



Delamination/Disbond Arrest Fasteners in Aircraft Composite Structures

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By

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Acknowledgements

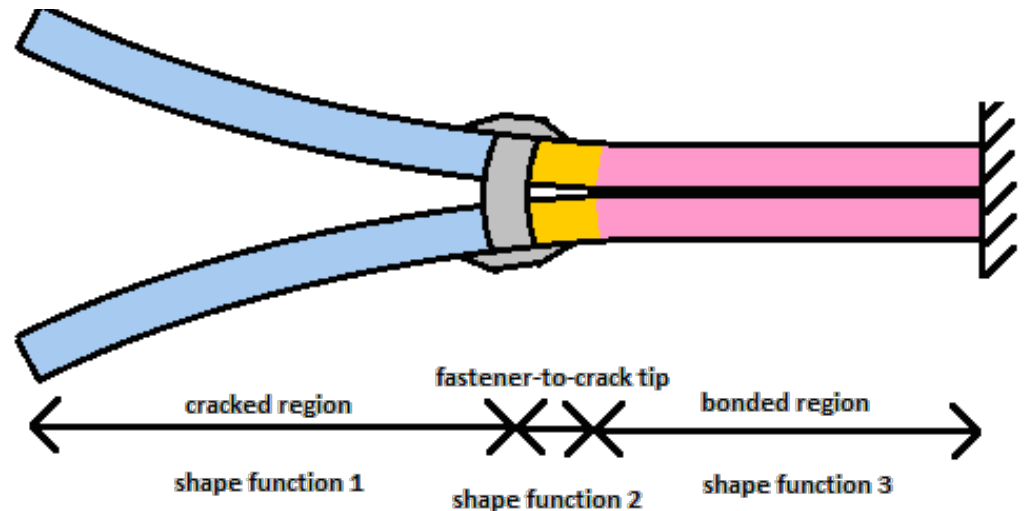
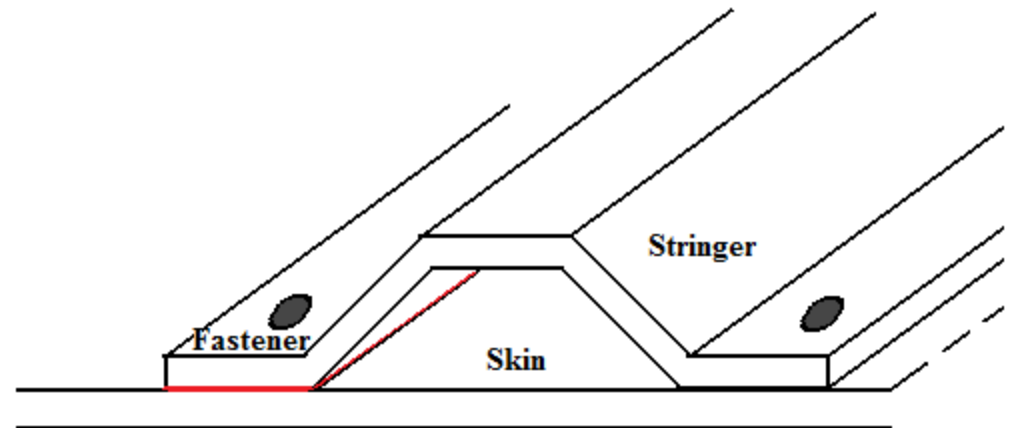
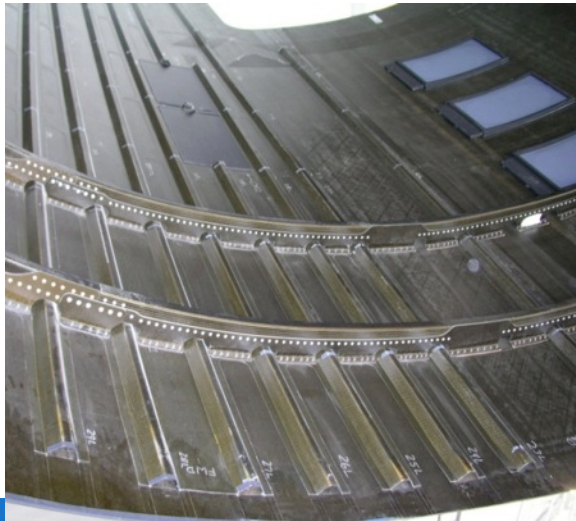
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Sponsored Project Information

- **Principal Investigator:**
 - Dr. Kuen Y. Lin, Aeronautics and Astronautics, UW
- **Research Assistants:** Eric Cheung, Luke Richard, Wenjing Liu
- **FAA Technical Monitor:** Lynn Pham
- **Other FAA Personnel:** Curtis Davies, Larry Ilcewicz
- **Industry Participants:**
 - **Boeing:** Marc Piehl, Gerald Mabson, Eric Cregger, Matthew Dilligan
 - **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

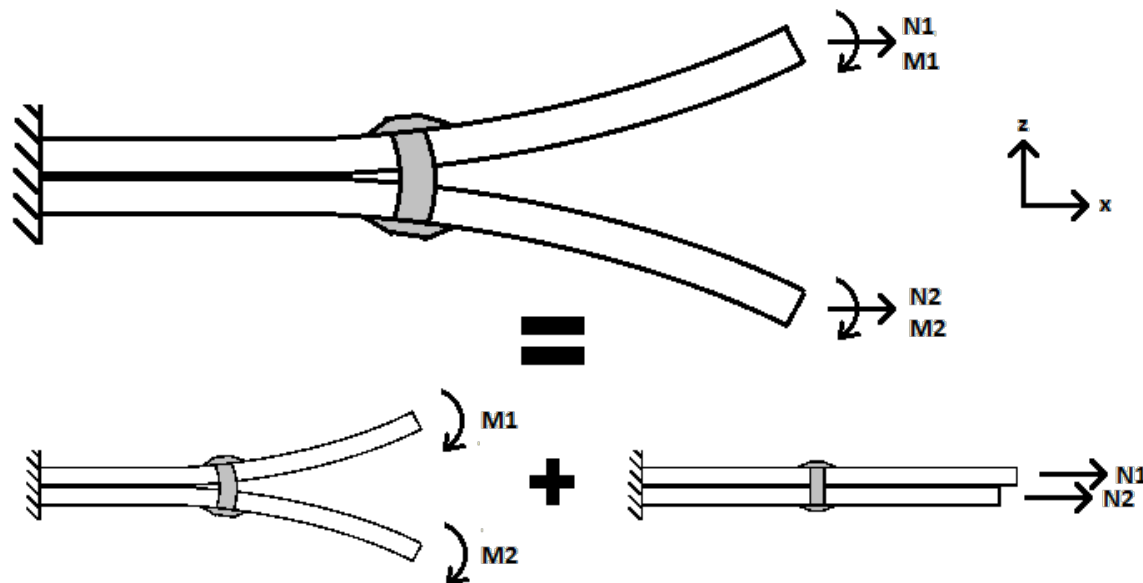
■ Technical Approach

- 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



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 = $\Pi = U - W$
- 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

