Disbond/Delamination Arrest Features in Aircraft Composite Structures

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The Joint Advanced Materials and Structures Center of Excellence

Sponsored Project Information

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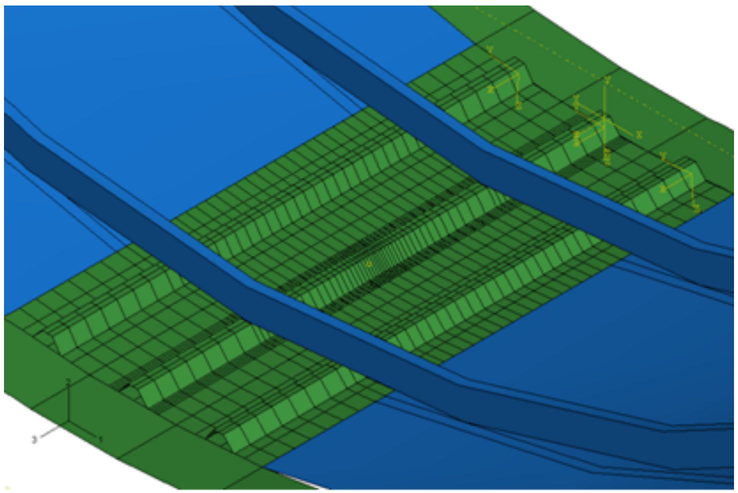
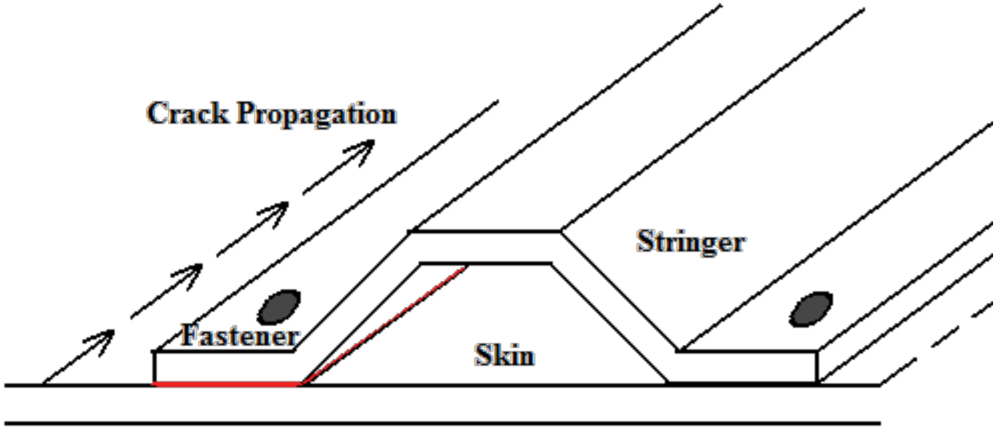
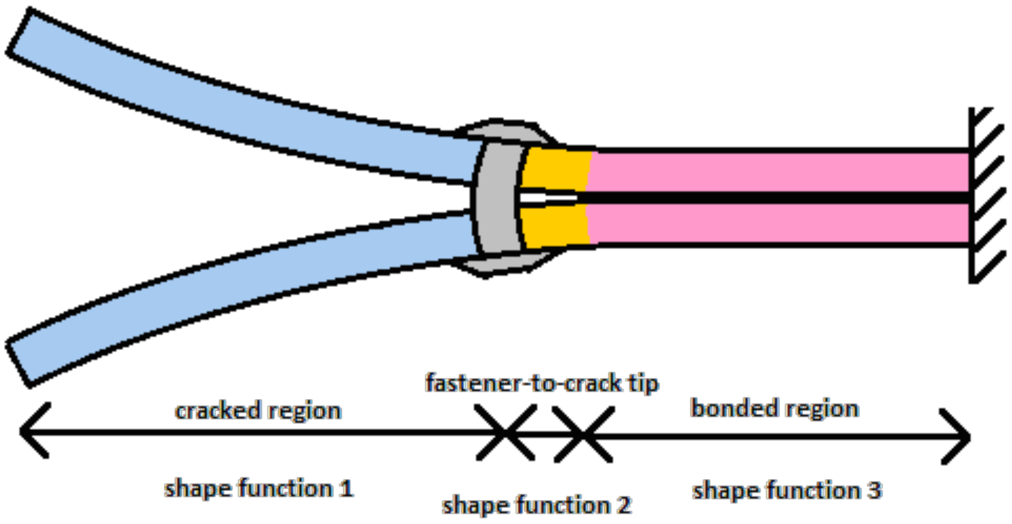
  - **Toray**: Kenichi Yoshioka, Dongyeon Lee, Felix Nguyen
- **Industry Sponsors: Boeing and Toray**

