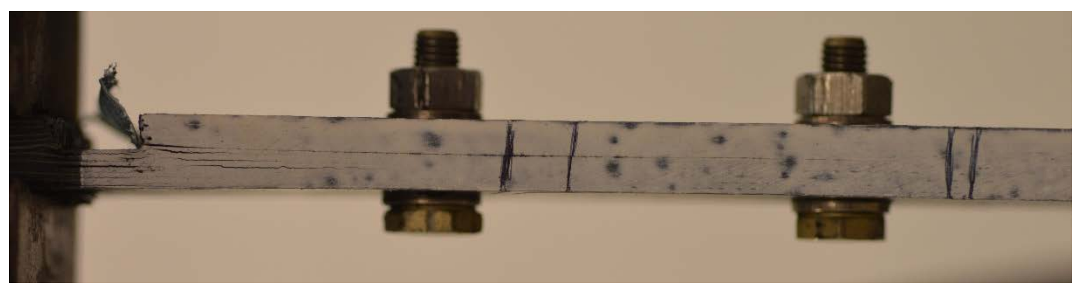
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Masahiro Hashimoto, Felix Nguyen
- **Industry Sponsors: Toray and Boeing**

Crack Arrest Mechanism by Fastener









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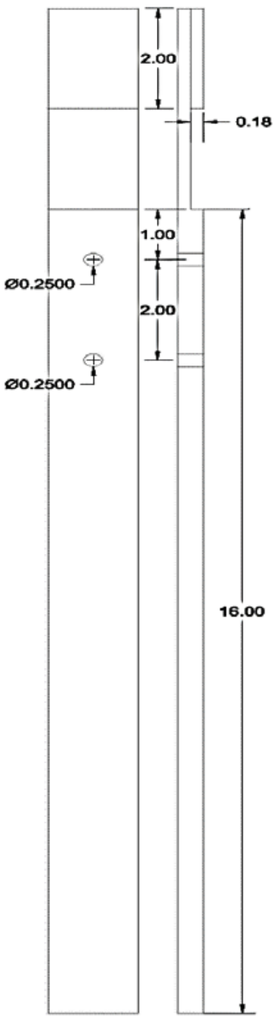
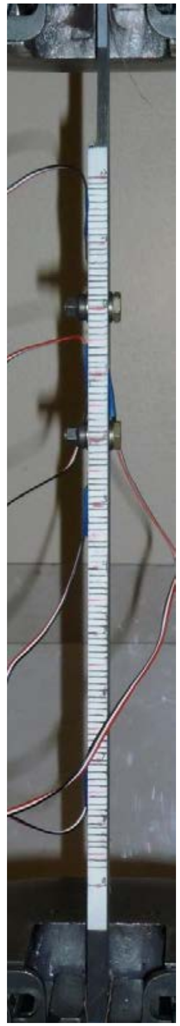
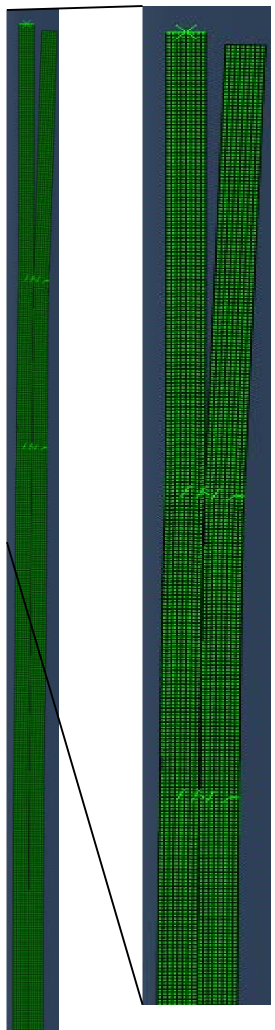
Research Objectives

- 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
- 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

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2-Plate Two-Fastener Finite Element Model