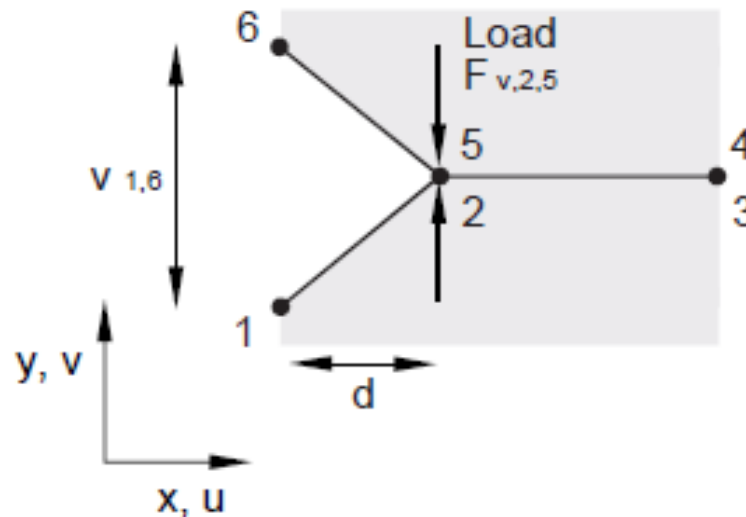
$$U = \frac{1}{2} k (u_i - u_j)^2$$



G_{II} from VCCT

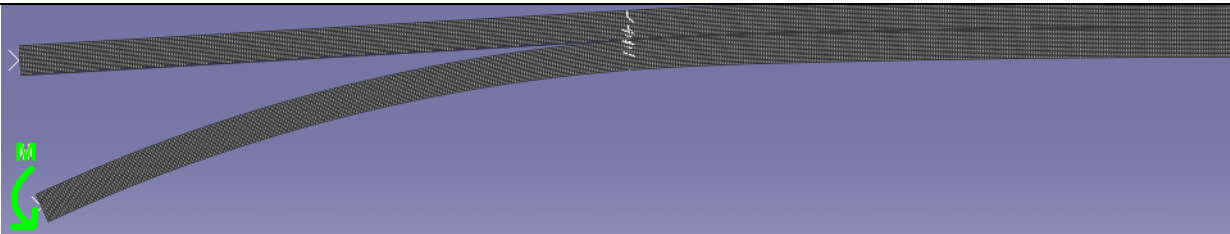
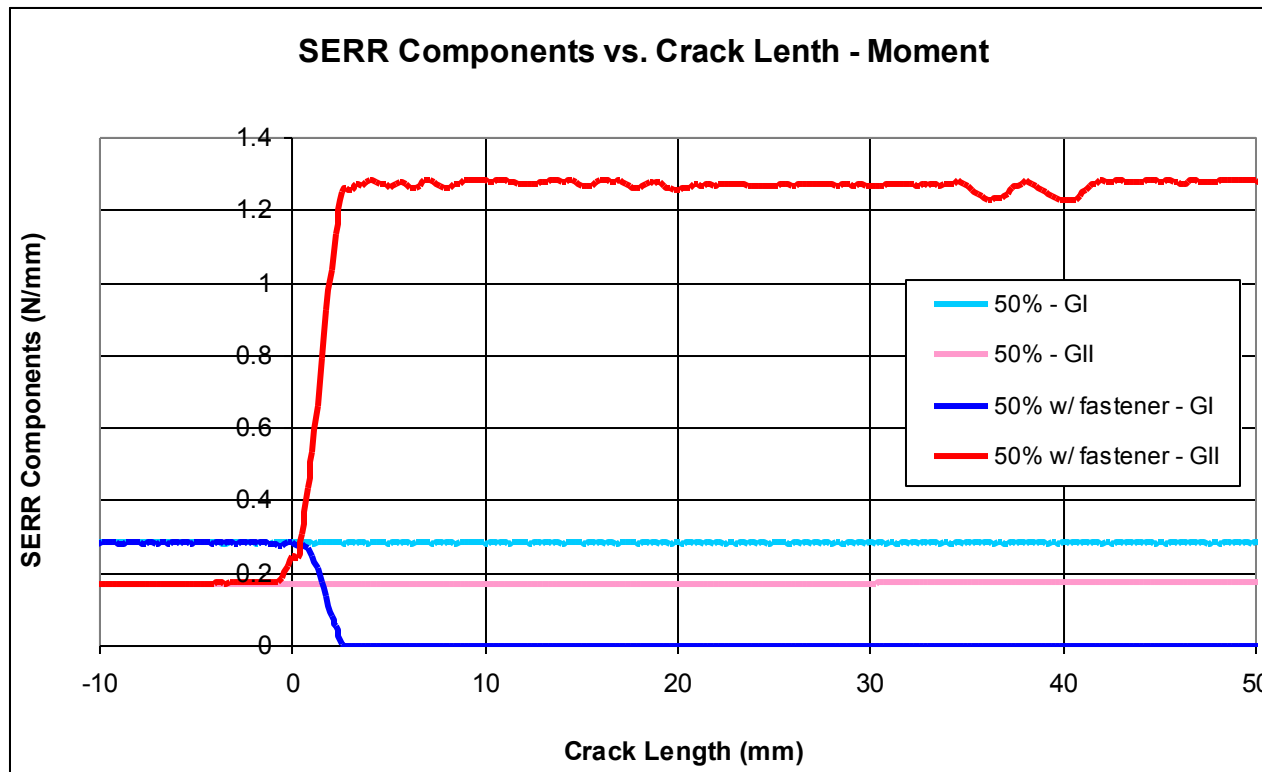
- Computes G_{II} from crack tip shear force and crack tip sliding displacement

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



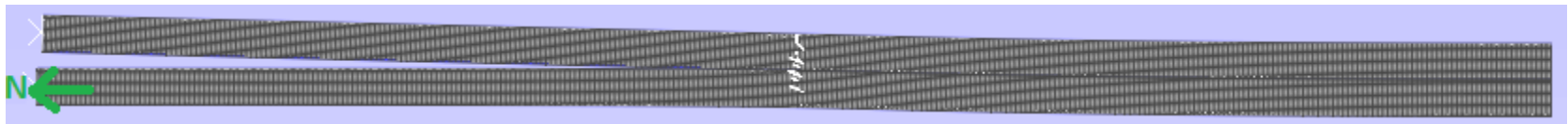
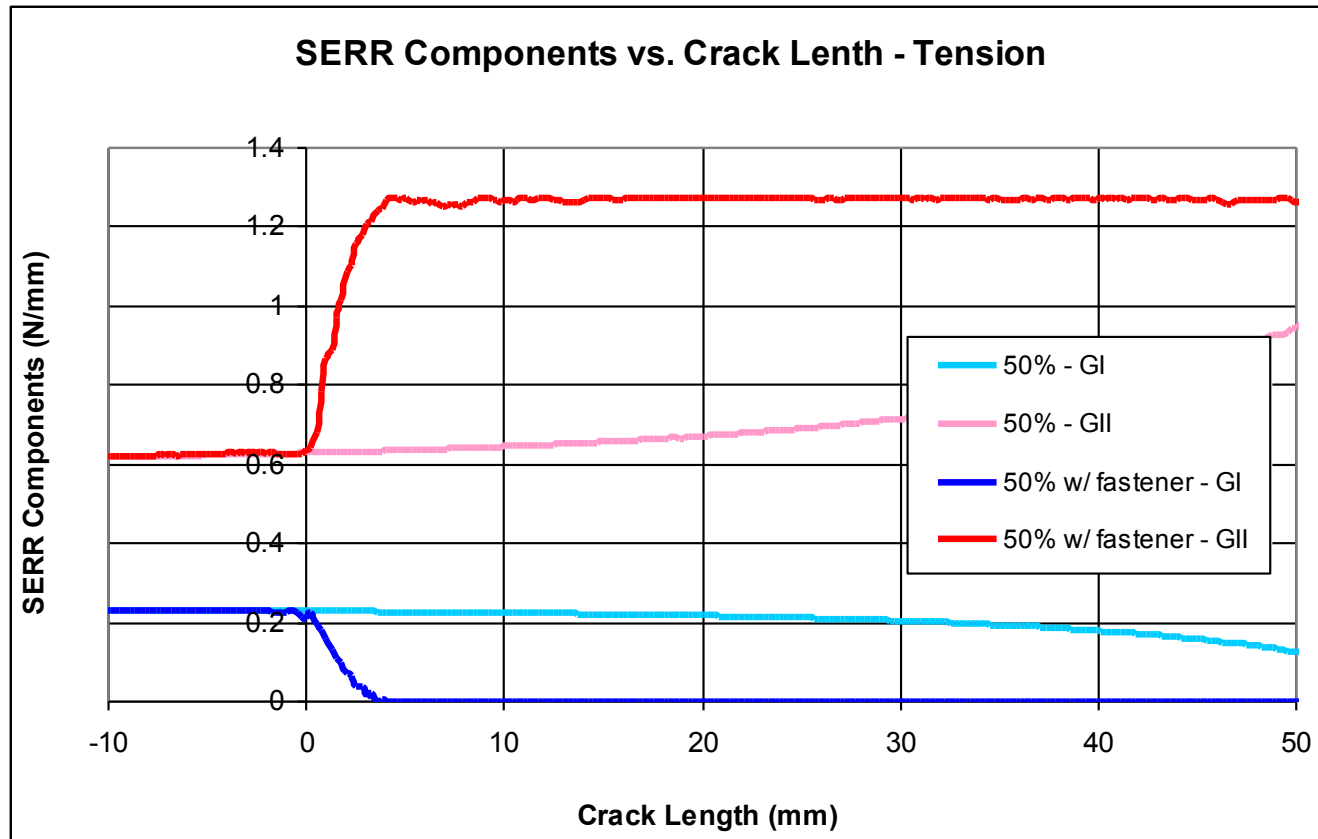