Crack Arrest Mechanism by Fastener







Objective and Approach

- **Objectives**

  - To understand the effectiveness of delamination/disbond arrest features

  - To develop analysis tools for design and optimization

- **Technical Approach**

  1). Establish Finite Element models in ABAQUS/VCCT

  2). Develop analytical capabilities for fast calculations

  3). Verify analysis results with experiments

  4). Conduct sensitivity studies on fastener effectiveness

  5). Provide tools for design and optimization

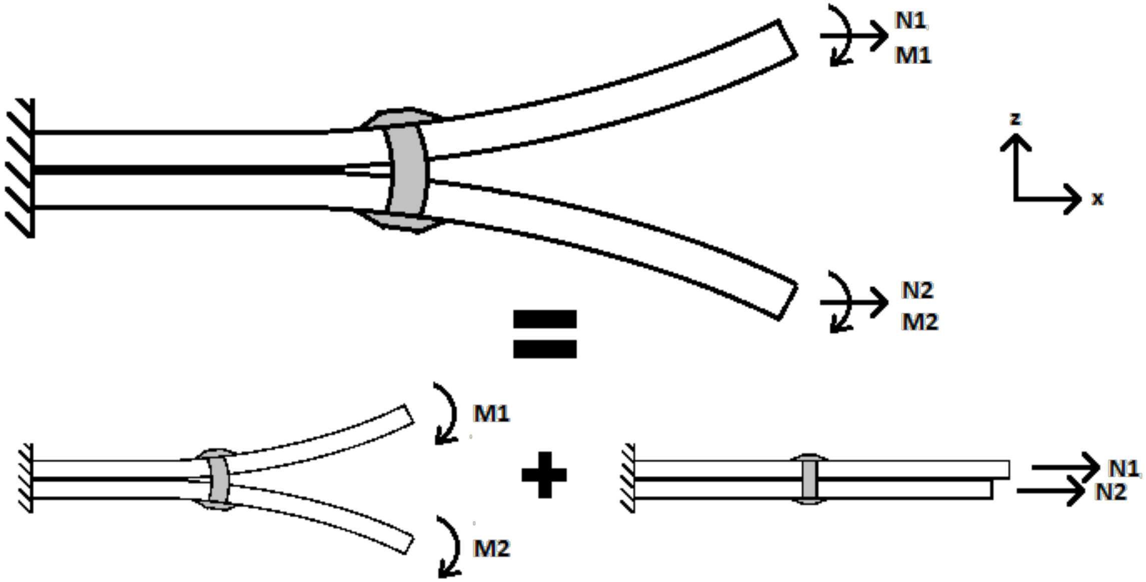
Previous Work Completed

1. Developed 1-D (beam) analytical solution
2. Developed and conducted validation experiments

   using 2-plate axial crack arrest specimen
3. Conduct sensitivity studies on fastener install torque and laminate stacking sequence
   - Stacking sequence: quasi-isotropic and 50% 0-deg
   - Fastener install torque: 0 to 80 in-lb

Analytical Model

- Model is composed of a beam-column part and a truss part
- Fastener is modeled by a tension spring which works with the beam-columns in bending; and a joint flexibility spring which works with the trusses
- Crack tip Energy Release Rate (ERR) is obtained using VCCT
- Friction and joint/hole clearance is also modeled



Method of Solution

- Total energy = Π = U – W
- Differentiate Π w.r.t. each degree of freedom

$$\delta\Pi = \delta U - \delta W = 0$$

- Results in a set of linear equations; solve linear system
- Obtain displacement solution
  - Forces and crack tip ERR are derived from the displacement solution
  - Crack propagation behavior and arrest effectiveness are analyzed

Beam-Column

- Polynomial shape function

$$w_i(x) = \sum_{j=0}^{n} \beta_{i,j} x^j$$

- Beam-Column energy

$$U_{bc,i} = \frac{1}{2} EI \int_{L_1}^{L_2} \left(\frac{d^2 w_i}{dx^2} \right)^2 dx + \frac{1}{2} N \int_{L_1}^{L_2} \left(\frac{dw_i}{dx} \right)^2 dx$$

Truss

- Polynomial shape function

$$u_i(x) = \sum_{j=0}^{n} \alpha_{i,j} x^j + \sum_{k=n+1}^{m} \alpha_{i,k} e^{c_k (x-L)}$$

- Truss energy

$$U_{truss,i} = \frac{1}{2} AE \int_{L_1}^{L_2} \left(\frac{du_i}{dx} \right)^2 dx$$