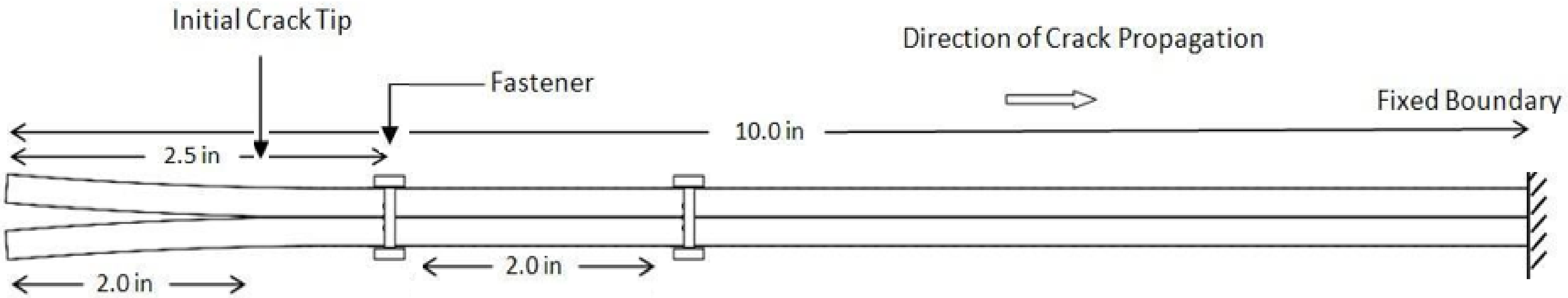
- Virtual Crack Closure Technique (VCCT) used for crack propagation
- Fracture parameters, G_{IC}=1.6 lb/in, Nominal G_{IIC}=G_{IIIC}=14 lb/in
  Measured G_{IIC}: 12 lb/in (BMS 8-276)
- Fixed boundary conditions, test figure not modeled
- Two Dimensional
  - Plane strain representing crack growth along 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

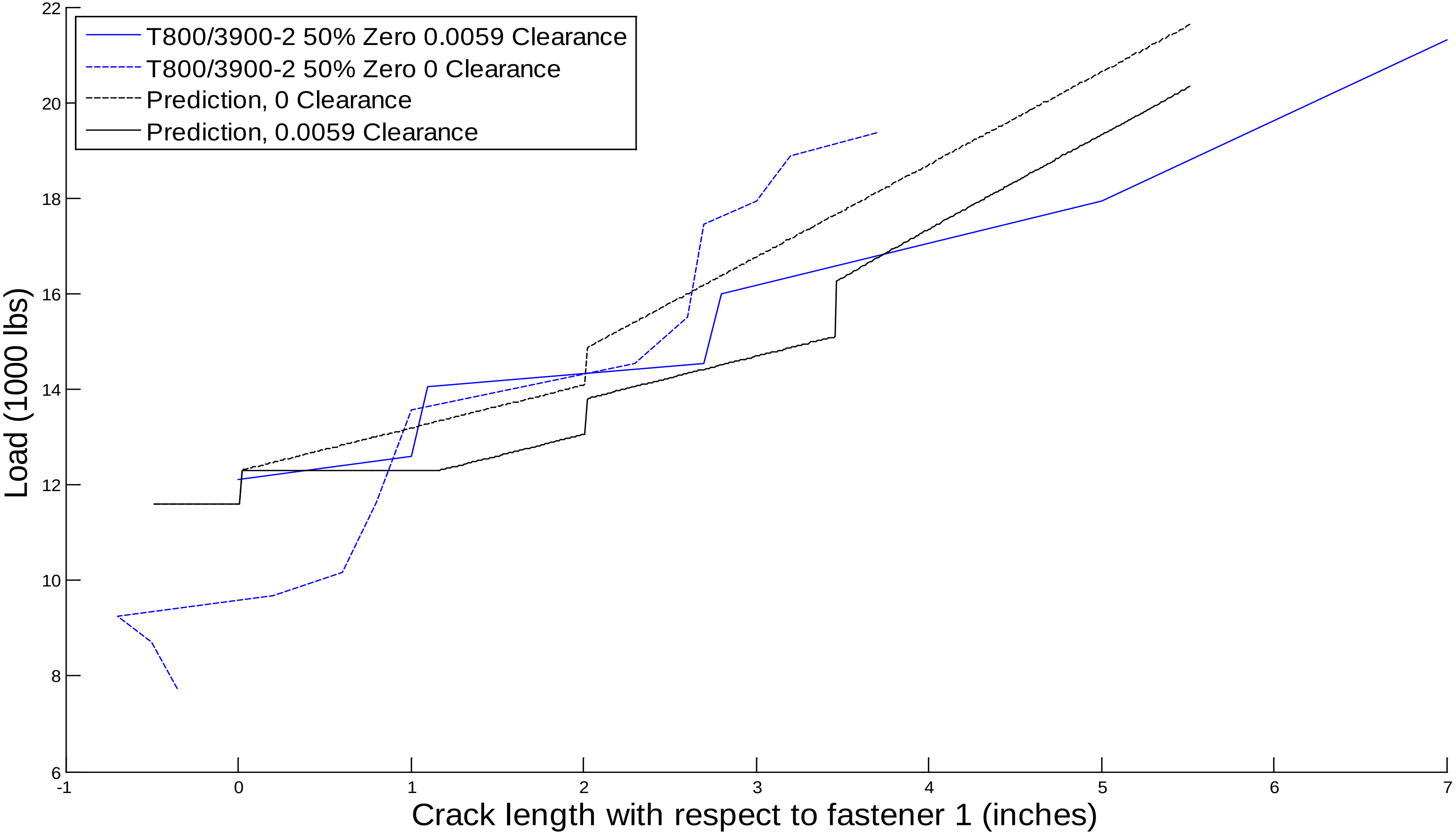
- Fastener flexibility (H. Huth, 1986) $C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{2 t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$
  - Thickness t_1=t_2=0.18 in., diameter d=0.25 in., E_x= laminate stiffness
  - Single Lap, bolted graphite/epoxy joint, constants taken as; a=2/3, b=4.2, n=1
- Fastener joint stiffness $k_{slide} = \frac{1}{C}$, Fastener tensile stiffness $k_{clamp} = \frac{AE}{(t_1 + t_2)}$