Mode Decomposition with Fastener: Applied Moment Only



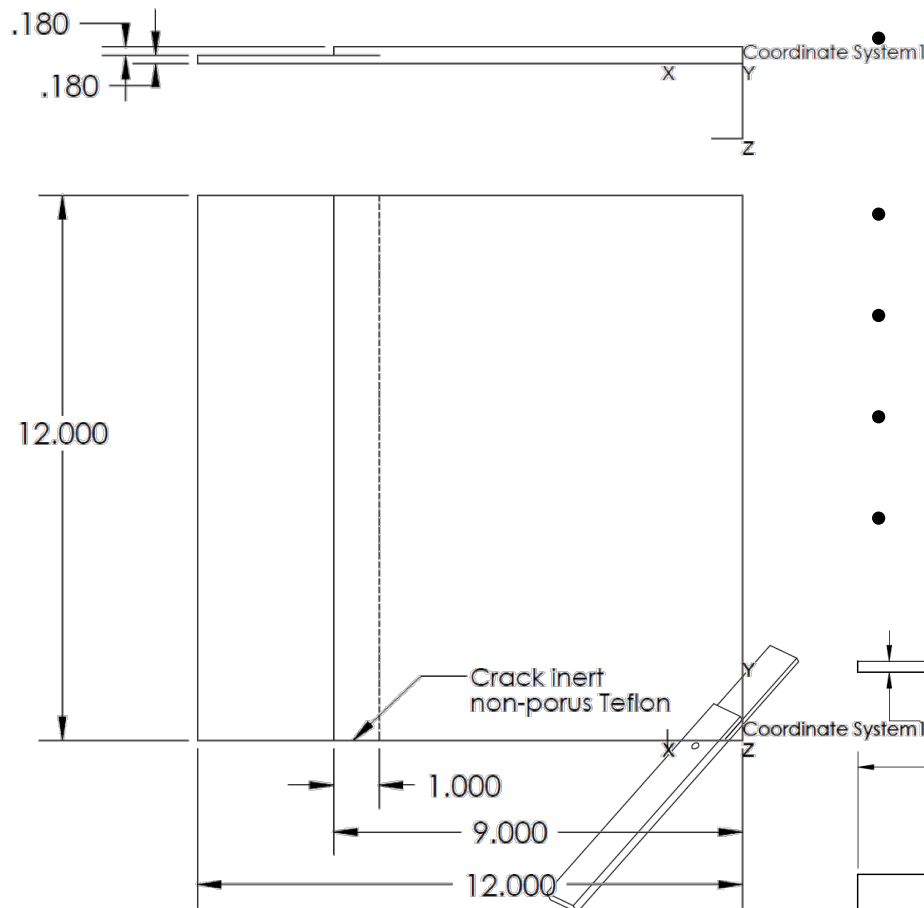


Mode Decomposition: Applied Tension Only

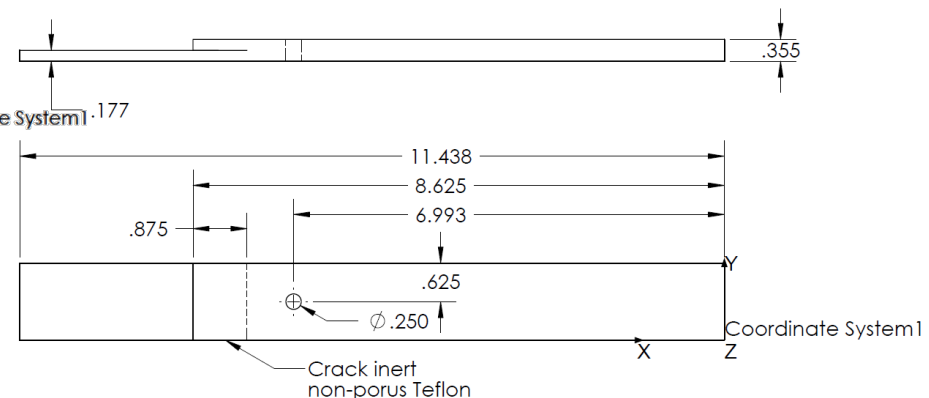




2-Plate Specimen Description



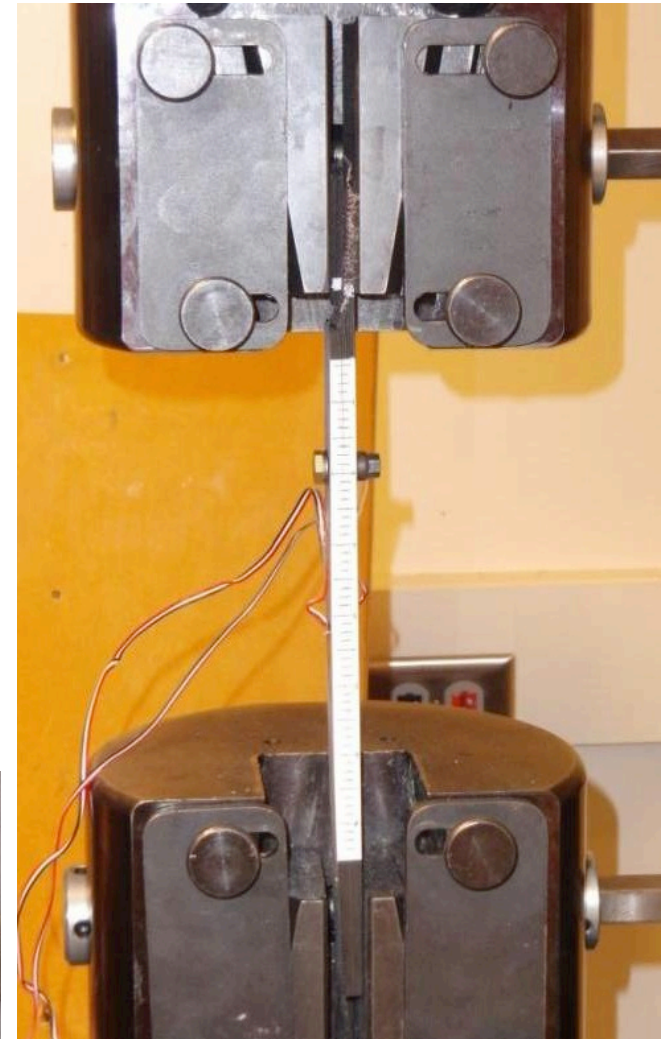
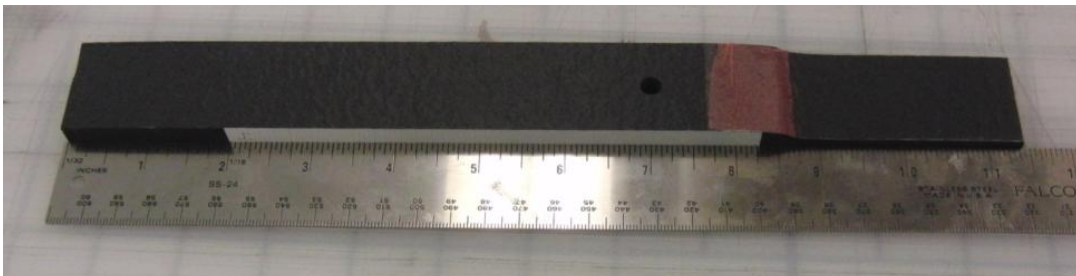
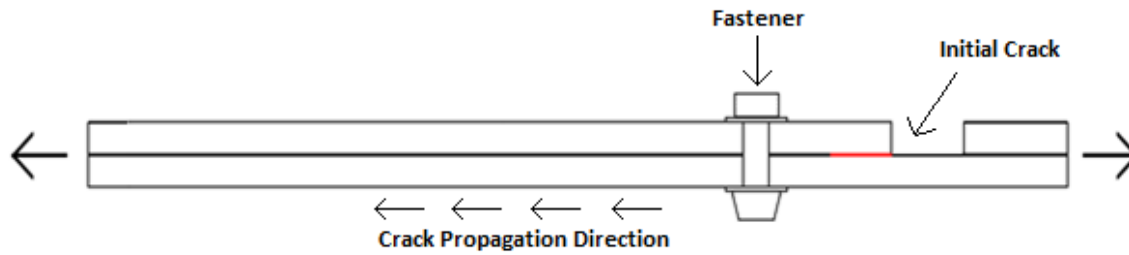
- BMS 8-276 (T800H/#3900-2) unidirectional pre-preg tape
- BMS 8-308 peel ply
- Titanium Fasteners
- $(0/45/90/-45)_3S$
- $(0/-45/02/90/45/02/-45/90/45/0)_S$





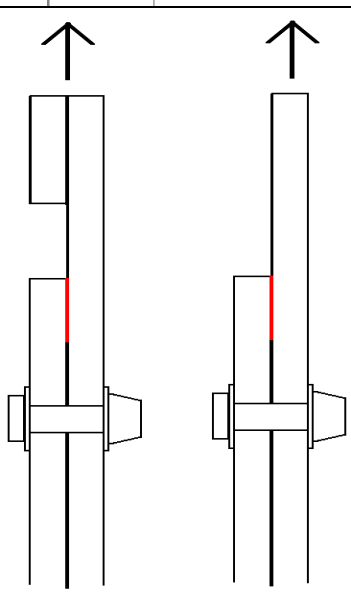
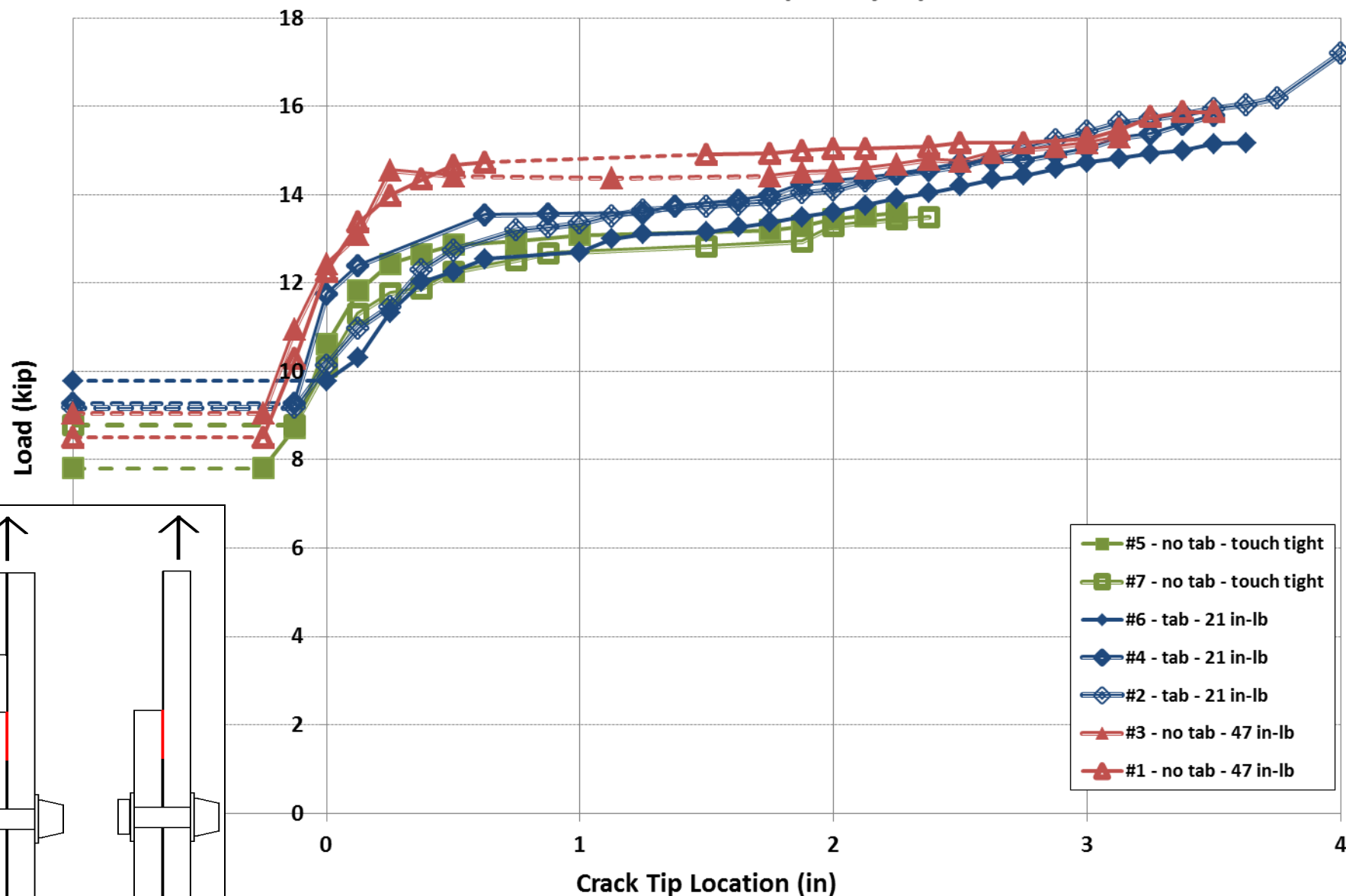
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2-Plate Specimen