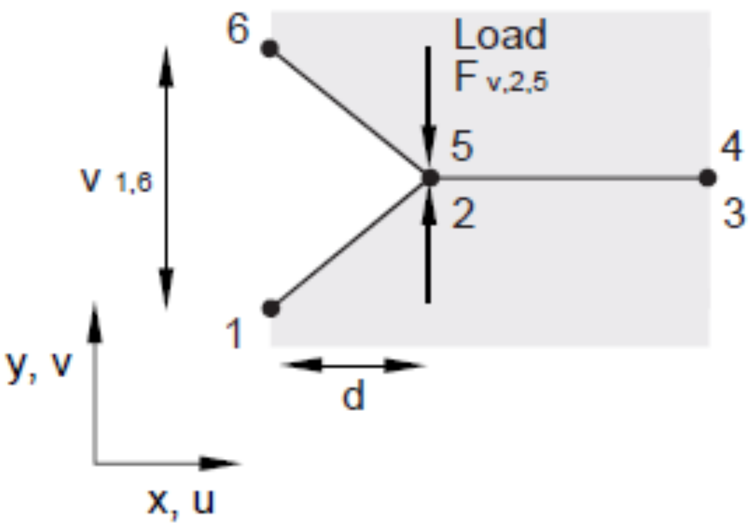
Fastener/Contact/Bond Springs

$$U = \frac{1}{2} k \left(u_i - u_j \right)^2$$

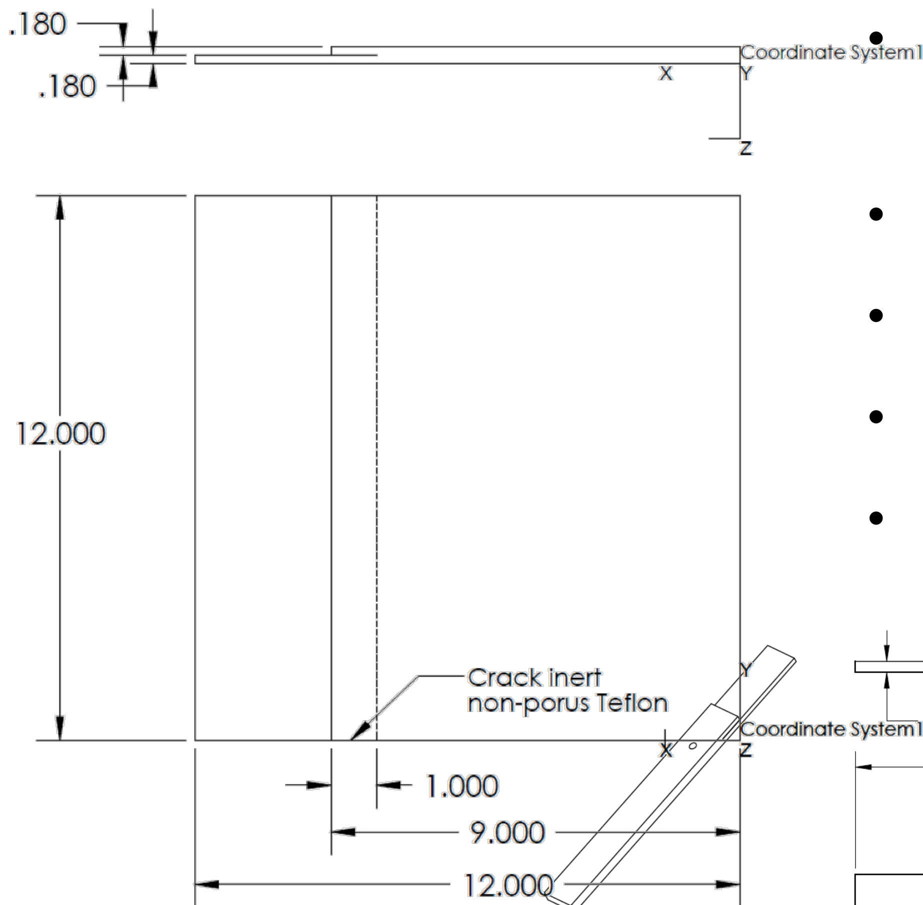
G_{II} from VCCT

- Computes G_{II} from crack tip shear force and crack tip sliding displacement

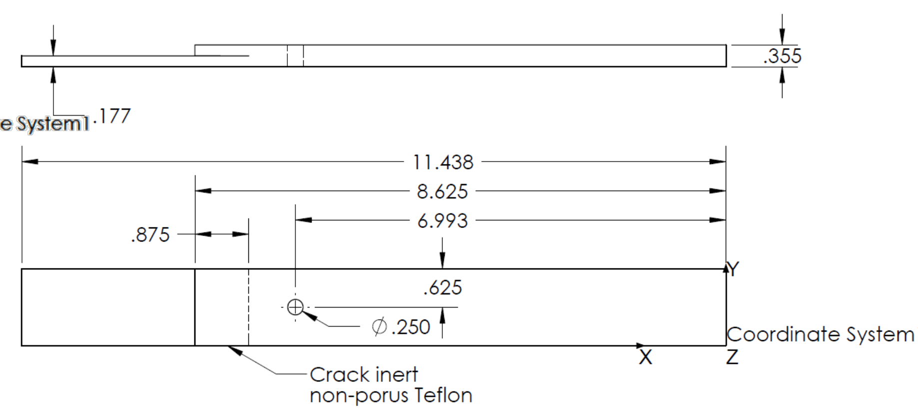
$$G_{II} = \frac{1}{2}\left(\frac{u_{1,6}F_{u,2,5}}{bd}\right)$$



2-Plate Specimen Description



- BMS 8-276 (T800H/#3900-2) unidirectional pre-preg tape
- BMS 8-308 peel ply
- Titanium Fasteners
- $(0/45/90/-45)_{3S}$
- $(0/-45/02/90/45/02/-45/90/45/0)_{S}$



