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Disbond/Delamination Arrest Features in Aircraft Composite Structures

2013 Technical Review

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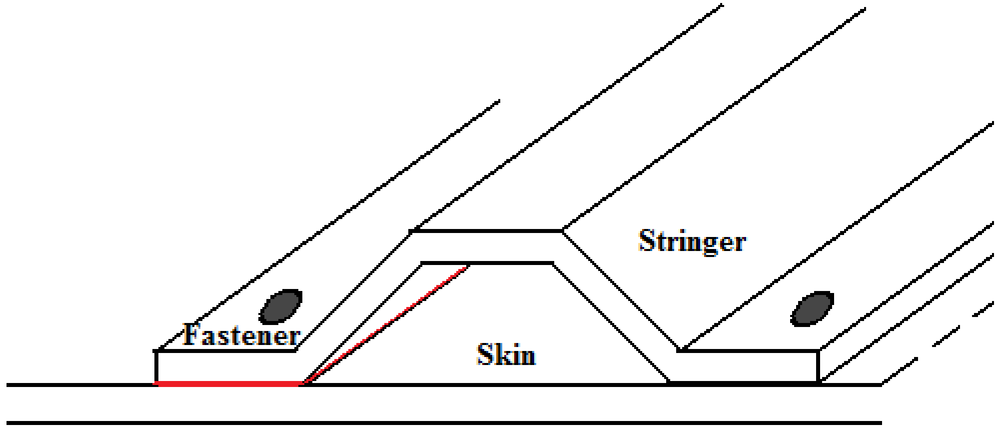
Project Information

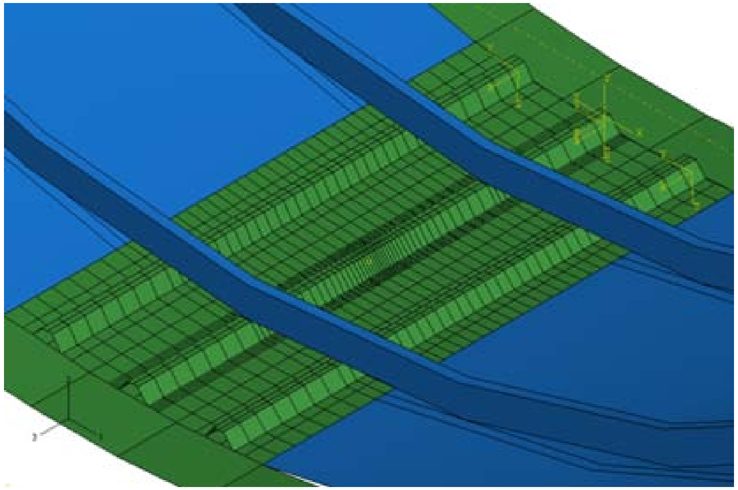
- Principal Investigator and Researchers (UW)
  - Prof. Kuen Y. Lin (PI)
  - Eric Cheung (Ph.D. student)
  - Wendy Liu (MS student)
  - Luke Richard (MS student)
- FAA Technical Monitor
  - Lynn Pham, Curtis Davies
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Boeing: Marc Piehl, Gerald Mabson, Eric Cregger, Matthew Dilligan (All from BR&T)
  - Toray: Kenichi Yoshioka, Don Lee, Felix Nguyen

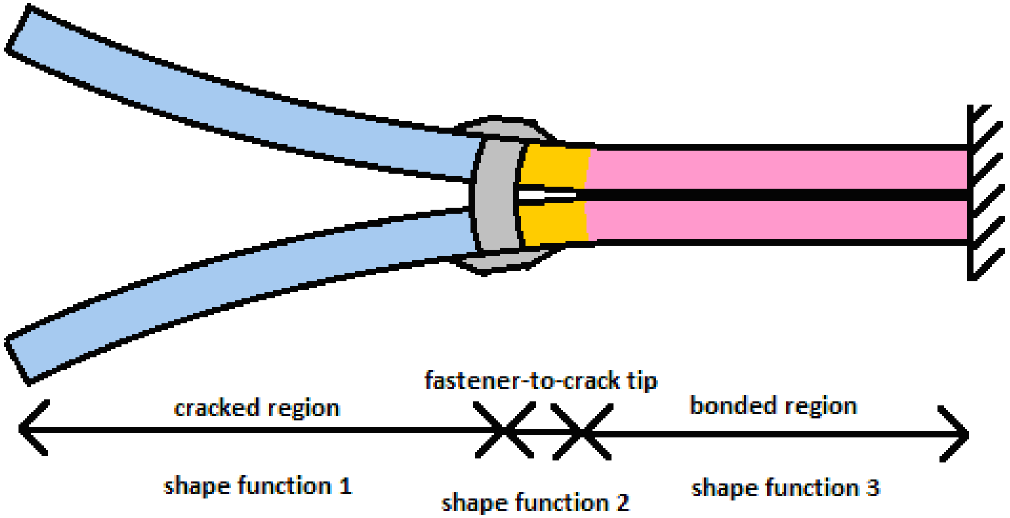
Background

- Motivation and Key Issues
  - Delamination is one of the key issues for laminated and "bonded" composite structures
- Objectives
  - To understand the effectiveness of delamination/disbond arrest features
  - To develop analysis tools for design and optimization
- Approach
  - Construct FEM models in ABAQUS with VCCT
  - Perform sensitivity studies on fastener effectiveness
  - Conduct coupon-level experiments using novel specimens
  - Develop analytical tools validated by FEM and test

Crack Arrest Mechanism by Fastener

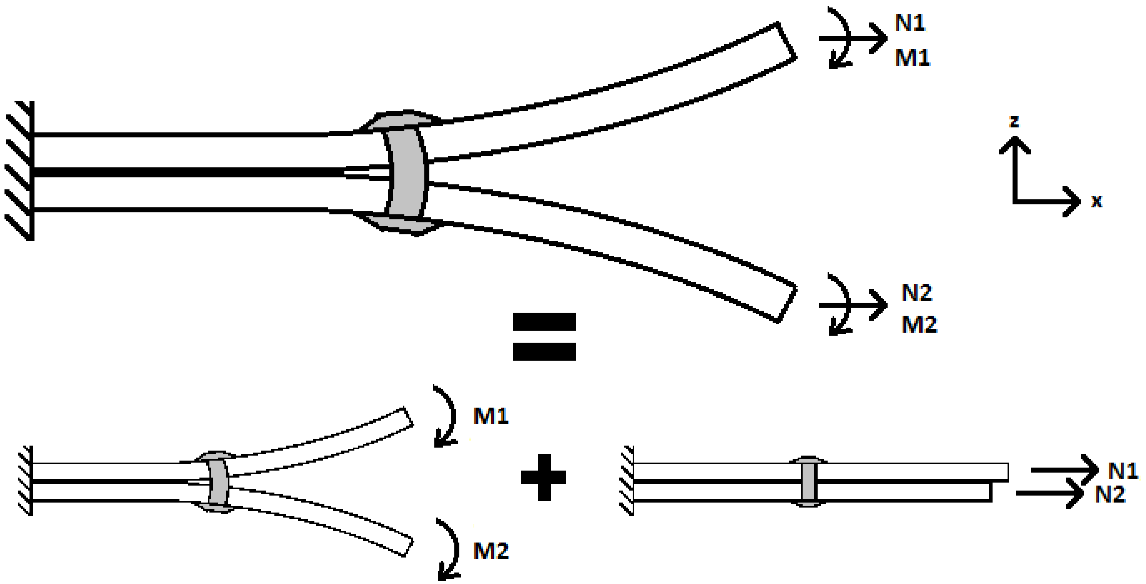






Analytical Model Development

- 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 ERR is obtained using VCCT
- Friction and joint/hole clearance is also modeled