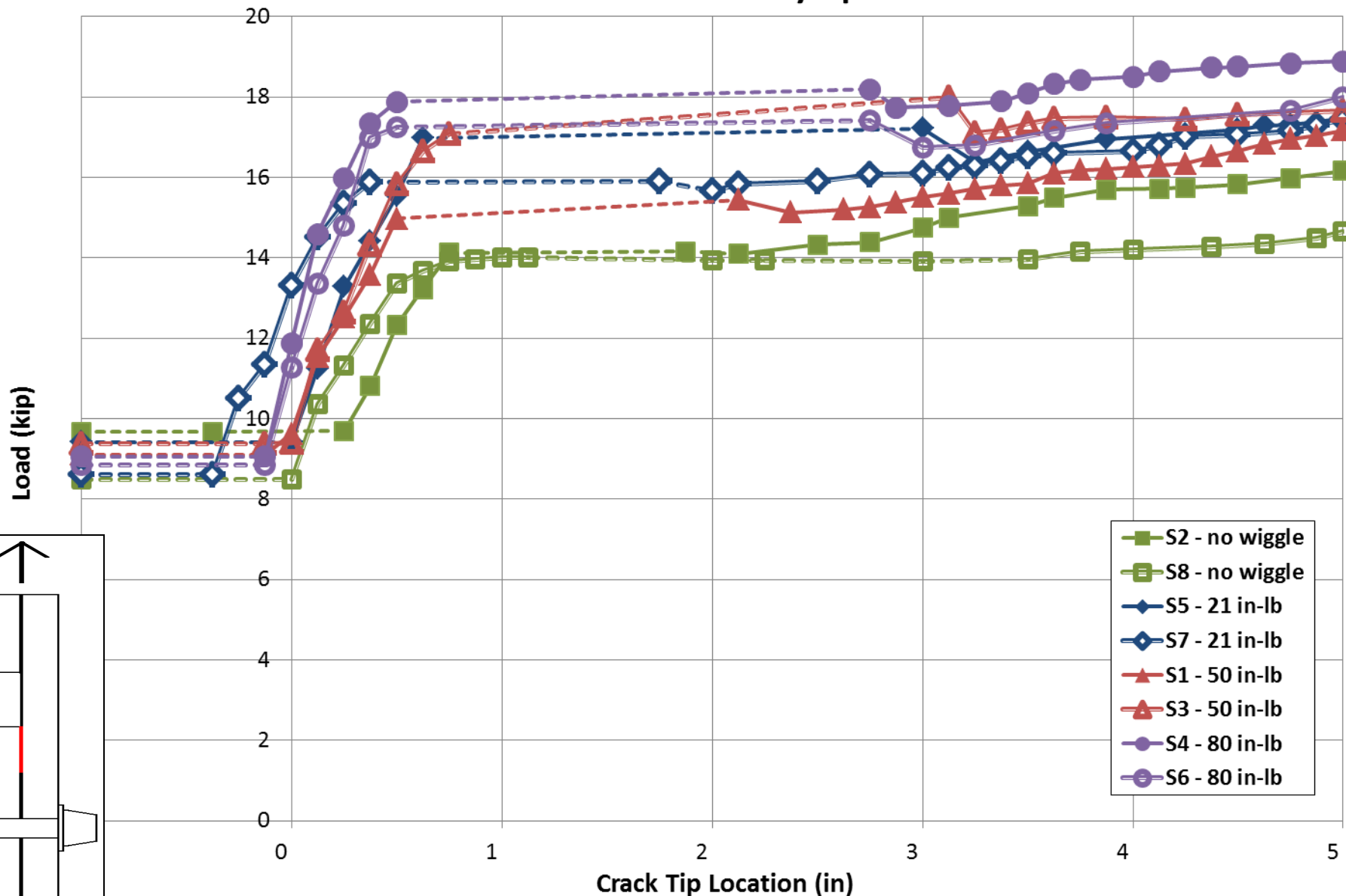


Load vs. Crack Tip Location

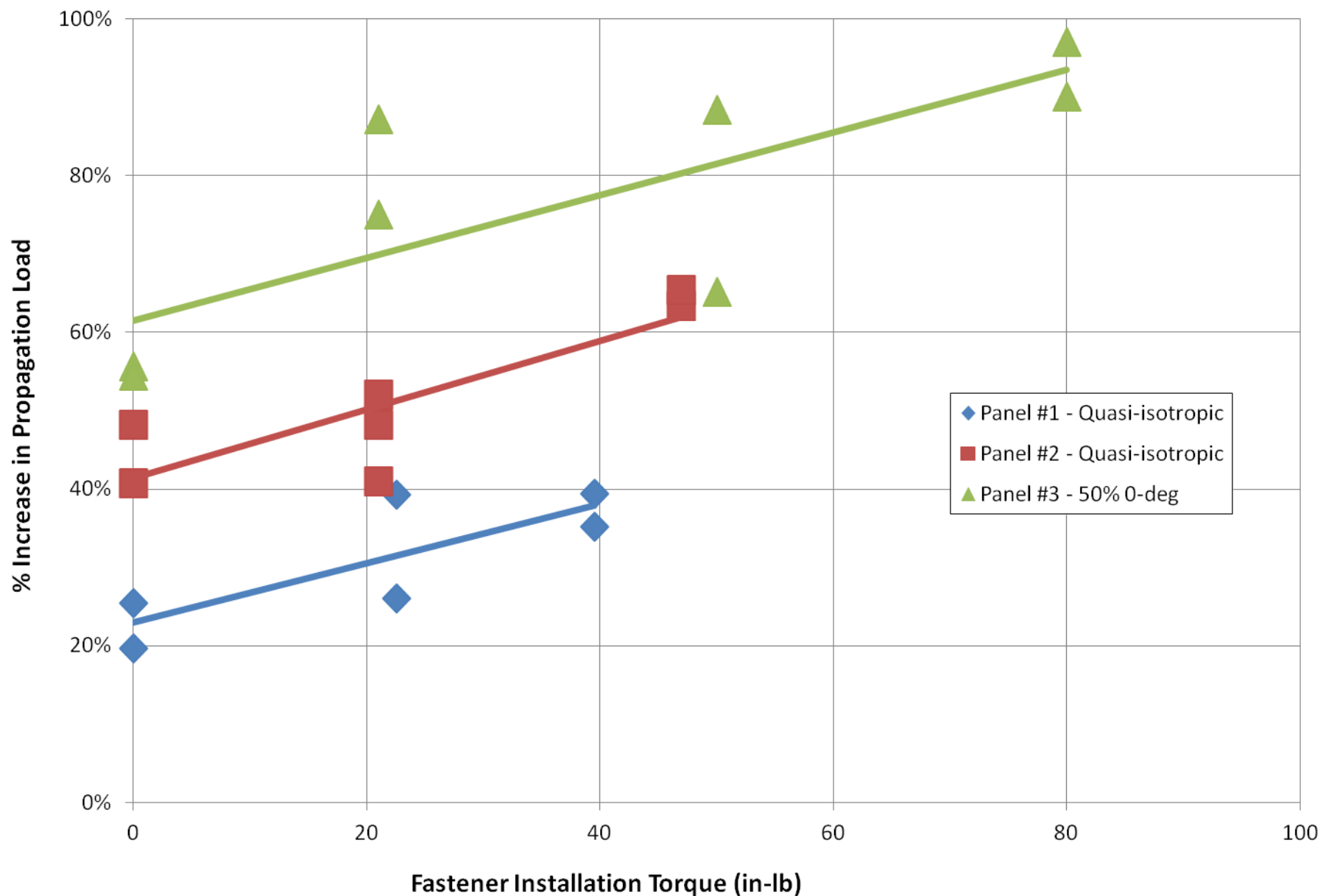
Batch #2 - Quasi-isotropic Lay-up



Load vs. Crack Tip Location Batch #3 - 50%-0 Lay-up



Arrest Capability vs. Fastener Torque





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

- $E_1 = 20 \times 10^6 \text{ psi}$
- $E_2 = 1.5 \times 10^6 \text{ psi}$
- $G_{12} = 1 \times 10^6 \text{ psi}$
- $t = 0.0075 \text{ in}$
- $G_{IIC} = 12 \text{ in-lb/in}^2$

■ Layups

- $(0/45/90/-45)_{3S}/\text{crack}/(0/45/90/-45)_{3S}$
- $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S/\text{crack}/$
 $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$