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

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

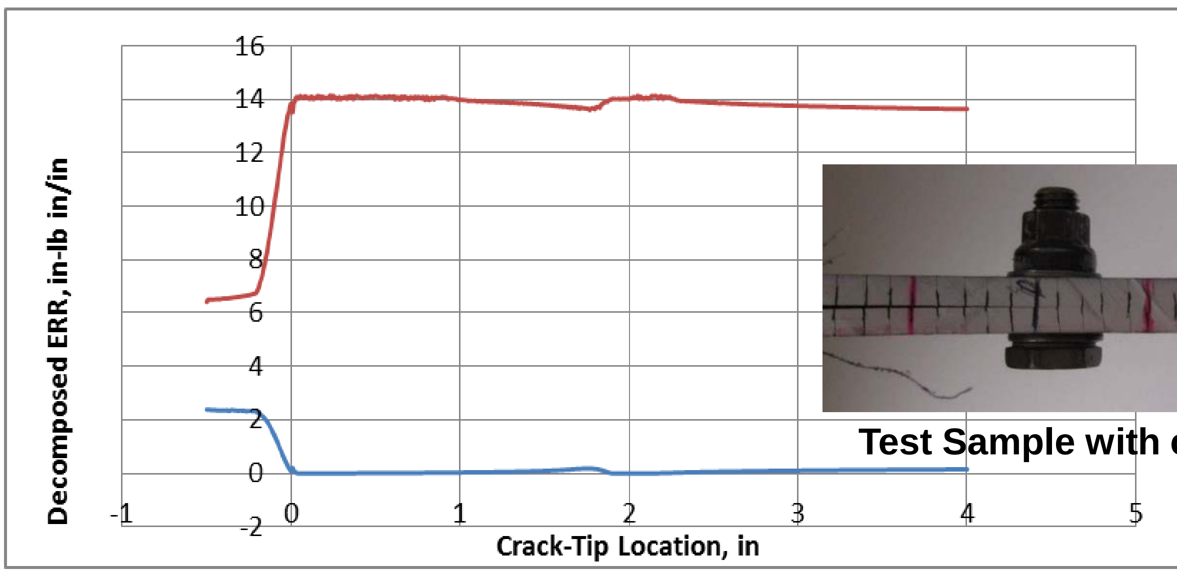


Static Test Results



Mode I Suppression

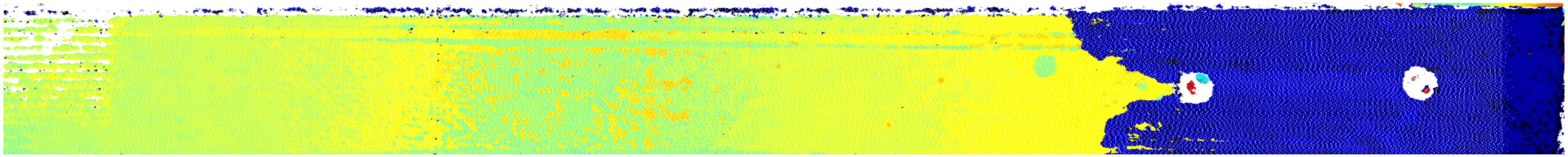
- First fastener effectively suppresses Mode I
  - Mode I suppression regardless of clearance value
    - Propagation load increases as $G_{IIC}>G_{IC}$
  - Fastener size excessive for Mode I suppression
    - 6-32 fasteners (D=0.1380) found to suppress mode I