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

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

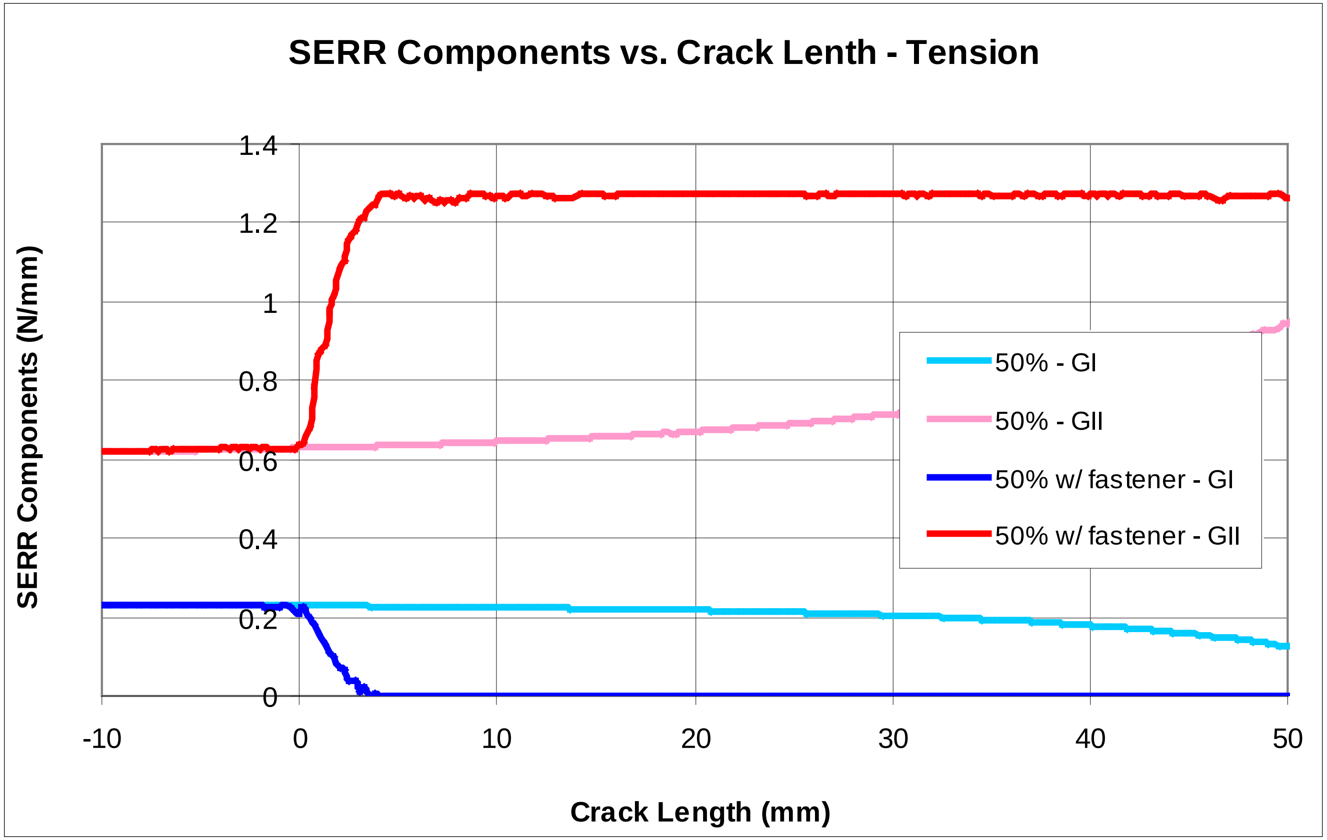
- Truss energy

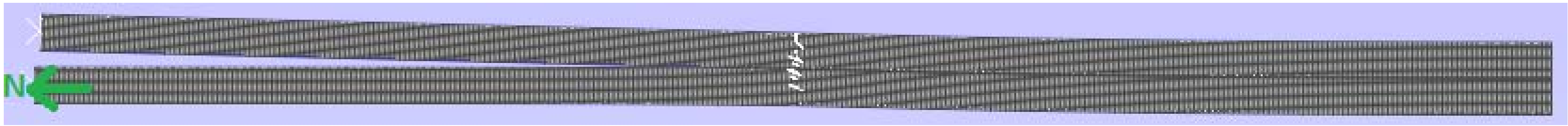
$$U_{truss,i} = \frac{1}{2} AE \int_{L_1}^{L_2} \left(\frac{du_i}{dx} \right)^2 dx$$