■ Fastener Stiffness

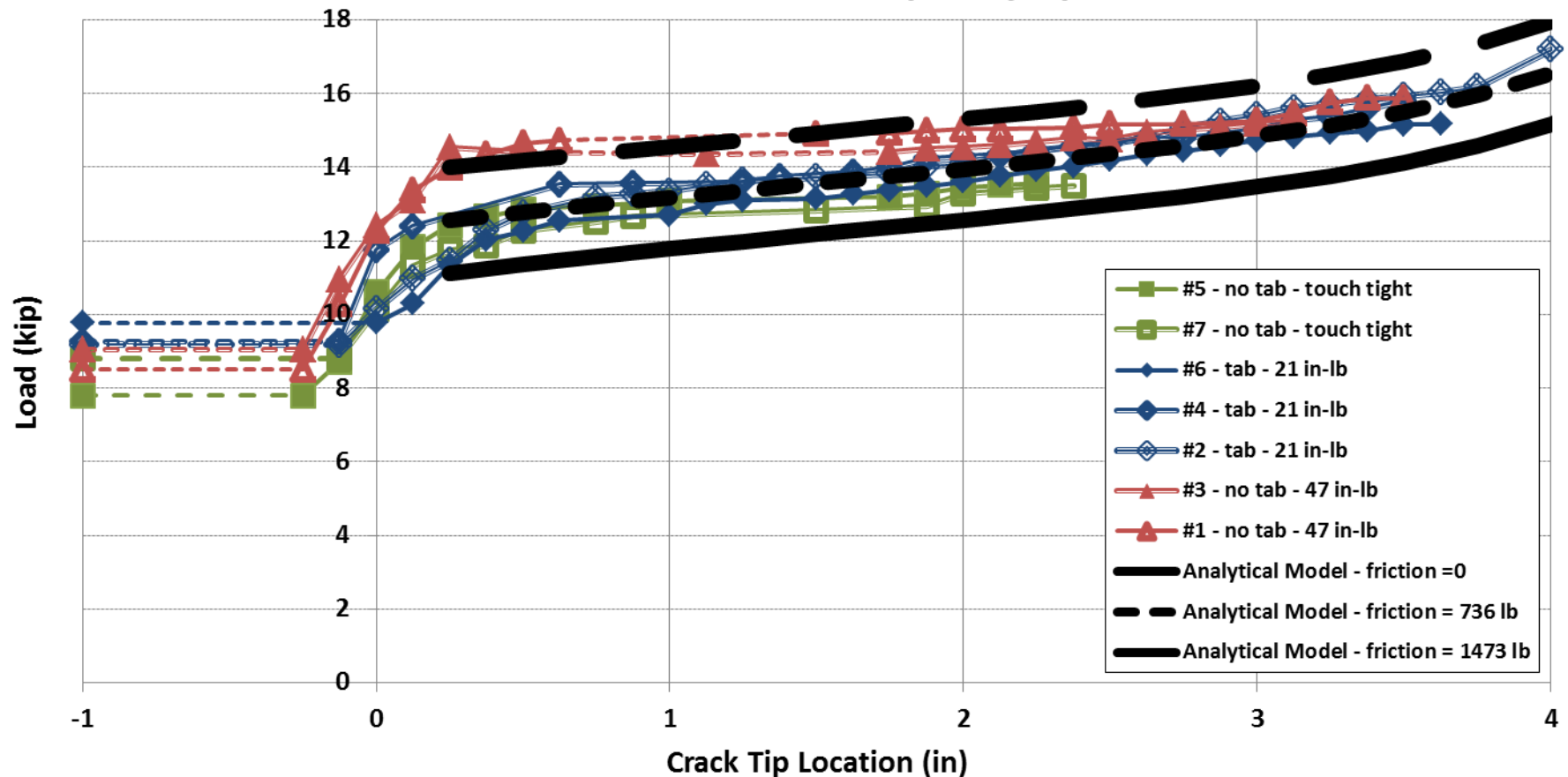
- 30% of Huth's Equation



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

- CLT $E_x = 7.99 \times 10^6$ psi
- Plain Strain $E_x = 8.76 \times 10^6$ psi
- Strain Gauge $E_x = 7.5 \times 10^6$ psi

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



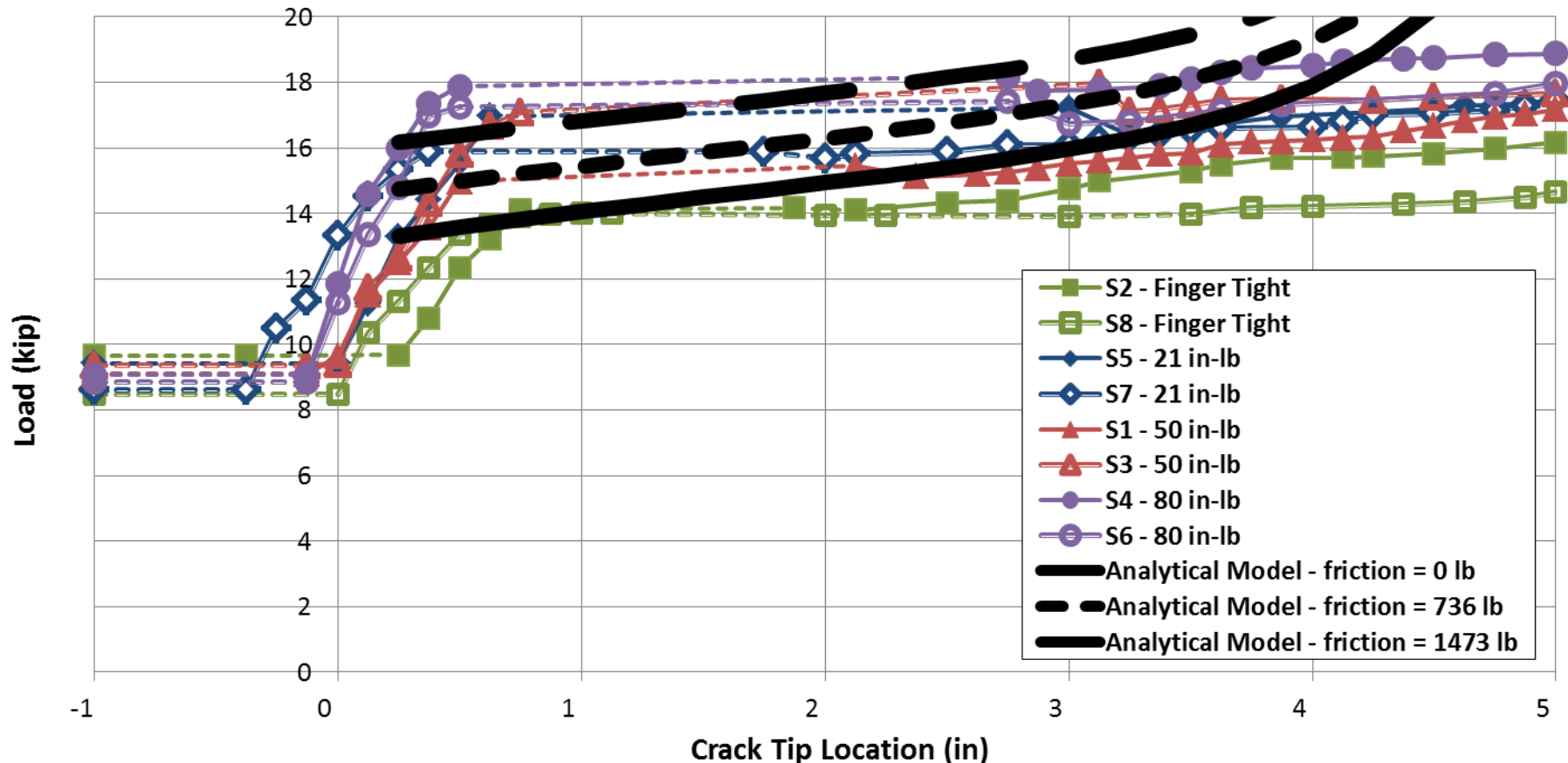
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**$(0/-45/0_2/90/45/0_2/-45/90/45/0)_s$ /crack/
 $(0/-45/0_2/90/45/0_2/-45/90/45/0)_s$**

- CLT $E_x = 12.00 \times 10^6$ psi
- Plain Strain $E_x = 12.56 \times 10^6$ psi
- Strain Gauge $E_x = 12.00 \times 10^6$ psi