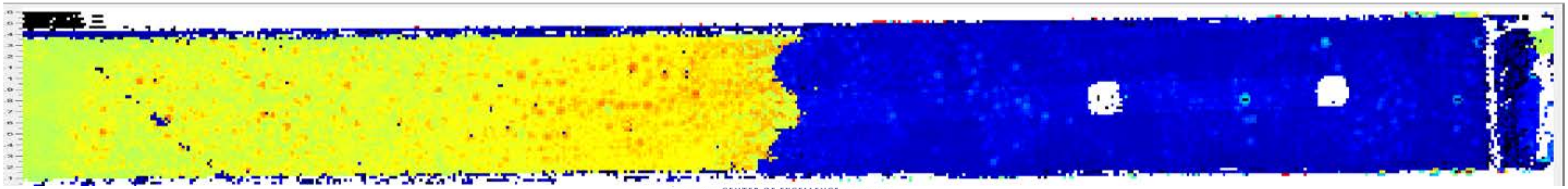


Test Sample with crack forced into Mode II

Friction and Crack Curvature

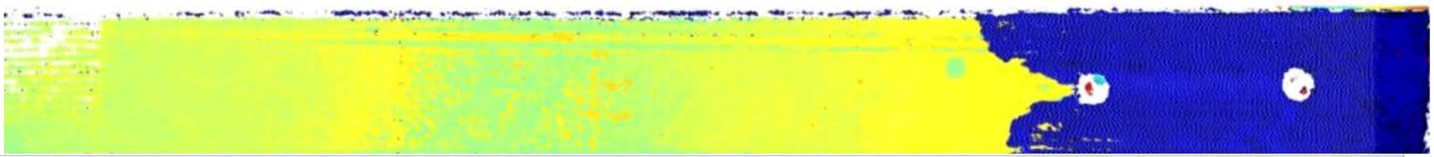
- 0/0 interface has minimum tested coefficient of static friction: 0.25
- Load transfer through friction is small compared to through fastener for static loading
  - 1000 lb preload results in 250 lb load transfer
  - Load transfer is non-negligible in fatigue loading
- Crack Curvature is extensive near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

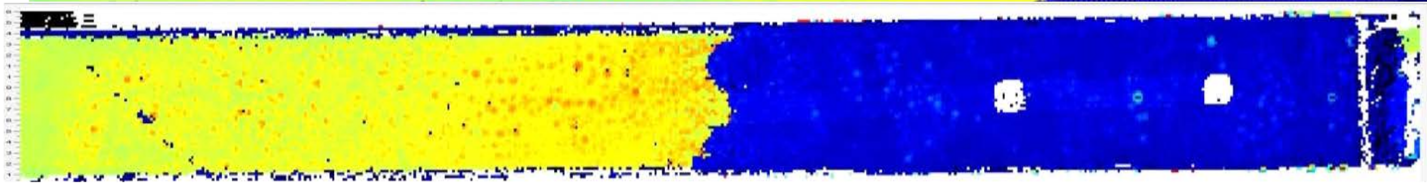


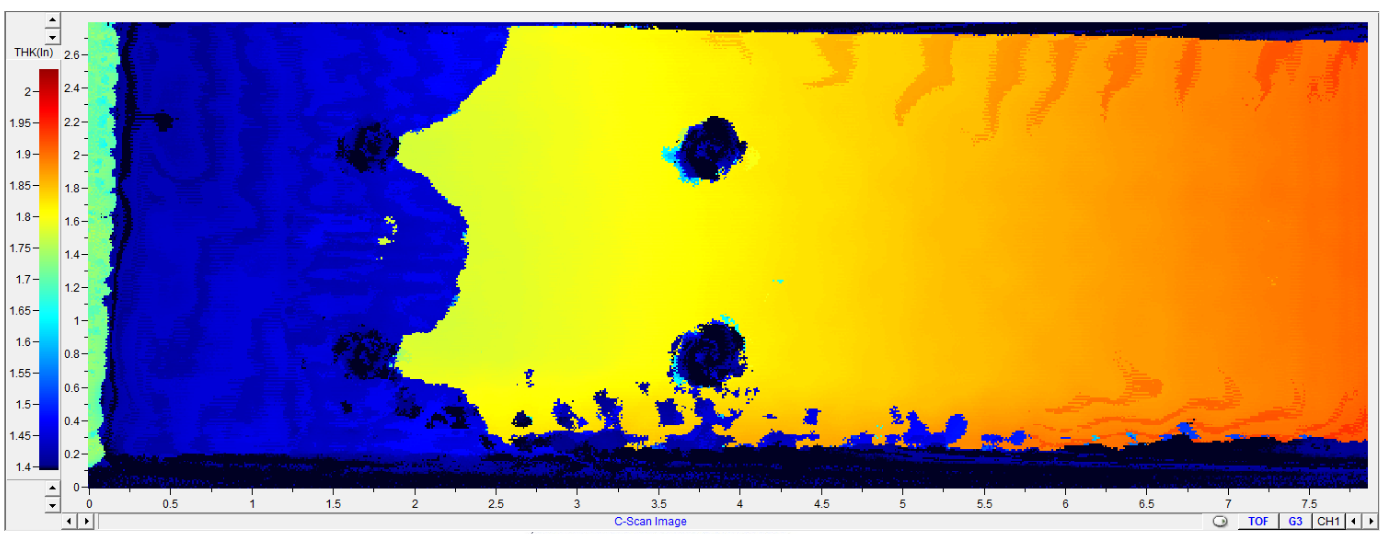


Friction and Crack Curvature

- Strip model assumption is valid based on comparison of double width specimen with single with test articles