Fastener/Contact/Bond Springs

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

Mode Decomposition with Single Fastener: Applied Tension Only



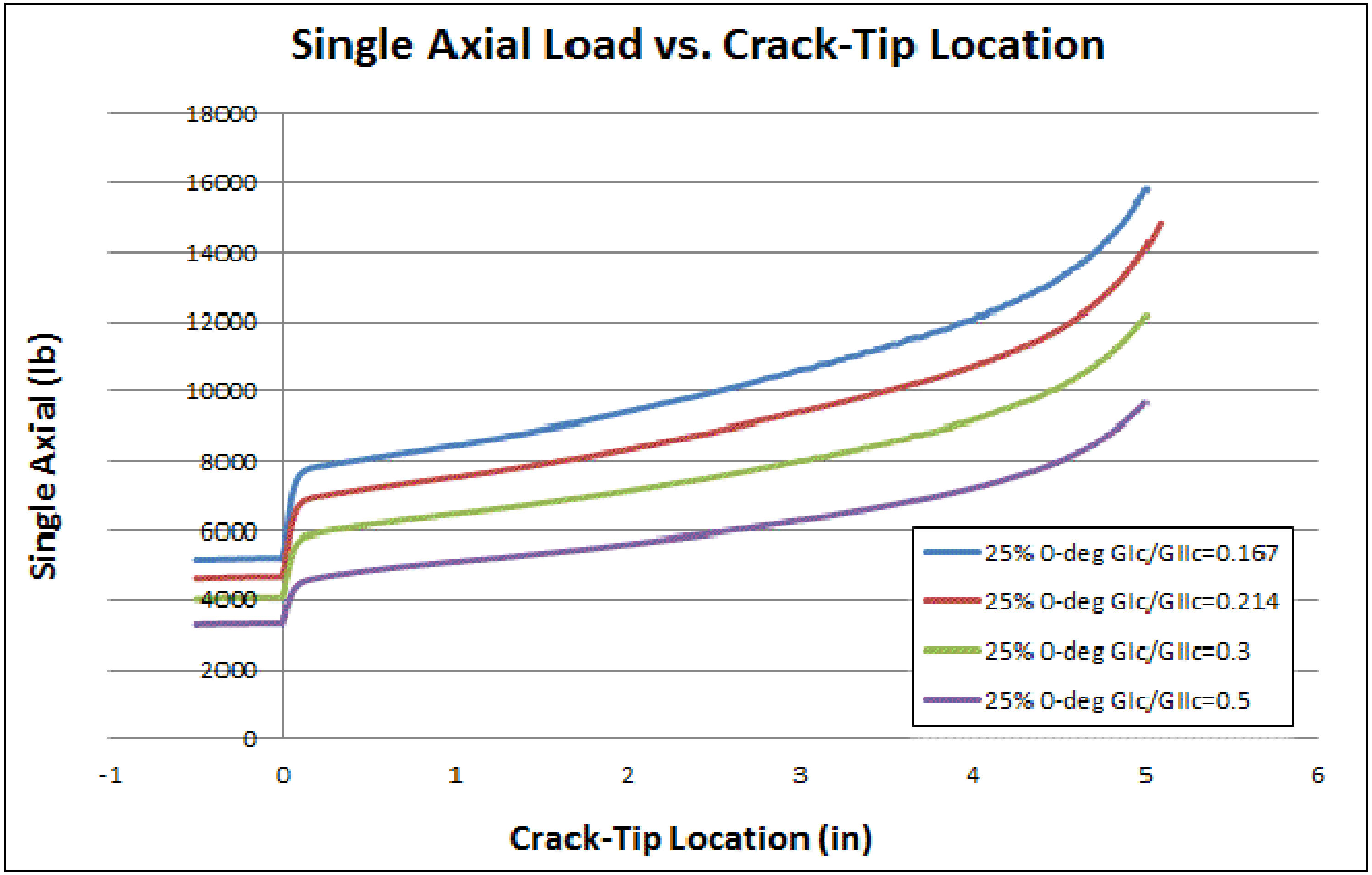


Effects of G_{IC}/G_{IIC} on Crack Propagation

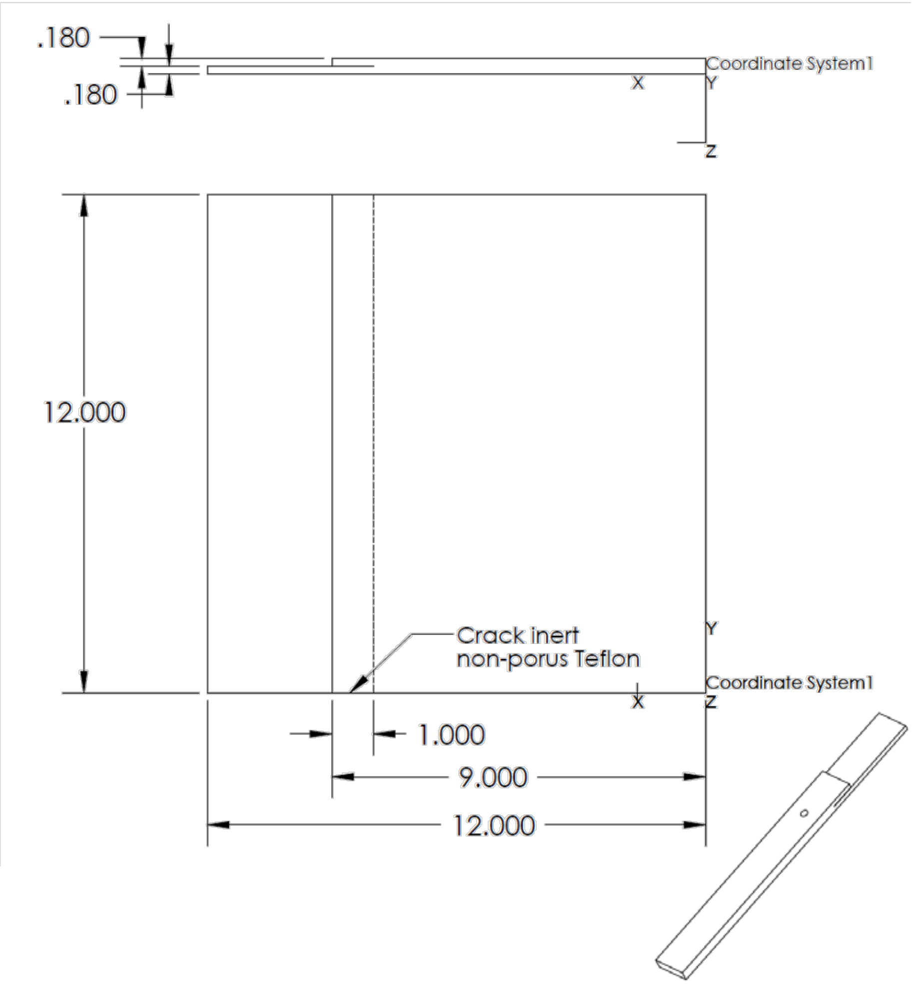
- Assume G_{IC}=constant, but varying G_{IIC}

G_{IC} (lb/in)	G_{IIC} (lb/in)	Ratio
1.5	3	0.500
1.5	5	0.300
1.5	7	0.214
1.5	9	0.167
1.5	12	0.125

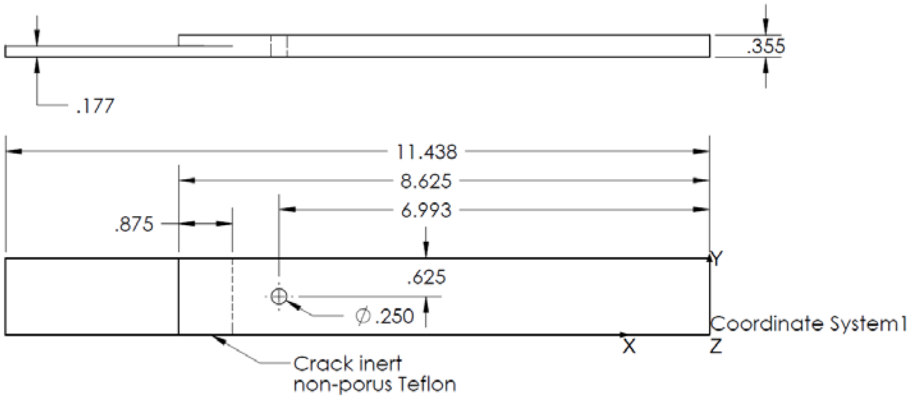
Effects of G_{IC}/G_{IIC} Ratios (Single Fastener)