**Load vs. Crack Tip Location
Batch #3 - 50%-0 Lay-up**



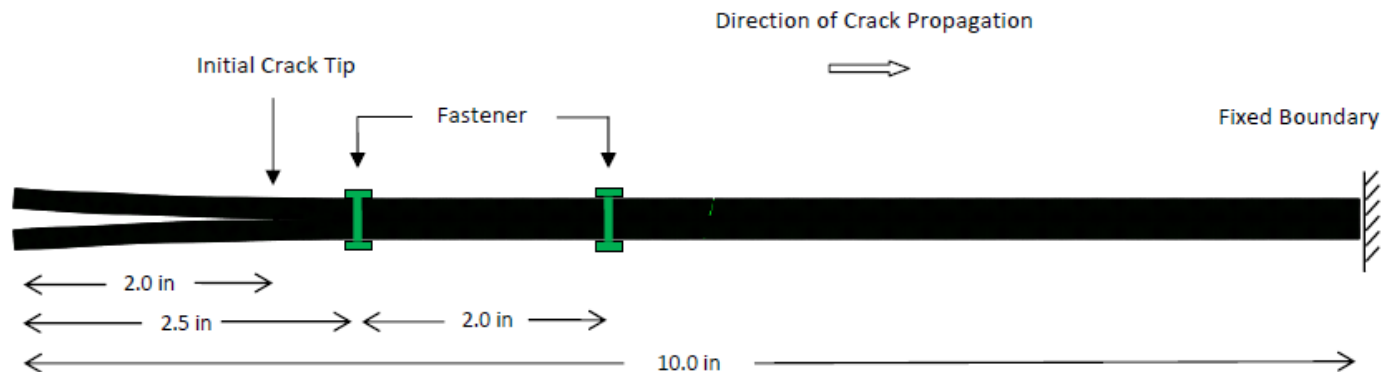
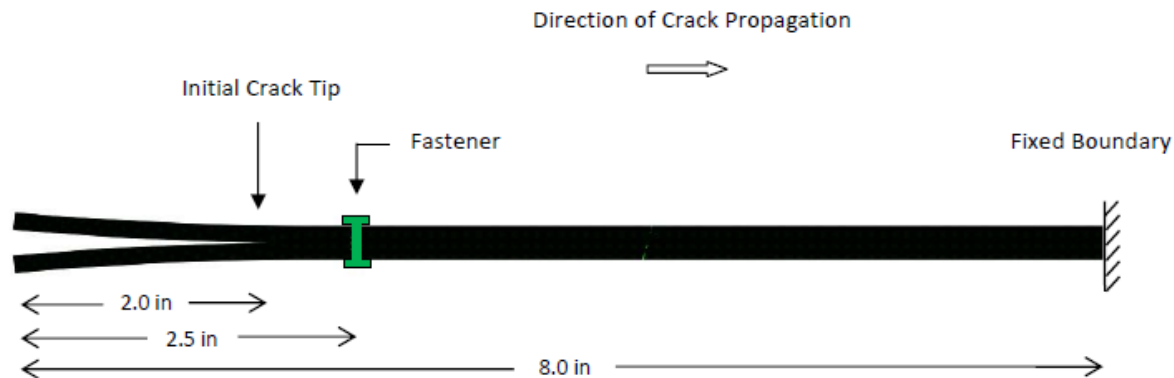


Future Research

- Conduct Parametric Studies on Crack Arrest by a Single Fastener
- Develop Analytical Tool to Study Crack Arrest by Multiple Fasteners
- Conduct Experiments to Determine the Fastener Arrest Effectiveness using Resin Systems with Different $G_{IC}:G_{IIC}$ Ratios
- Experimental Investigation of Delamination Propagation with Two Fasteners in Series



Delamination Arrest by One and Two Fasteners





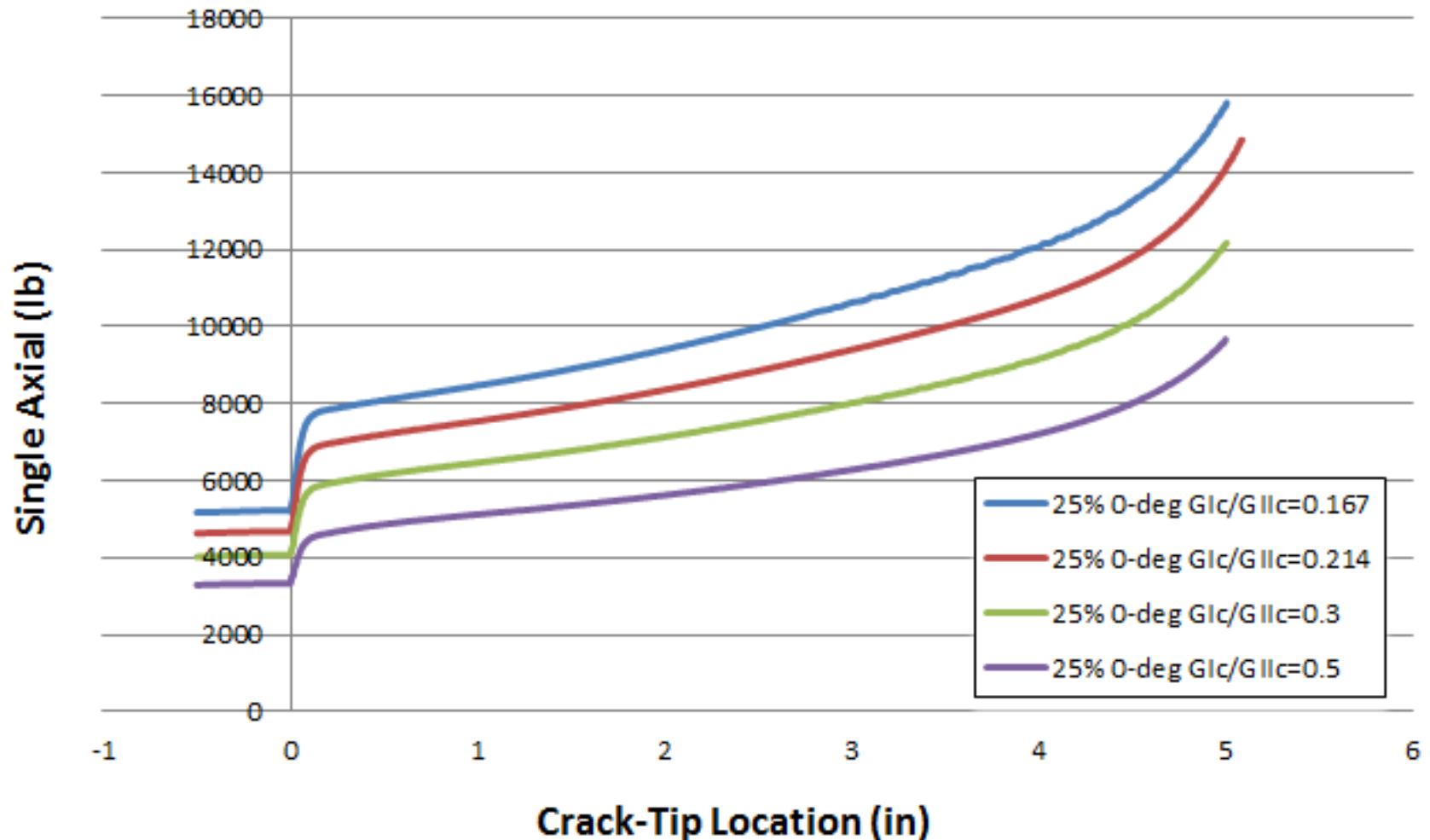
Simulation of Varying G_{IC}/G_{IIC} Ratios

- Step in load proportional to G_{IIC} step value
- Data has not yet been corrected for increasing G_{eqC}

G_{IC}	G_{IIC}	Ratio
1.5	3	0.5
1.5	5	0.3
1.5	7	0.214
1.5	9	0.167
1.5	12	0.125



Single Axial Load Vs. Crack Tip Location





Summary

- Technical approach to disbond/delamination arrest features in aircraft composite structures have been presented.
- Analytical and experimental results on delamination arrest by fastener has been presented.
- Future research on the delamination arrest by fasteners has been identified.



Thanks for Attending

Questions?

Suggestions?

Comments?