Fatigue Modeling

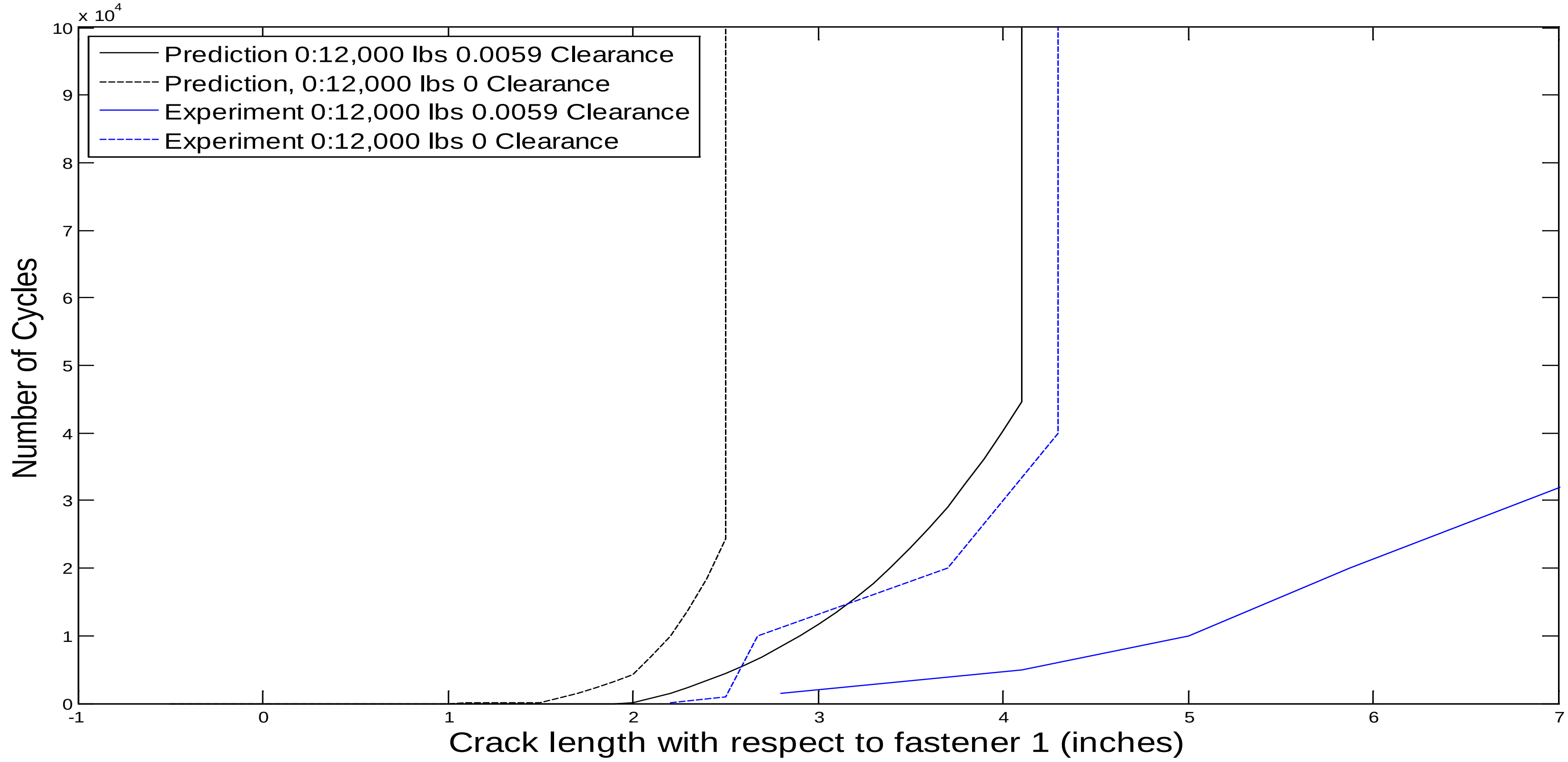
- Identical two and one dimensional models
  - Constant and Variable amplitude loading simulated
    - Paris Law and Miner's rule assumed to apply
  - Zero and positive clearance simulated
- Dramatic fatigue life difference due to clearance
  - Even 0.001 inch clearance shows dramatic simulated fatigue life difference
  - Consistent result both in tension-tension and tension-compression loading