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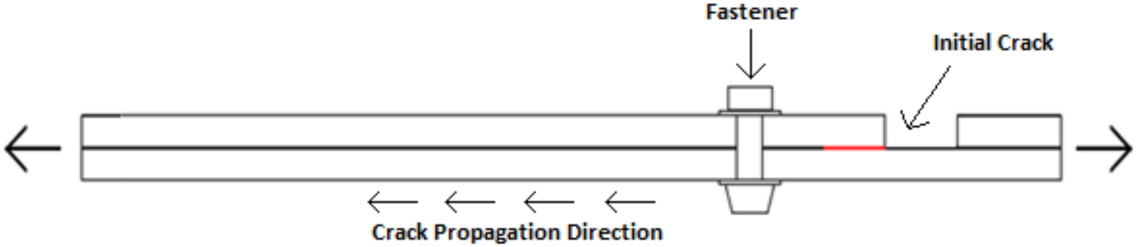
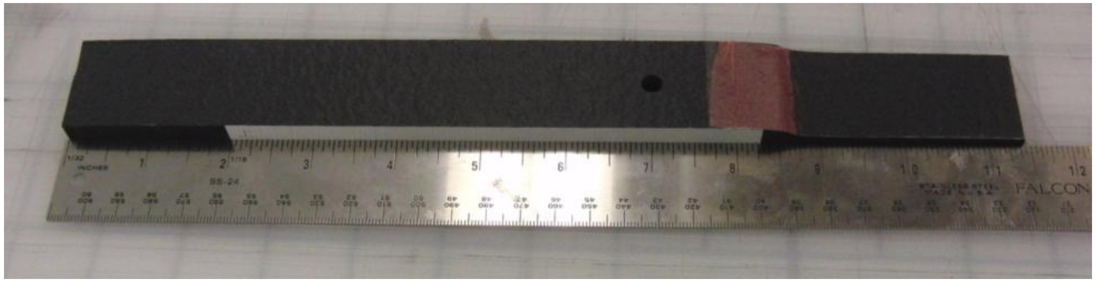
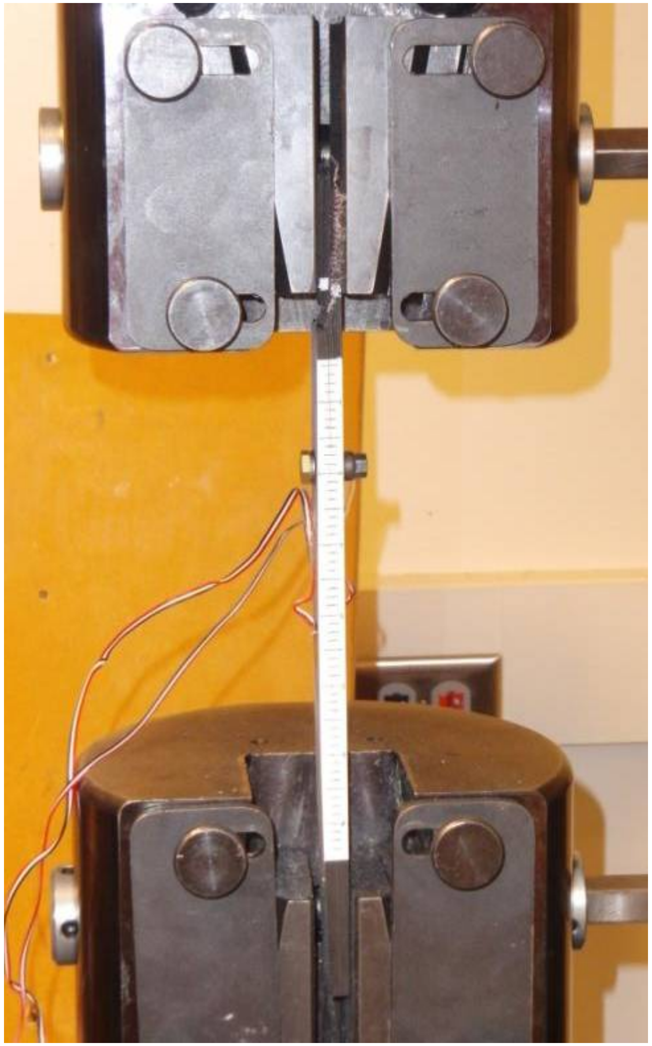
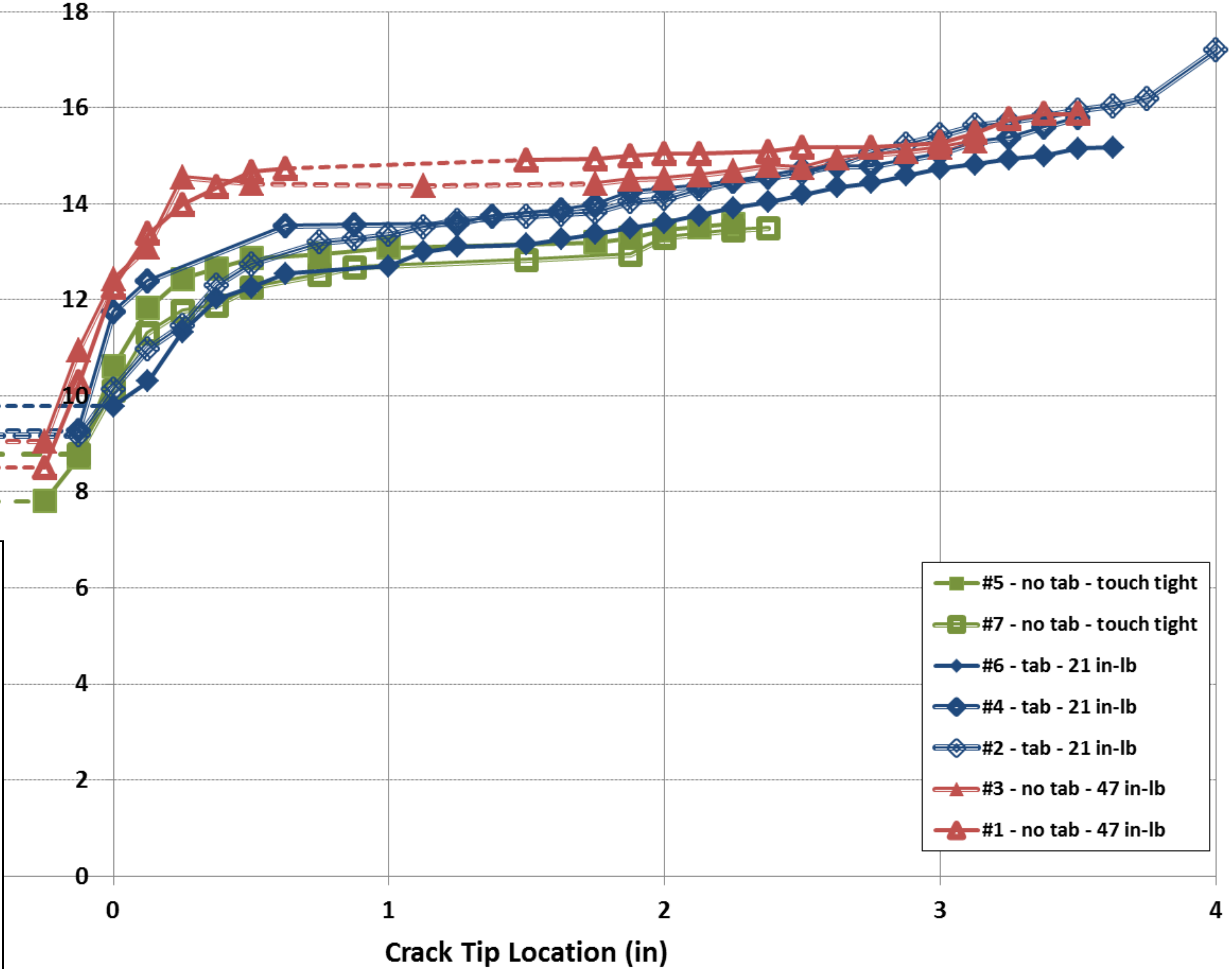
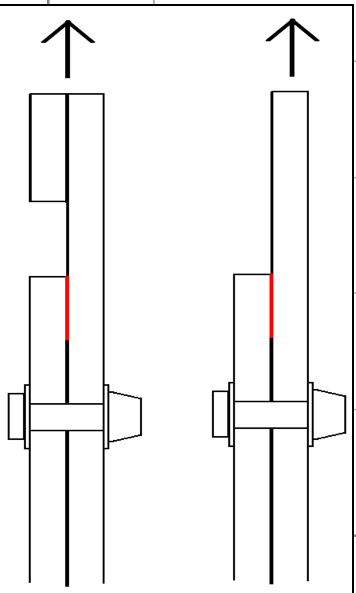