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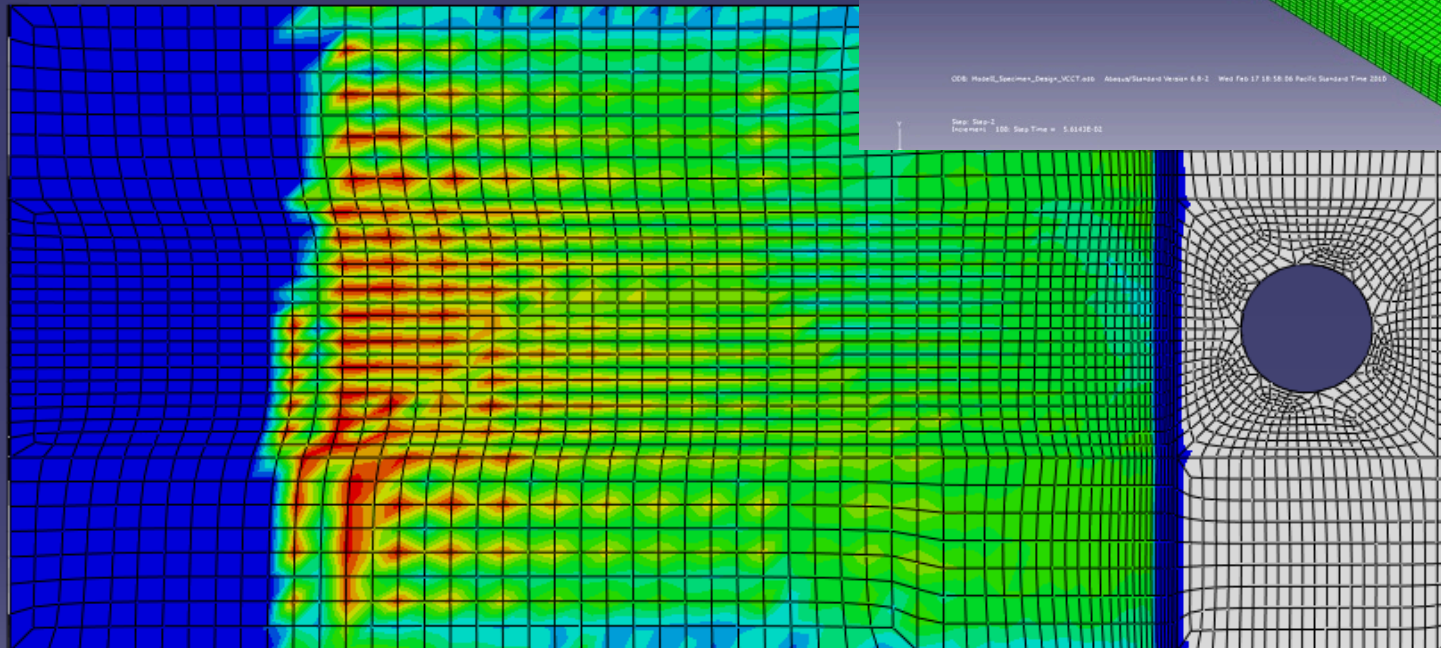
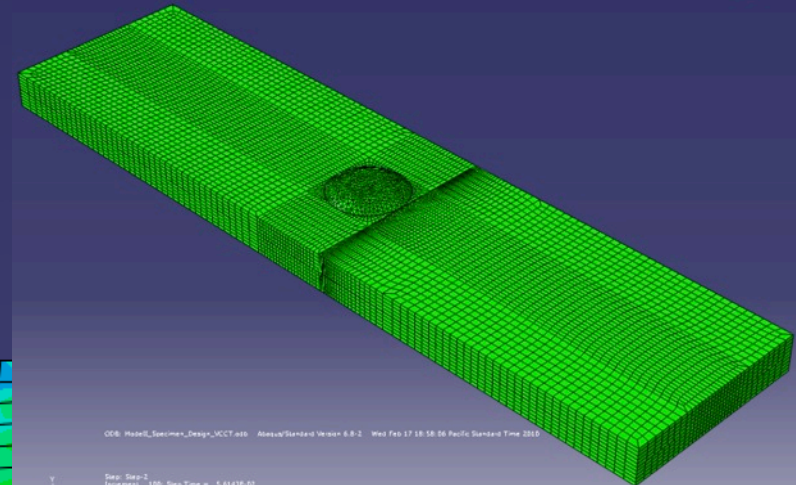
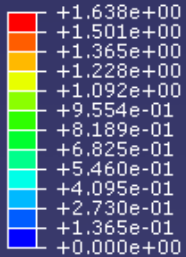
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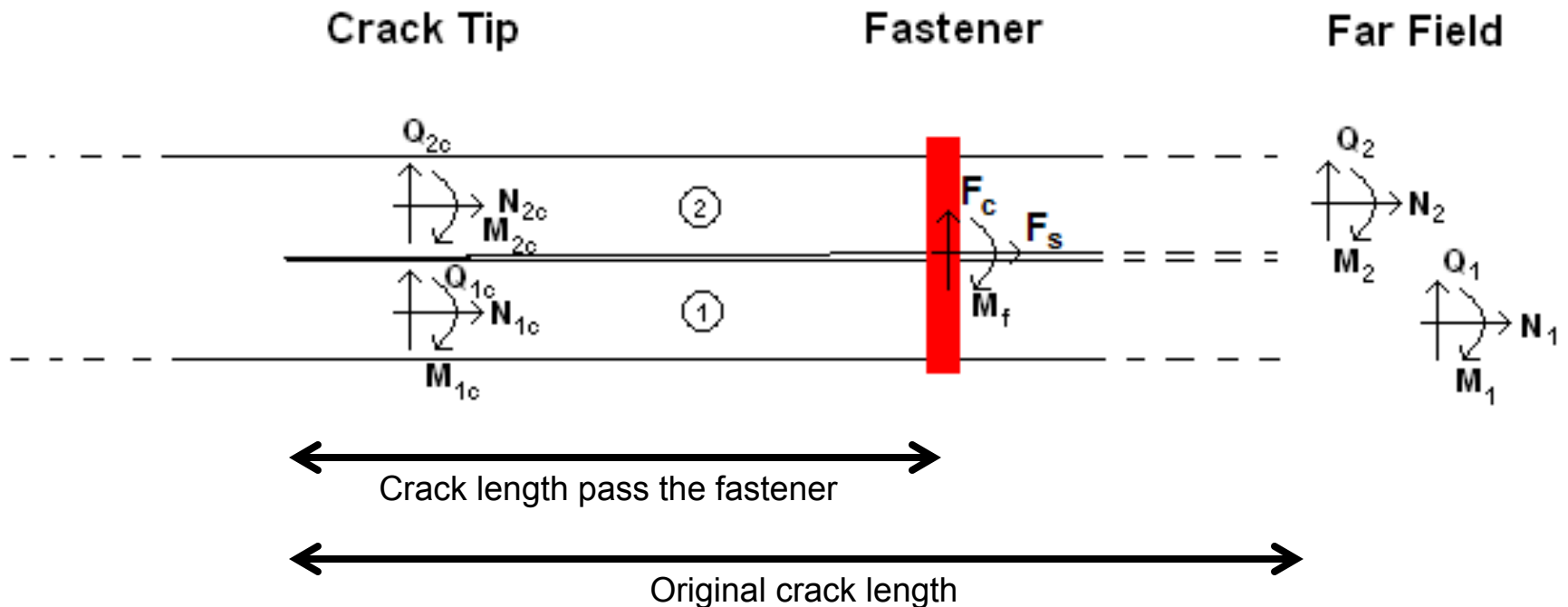
Mode II Test Specimen in 3-D

ENRRT11 ASSEMBLY_CENTERBEAM_BOND_FACE/ASSEMBLY_SIDEBEAM_BOTTOMFACE





Analytical Model



- 16-ply CFRP ($t = 0.0075'' \times 16 = 0.12''$)
- Lay-ups
 - Percentage of 0-deg: 25% / 37.5% / 50% / 62.5%
- Fastener
 - Ti-Al6-V4 ($E = 16.5 \times 10^6 \text{psi}$)
 - $d = 0.25 \text{ in}$
- Fastener Flexibility (H. Huth, 1986)

$$C = \left(\frac{t_1 + t_2}{2d} \right)^a \frac{b}{n} \left(\frac{1}{t_1 E_1} + \frac{1}{nt_2 E_2} + \frac{1}{nt_1 E_3} + \frac{1}{2nt_2 E_3} \right)$$

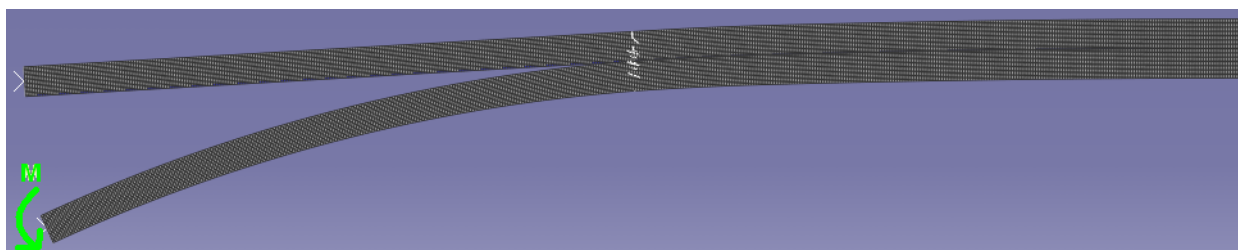
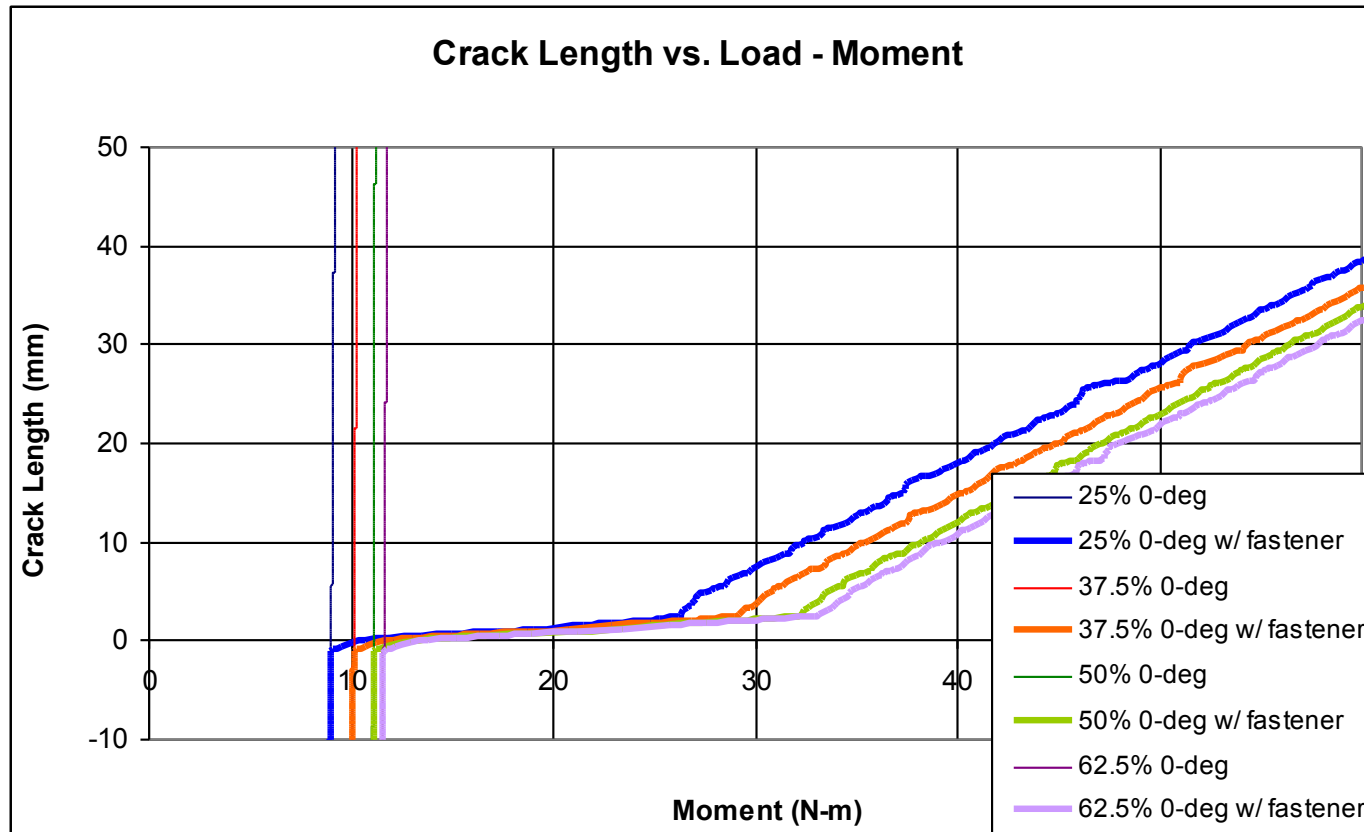