Fatigue Testing

- Below fatigue threshold, fastener has no effect
- Crack arrest capability reduced by clearance
- R Ratio and compression Tested
  - Compression behaved in similar manner to tension
  - R=0.2, 0.33, 0.5 with load amplitude=4,000 lbs
- Hole damage may be a critical factor
  - Visible on samples where crack growth did not occur
  - Increasing clearance value improves agreement on certain tests

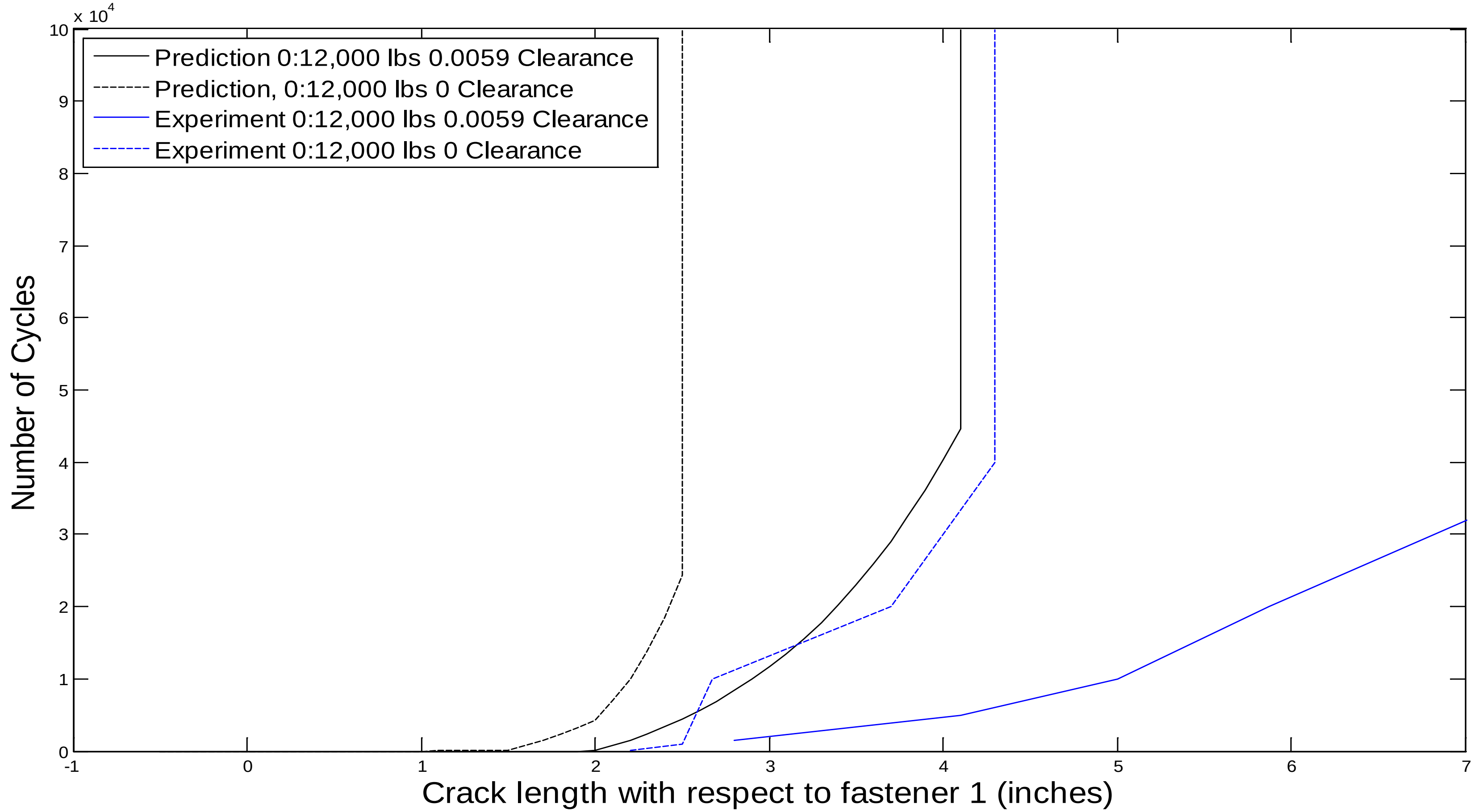
Fatigue Results (High Loading)