2-Plate Single Fastener Specimen



- 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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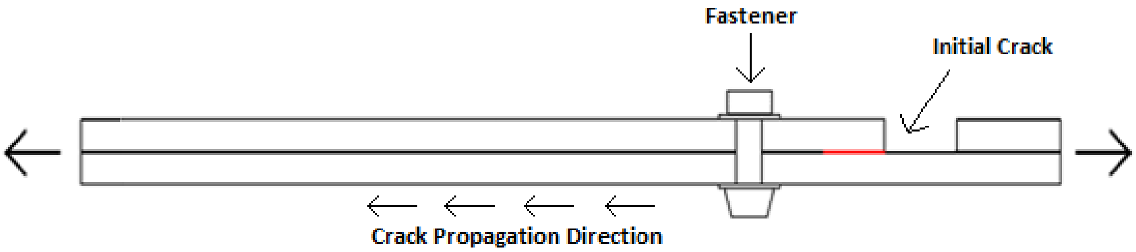
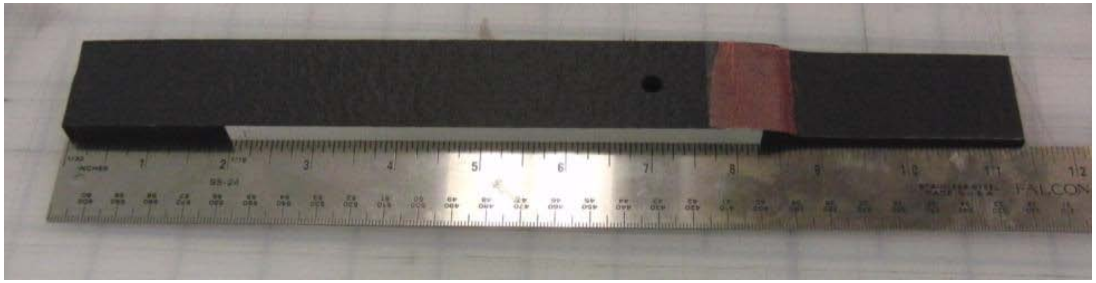
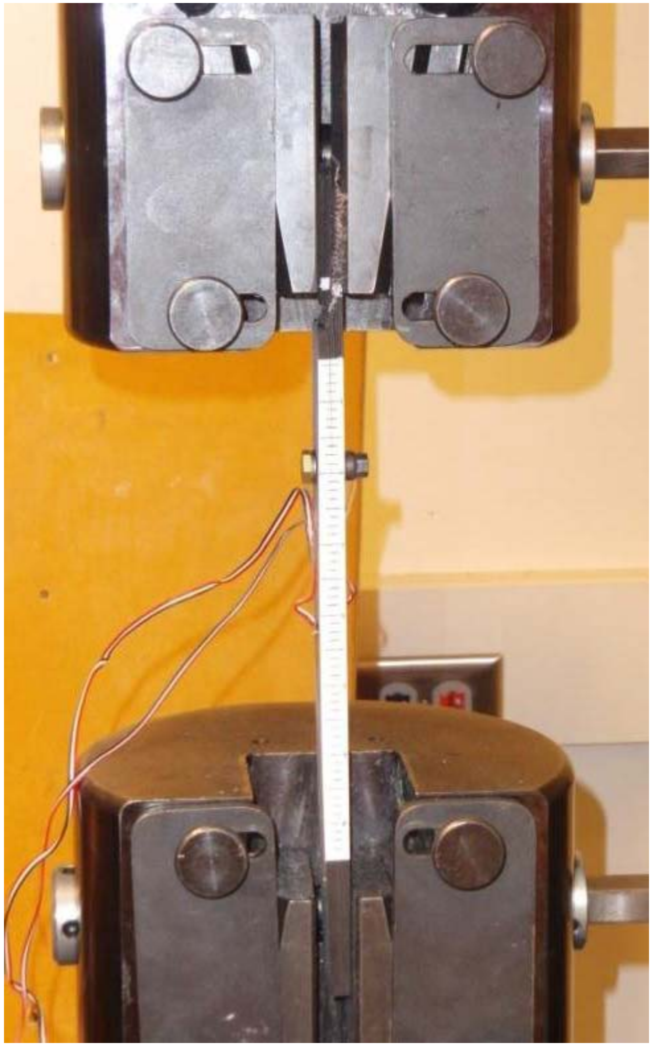
2-Plate Single Fastener Specimen



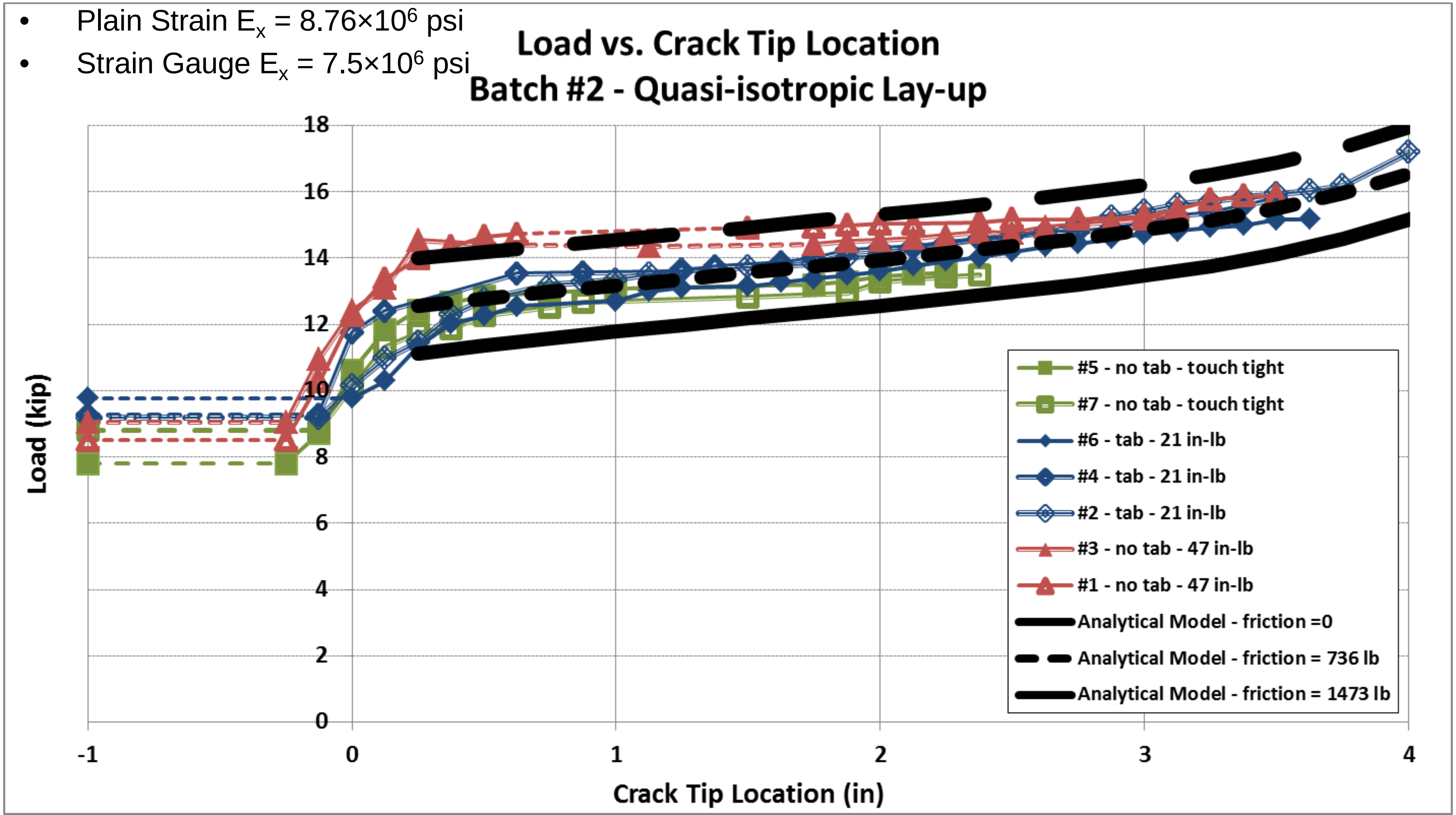




2-Plate Single Fastener Specimen:

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

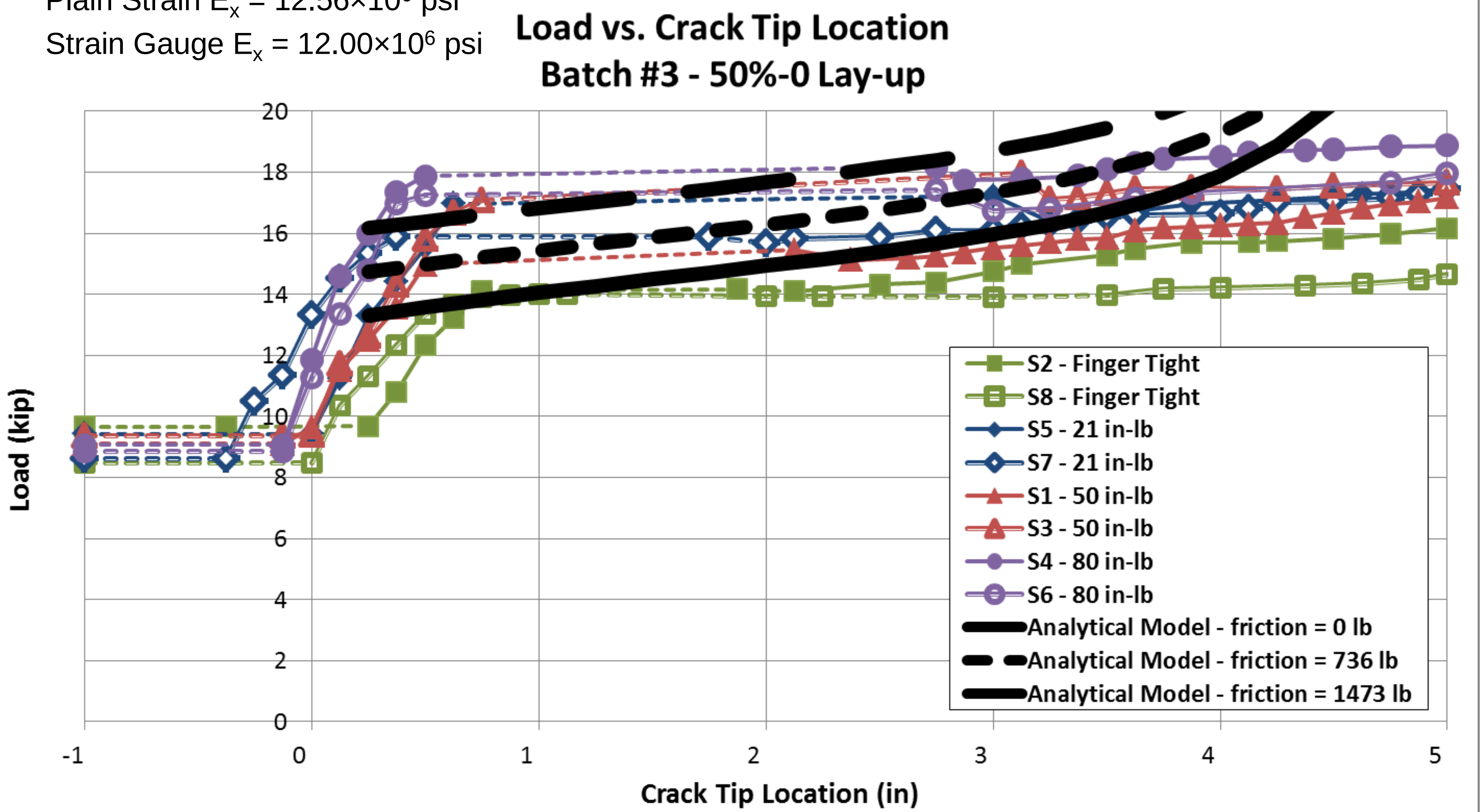
- CLT $E_x = 7.99 \times 10^6$ psi
- Plain Strain $E_x = 8.76 \times 10^6$ psi
- Strain Gauge $E_x = 7.5 \times 10^6$ psi



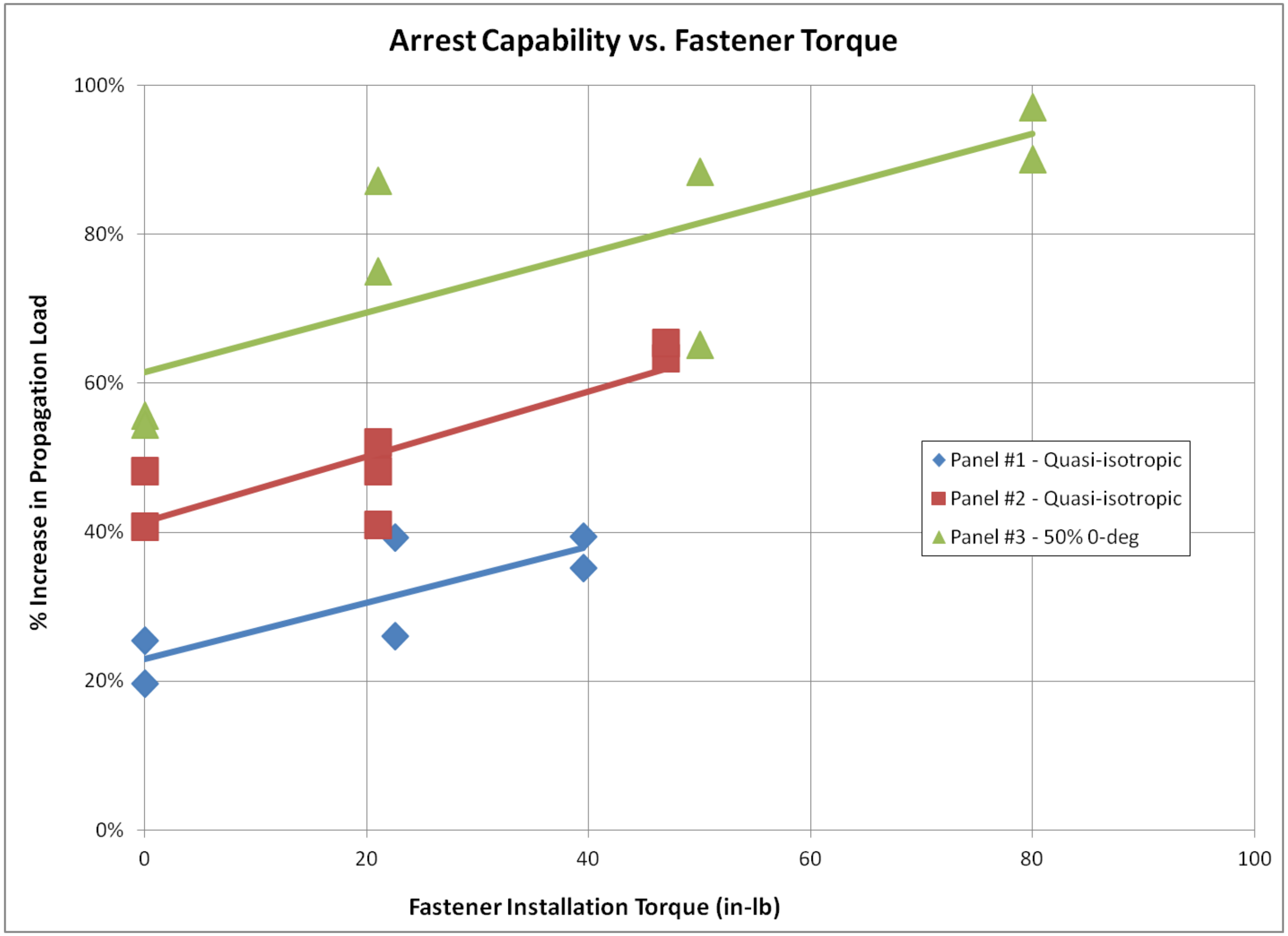
2-Plate Single Fastener Specimen:

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

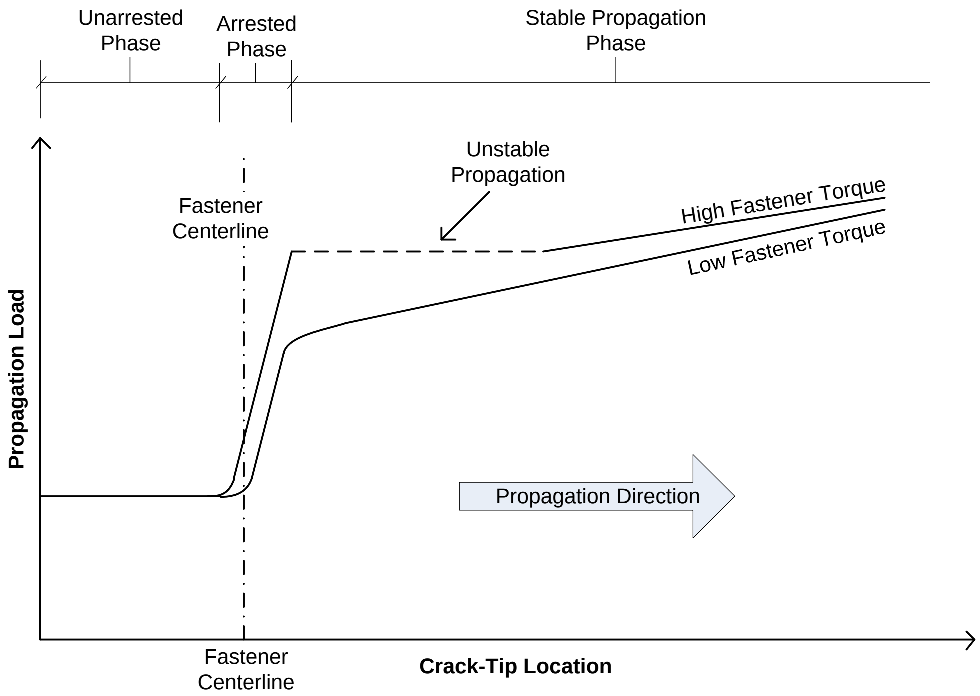
- CLT $E_x = 12.00\times10^6$ psi
- Plain Strain $E_x = 12.56\times10^6$ psi
- Strain Gauge $E_x = 12.00\times10^6$ psi