Discrepancies and Unknowns

- 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

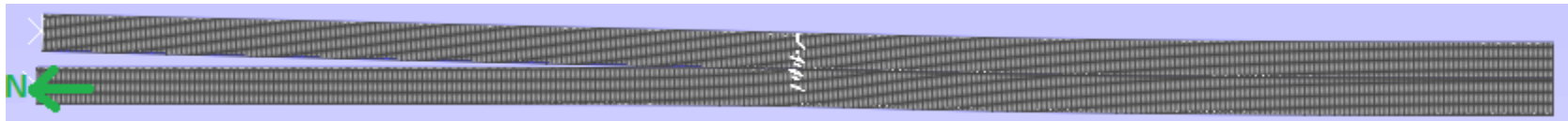
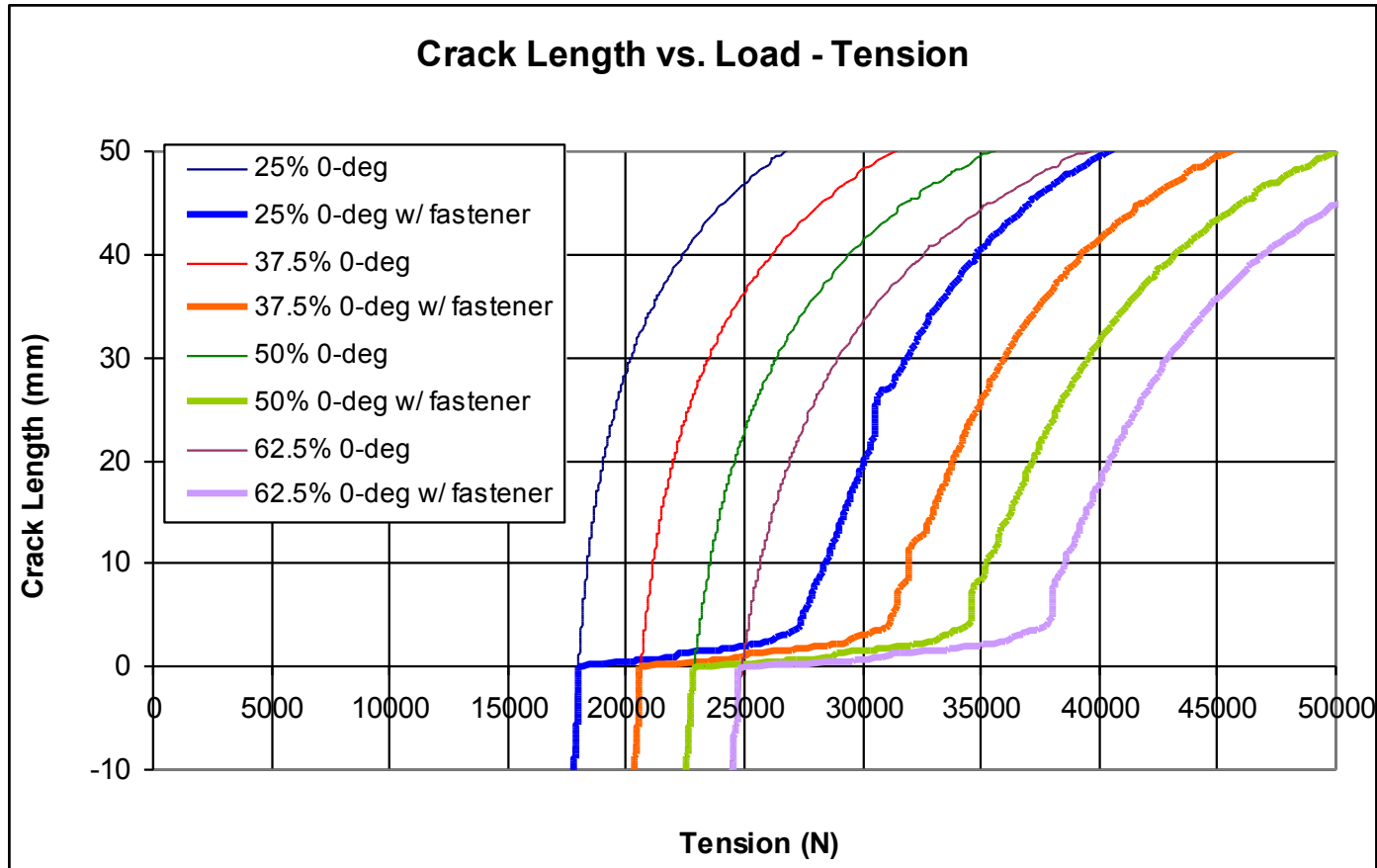


Results: Applied Moment Only



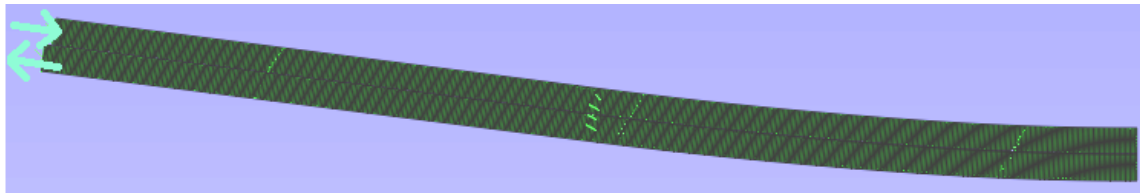
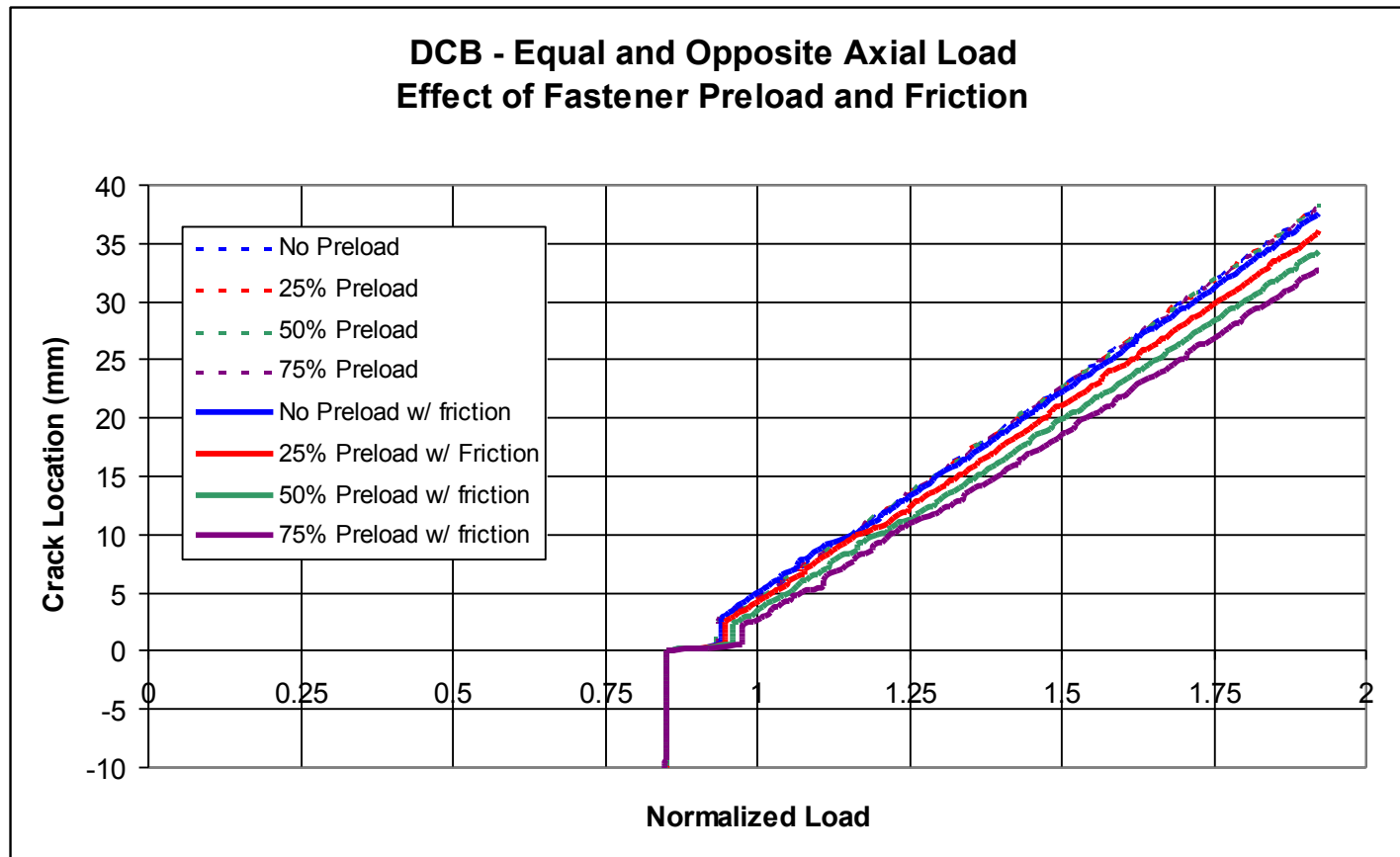


Results: Applied Tension Only





Friction and Fastener Preload





Mode II Test Specimen Preliminary Findings