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



Fatigue Results (High Loading)

- Fatigue model and test results agree better when identical (quasi-isotropic) layup used for fatigue properties



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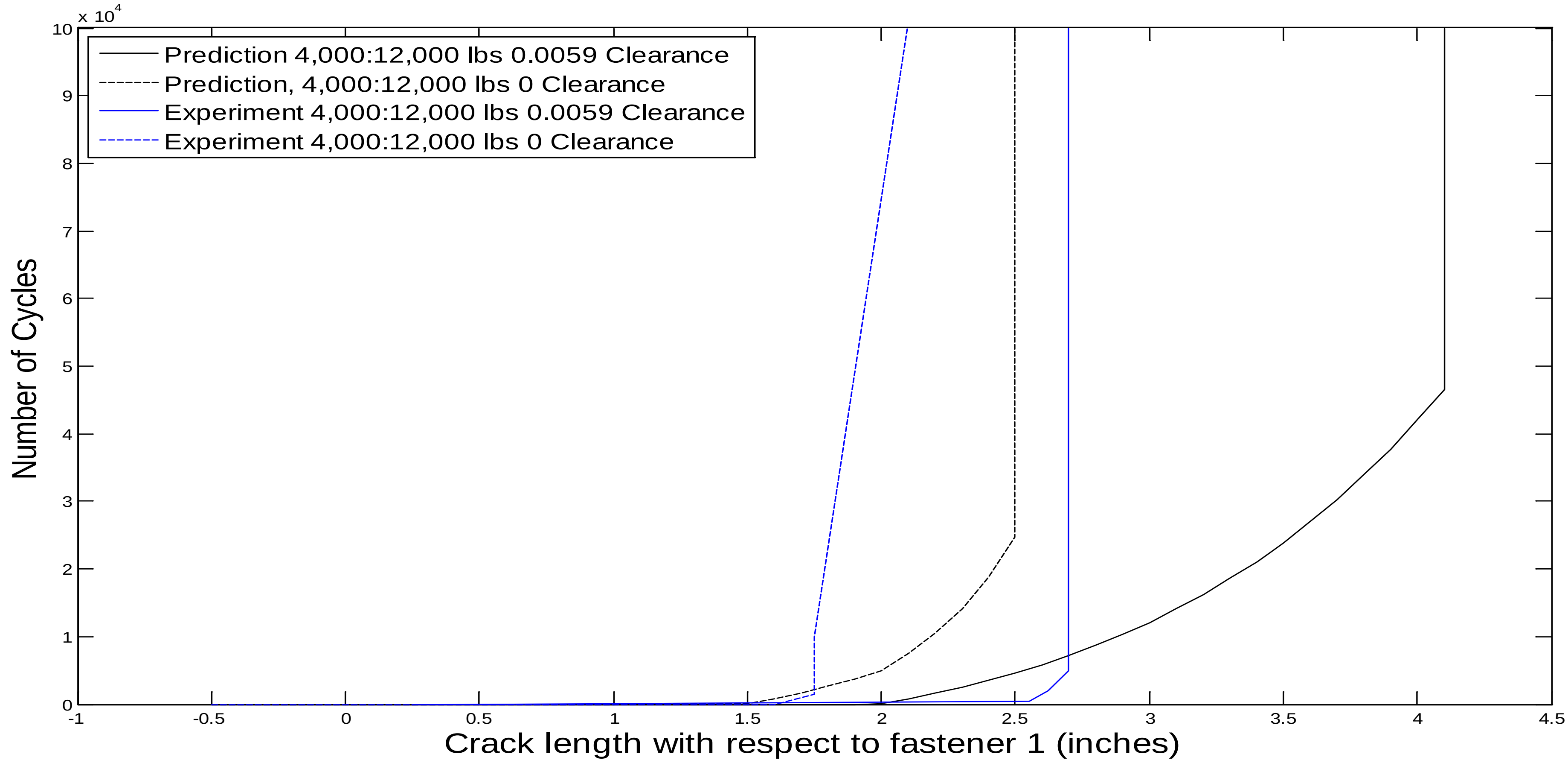
Fatigue Results (High Loading)

- Hole damage apparent during testing
  - Including a hole decay in the model improved agreement
  - No current scientific basis for the model
- 1D modeling provided better agreement
  - Fastener modeling becomes increasingly important

Fatigue Results (R Ratio)