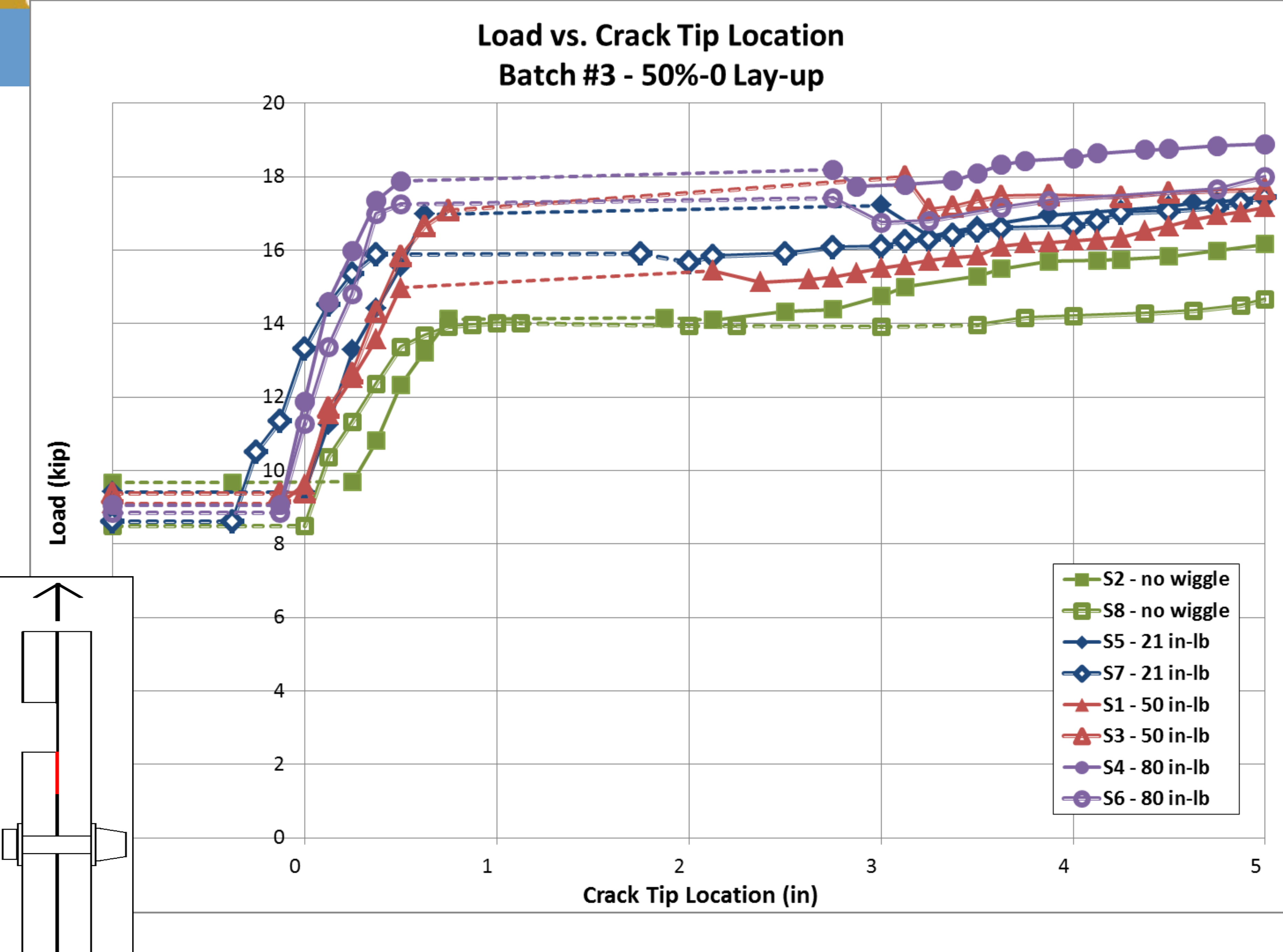


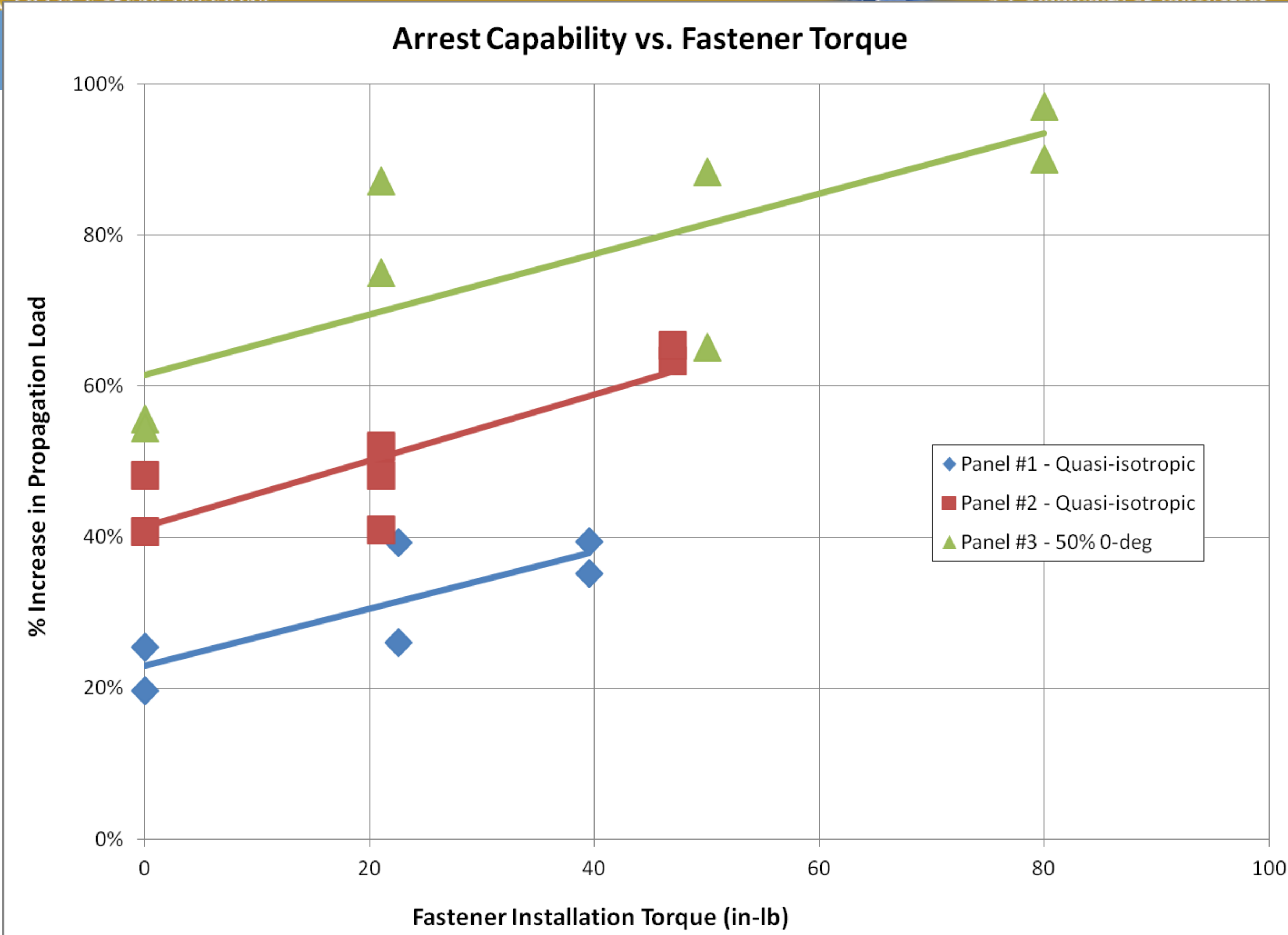


Load vs. Crack Tip Location
Batch #2 - Quasi-isotropic Lay-up






Load vs. Crack Tip Location
Batch #3 - 50%-0 Lay-up
Load (kip)
Crack Tip Location (in)
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
S2 - no wiggle
S8 - no wiggle
S5 - 21 in-lb
S7 - 21 in-lb
S1 - 50 in-lb
S3 - 50 in-lb
S4 - 80 in-lb
S6 - 80 in-lb