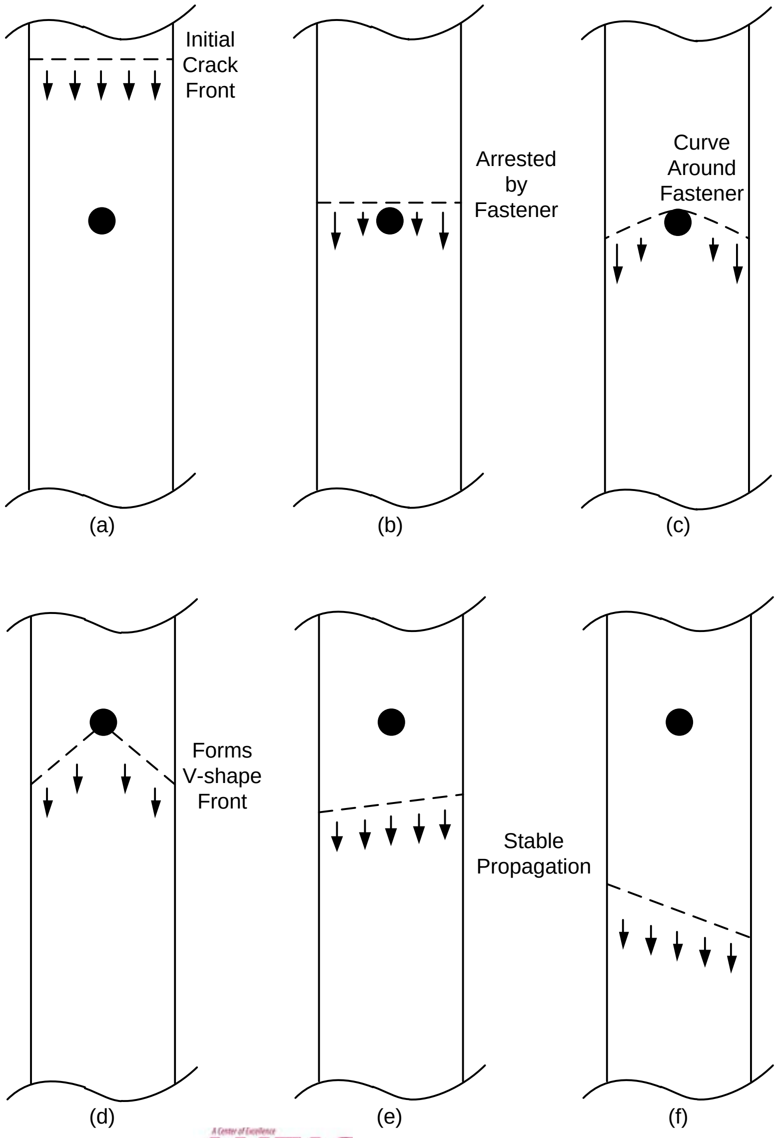


Arrest Capability vs. Fastener Torque



Arrest Mechanisms



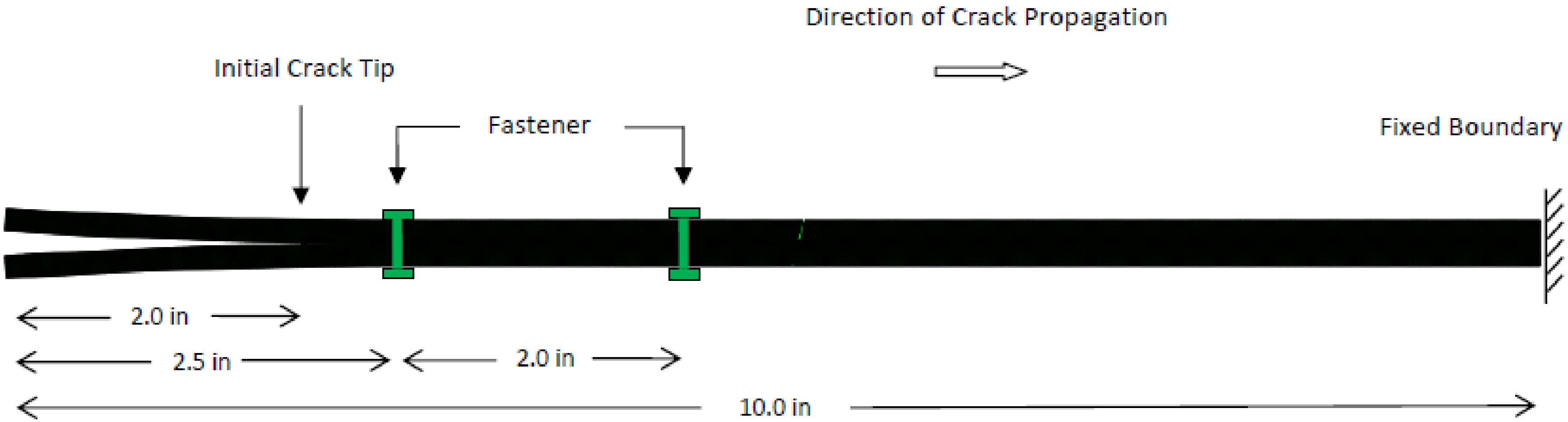


Summary of Single Fastener Results

- **Delamination Arrest Mechanism**
  - Mode I suppression
  - Crack-face friction caused by fastener preload
  - Fastener flexibility
- **Limitations**
  - Fasteners do not guarantee arrest in mode II → current research
  - Fastener preload vs. installation torque is hard to control and measure
  - Crack-face friction is poorly understood and rarely studied, even more difficult to model
  - Delamination could steer around the fastener grip

2-Plate Two-Fastener Specimen

- $((0/45/90/-45)_6\ /Crack)_S$
- Specimen width 1.25”
- T-800S (350°F cure for 2.5hrs)
- 0.25” diameter Ti fasteners, 8D spacing
- Fasteners installed at 40 in-lb (half-torque)
- Holes drilled with aluminum backing
- Load rate 0.1mm/min during crack propagation