- Various R ratios tested with amplitude of 8,000 lbs



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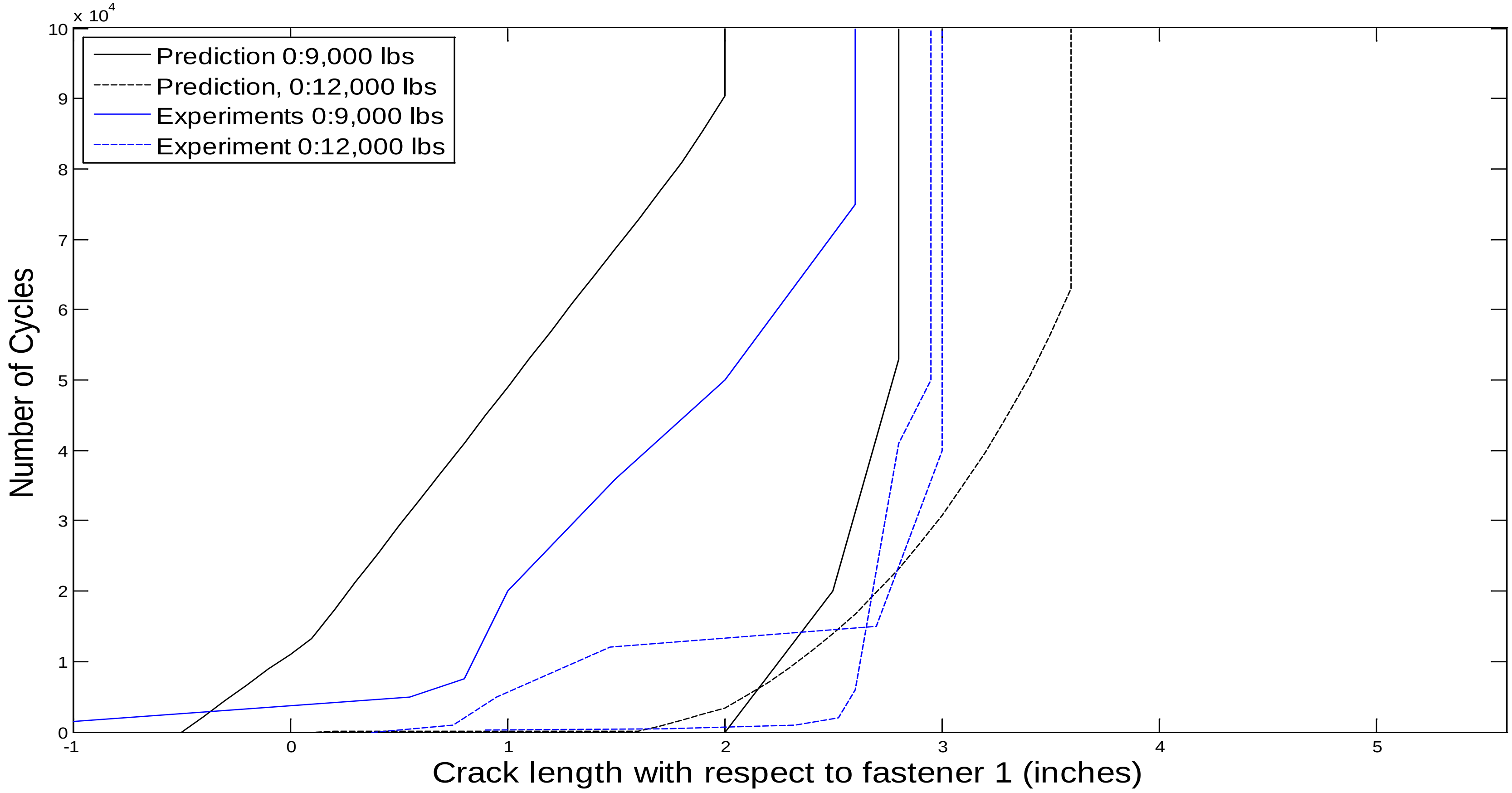
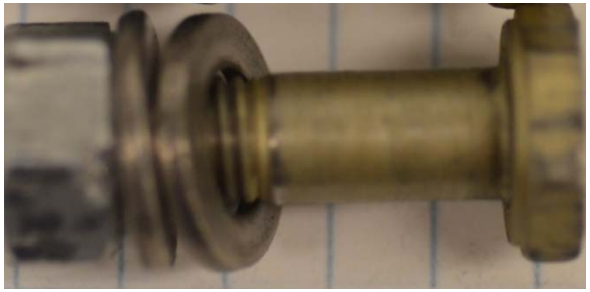
Fatigue Results (50% Zero)

- 50% Zero results showed lower relative capability in fatigue
  - Greater crack growth at lower percentage of failure load



Future Work

- Hole Damage Modeling
  - Including a model of increasing clearance/cycle improves agreement
  - Establish a model
- Variable Amplitude Testing
- Mode III
  - None of the testing considers mode III



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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