Arrest Capability vs. Fastener Torque
100%
80%
60%
40%
20%
0%
% Increase in Propagation Load
0
20
40
60
80
100
Fastener Installation Torque (in-lb)
Panel #1 - Quasi-isotropic
Panel #2 - Quasi-isotropic
Panel #3 - 50% 0-deg

Summary of Test Results

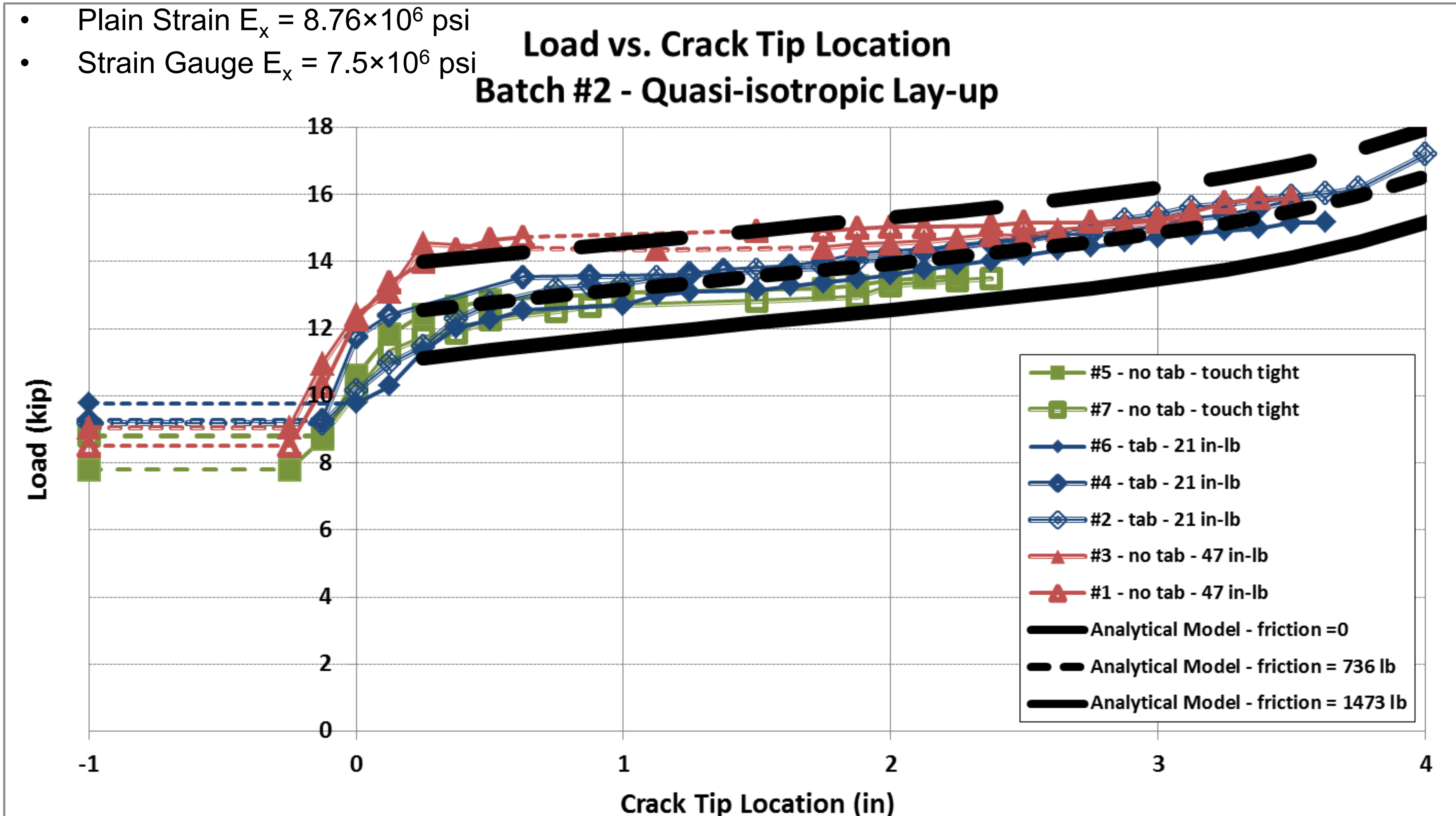
- Propagation arrestment and stable propagation thereafter demonstrated.
- Fastener install torque (friction) is a major driver of crack arrest capability.
- High-stiffness lay-up experience more increase in arrest capability for the same fastener size and torque.
- Fabrication of thick specimens is difficult.
- Crack front is not symmetric across the width of the specimen, especially near the fastener.

Analytical Solution vs. Experiment

- Properties used
  - E_1 = 20×10^6 psi
  - E_2 = 1.5×10^6 psi
  - G_{12} = 1×10^6 psi
  - t = 0.0075 in
  - G_{IIC} = 12 in-lb/in^2
- Layups
  - $(0/45/90/-45)_{3S}$/crack/$(0/45/90/-45)_{3S}$
  - $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$/crack/ $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$
- Fastener Stiffness
  - 30% of Huth's Equation