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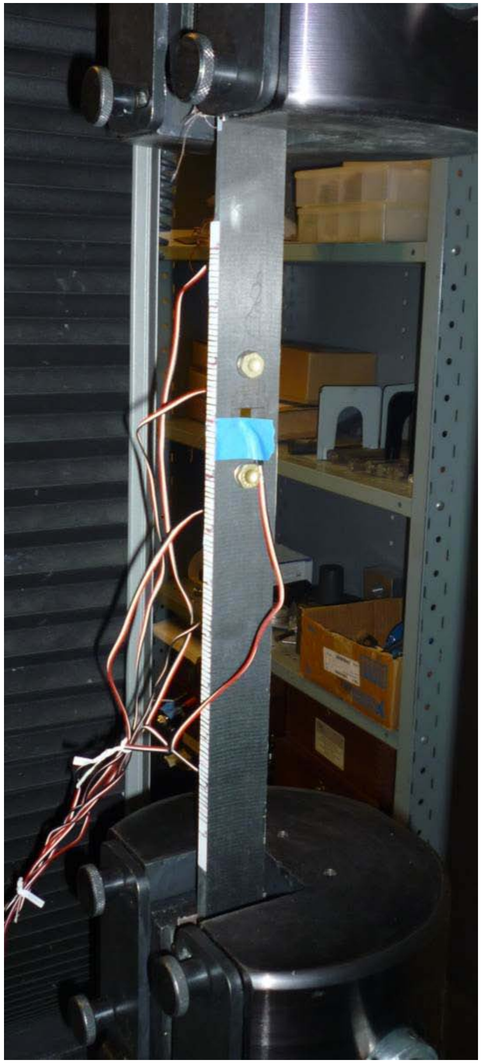
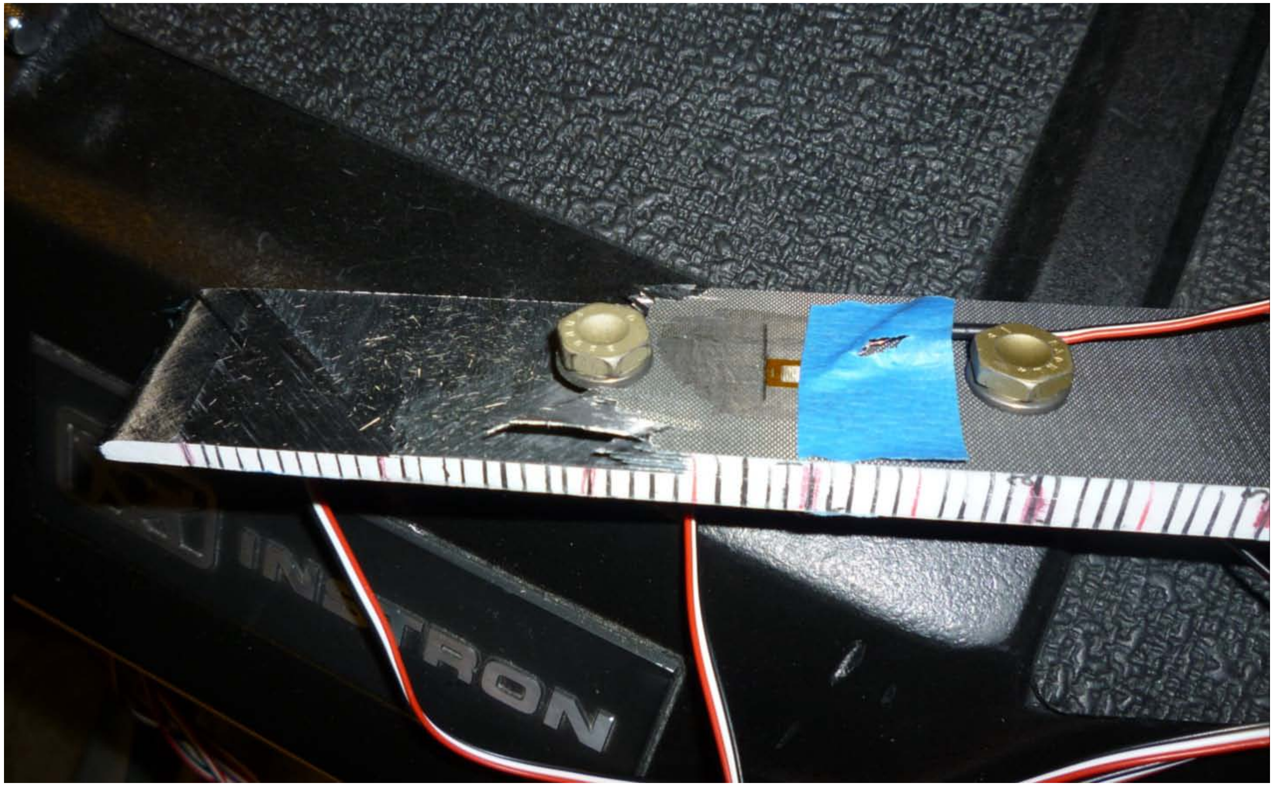
2-Plate Two-Fastener Specimen





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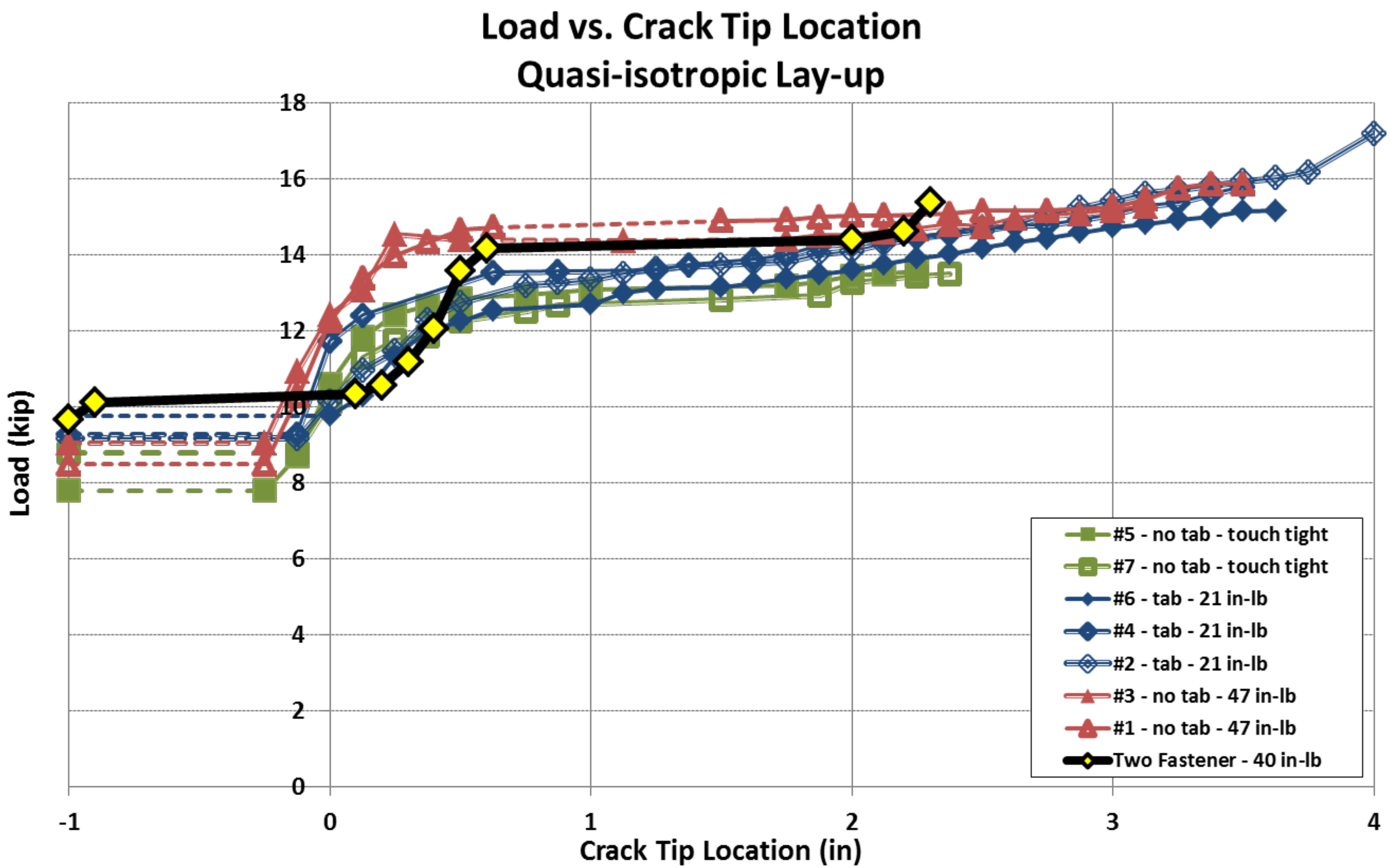
Preliminary Test Results



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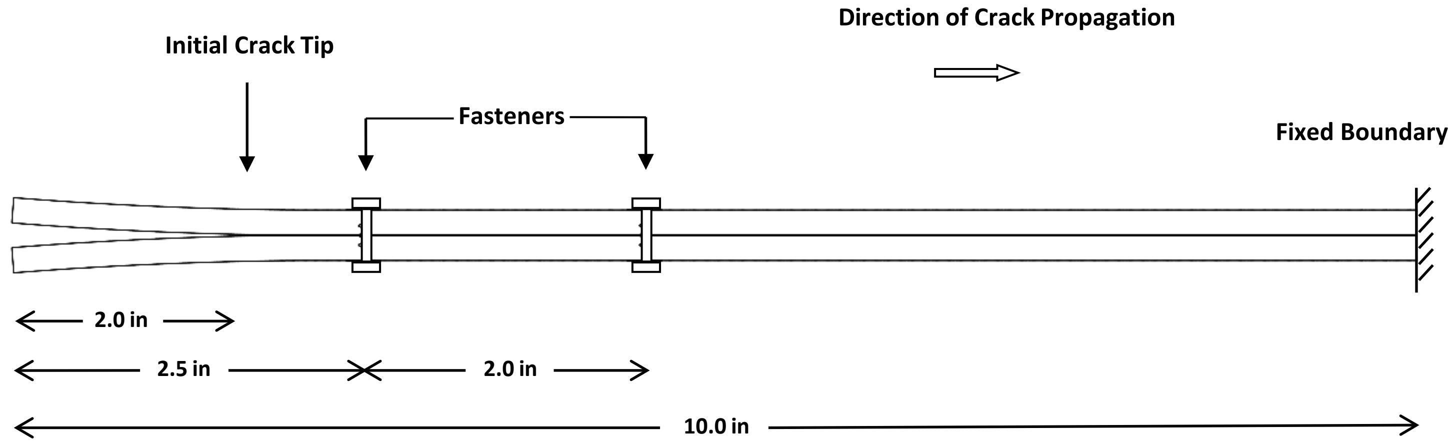
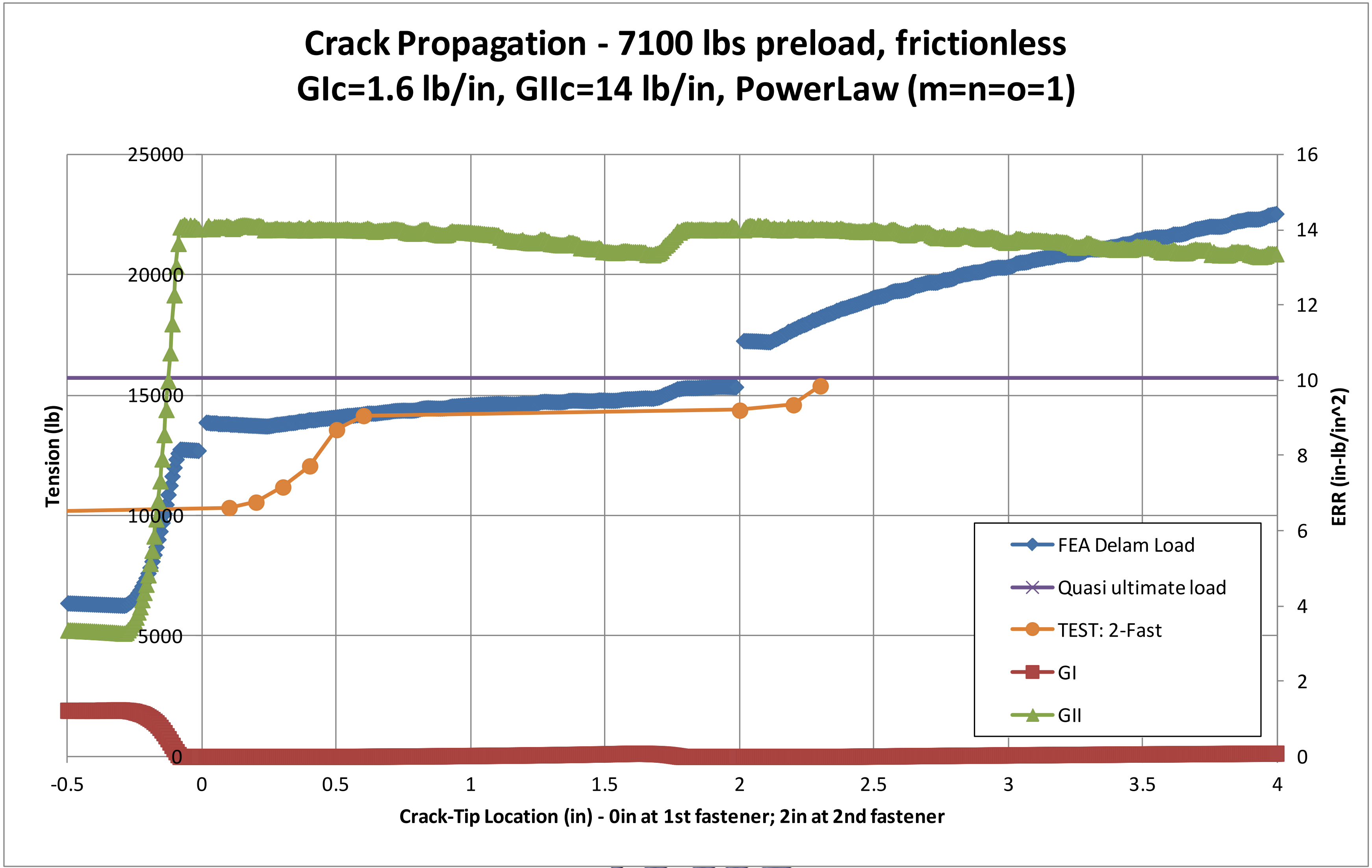
2-Plate Two-Fastener FEA Model



- $((45°/0°/-45°/90°)_3)_S$, ABAQUS CPE4R Element
- Ti-Al6-V4 Fastener, d = 0.25 in; T800/3900, G_{IC}=1.6 lb/in, G_{IIC}=14 lb/in
- Use fastener flexibility (H. Huth, 1986) and fastener tensile stiffness
- B-K law for mixed-mode VCCT criteria

2-Plate Two-Fastener FEA vs. Test Results



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Future Tasks

- Finite Element Analysis
  - Design viable 2-fastener specimens
  - Validate model with test results
  - Perform parametric studies on select factors
- Experiment
  - Design viable 2-fastener specimens
  - Manufacture and conduct tests
  - Focus on key factors such as fastener parameters, friction, etc.

Looking Forward

- Benefit to Aviation
  - Tackle one of the main weakness of laminate composite structures
  - Reduce risks (analysis, schedule/cost, re-design, etc.) associated with 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
  - Initiate research areas core to the interlaminar mode of failure, e.g. friction, fastener clamp-up
  - Industry/regulatory agency inputs related to the application, design, and certification of this type of crack arrest features

End of Presentation

Thank you!

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