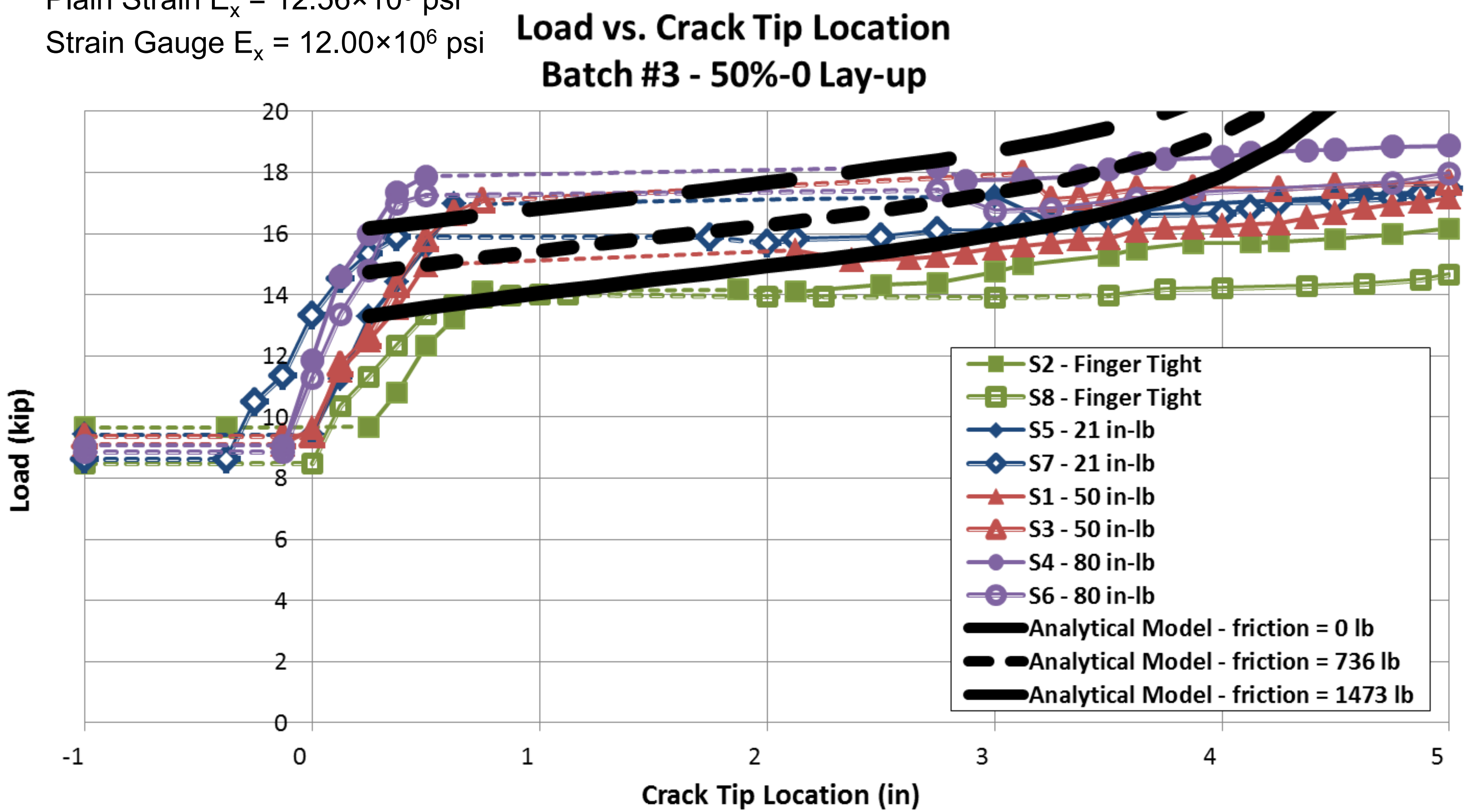
$(0/45/90/-45)_{3S}$/crack/$(0/45/90/-45)_{3S}$

- CLT $E_x = 7.99\times10^6$ psi
- Plain Strain $E_x = 8.76\times10^6$ psi
- Strain Gauge $E_x = 7.5\times10^6$ psi



$(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$/crack/ $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$

- CLT $E_x = 12.00\times10^6$ psi
- Plain Strain $E_x = 12.56\times10^6$ psi
- Strain Gauge $E_x = 12.00\times10^6$ psi



2012 (Sept)- 2013 (Aug) Tasks

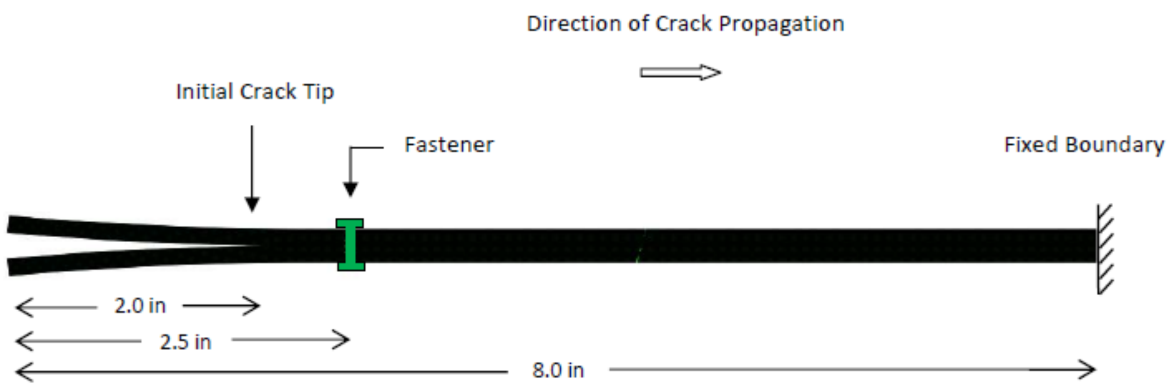
Task 1: Conduct Parametric Studies on Crack Arrest by a Single Fastener

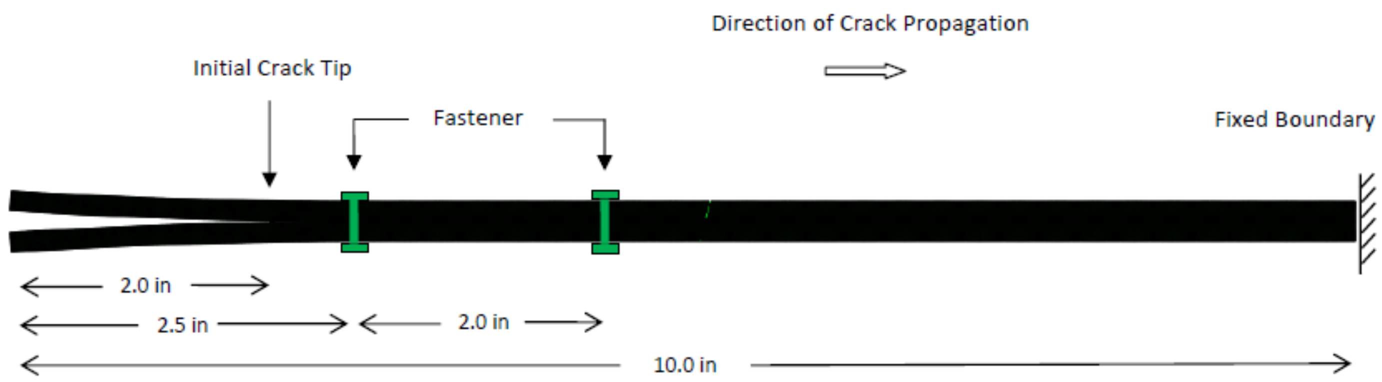
Task 2: Develop Analytical Tool to Study Crack Arrest by Multiple Fasteners

Task 3: Conduct Experiments to Determine the Fastener Arrest Effectiveness using Resin Systems with Different G_{IC}:G_{IIC} Ratios

Task 4: Experimental Investigation of Delamination Propagation with Two Fasteners in Series

Work in Progress (Tasks 1, 2)

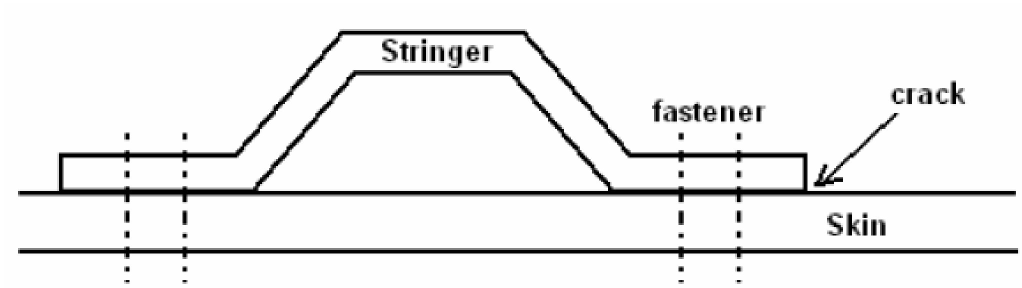


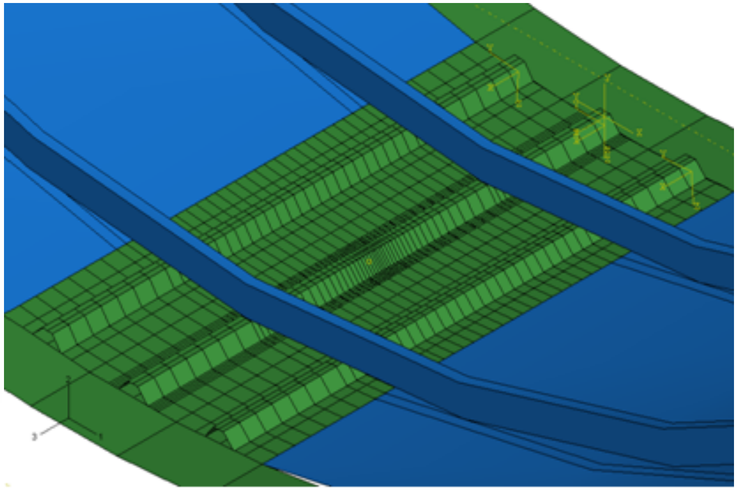


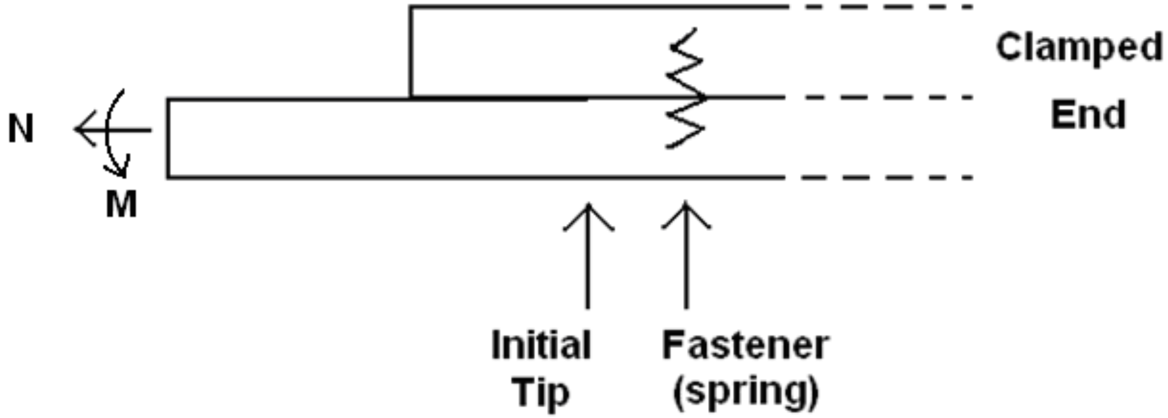
Summary

- Technical approach to disbond/delamination arrest features in aircraft composite structures have been presented.
- Work accomplished during 2011-2012 has been discussed.
- Delamination arrest by fastener has been demonstrated.
- The 2012- 2013 new tasks have been presented.

Bonded Skin/Stiffener with Fasteners







Model Description

- 16-ply CFRP (t = 0.0075” x 16 = 0.12”)
- Lay-ups
  - Percentage of 0-deg: 25% / 37.5% / 50% / 62.5%
- Fastener
  - Ti-Al6-V4 (E = 16.5×10^6psi)
  - d = 0.25 in
- Fastener Flexibility (H. Huth, 1986)

$$C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{n t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$$

Work in Progress / Future Work

- Refine FEA models and procedures
- Develop analysis capabilities
- Understand disbond/delamination propagation around the fastener in 3-D
- Consider multiple fasteners and multiple failure modes
- Perform parametric/sensitivity studies
- Identify key variables for design and optimization
- Design validation experiments

Discrepancies and Unknowns

- Discrepancies
  - CLT E_x/Plain Strain E_x does not correspond to strain gauge E_x
  - Fastener joint has only 30% of the stiffness as predicted by Huth's model
  - Fastener hole begins to crush, and fastener rotates as load increases
- Unknowns
  - G_{IIC}
  - Contact Friction as a result of install torque

A Look Forward

- **Benefit to Aviation**
  - The present method allows engineers to design damage tolerant composite structures for a predetermined level of reliability, as required by FAR 25.
  - The present study makes it possible to determine the relationship among the reliability level, inspection interval, inspection method, and repair quality to minimize the maintenance cost and risk of structural failure.
- **Future needs**
  - A standardized methodology for establishing an optimal inspection schedule for aircraft manufacturers and operators.
  - Enhanced damage data reporting requirements regulated by the FAA.
  - A comprehensive system of characterizing material and processing variability for damage tolerant bonded structures.