Delamination/Disbond Arrest Features in Aircraft Composite Structures

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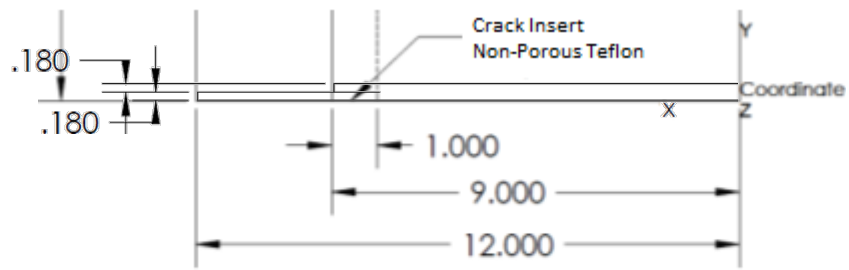
Research Objectives

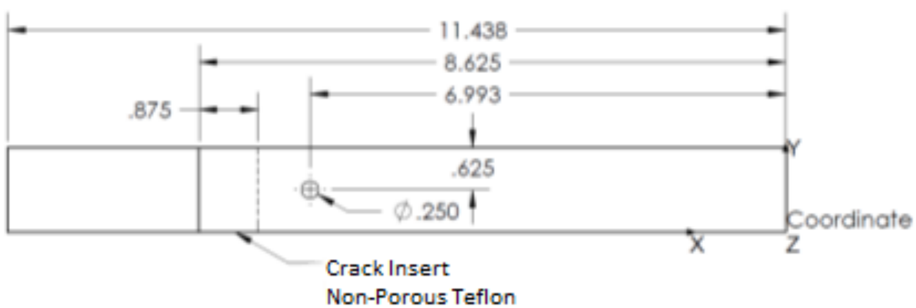
- Develop understanding of crack propagation and arrest by multiple fasteners
- To quantify and characterize coefficient of friction and its variance in delaminated surfaces
- Develop knowledge to apply findings to improve crack arrest predictions for various laminate and fastener configurations

Background

- Motivation and Key Issues
  - Delamination mode of damage is one of the key issues for laminated and bonded composite structures
  - Isolated fastener is unable to fully arrest delamination
- Objective
  - To understand the effectiveness of delamination/disbond arrest features
  - To develop analysis tools for design and optimization
- Approach
  - Perform FEM analyses in ABAQUS with VCCT
  - Conduct sensitivity studies on fastener effectiveness
  - Conduct coupon-level experiments using novel specimens

2-Plate Specimen Description



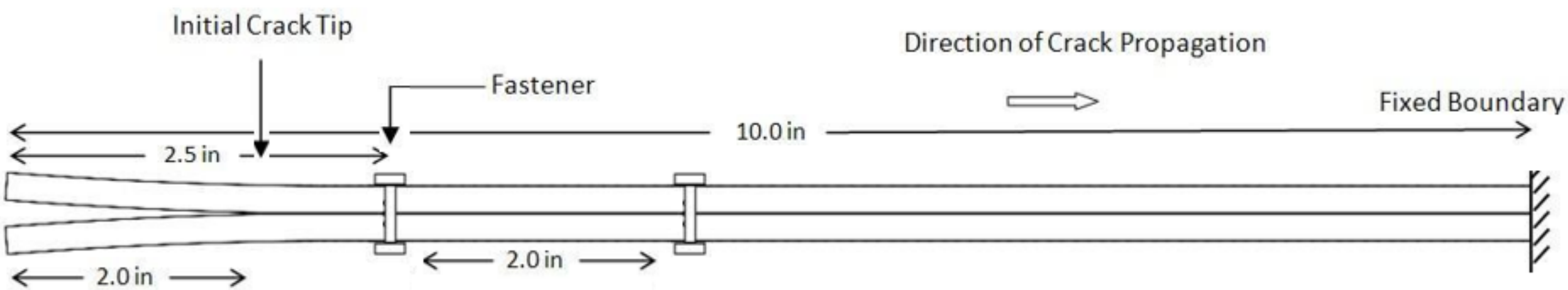


- T800S/3900-2B (BMS 8-276) unidirectional pre-preg tape
- BMS 8-308 peel ply
- 0.25 Inch titanium fasteners
- $(0/45/90/-45)_{3S}$
- $(0/-45/0_2/90/45/0_2/-45/90/45/0)_S$
- Load rate 0.1 mm/in
- Crack tip tracked visually

2-Plate Two-Fastener Finite Element Model

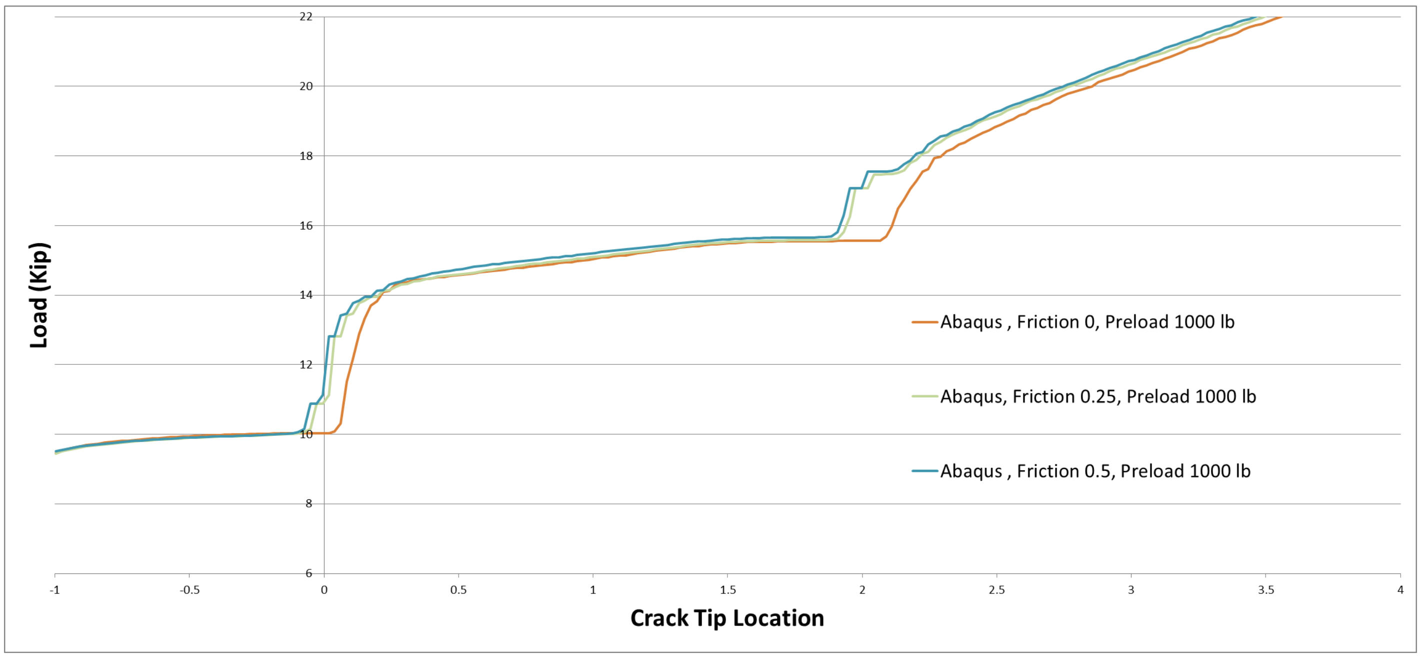
- Fastener flexibility (H. Huth, 1986) $C = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{2 t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$
  - Thickness $t_1 = t_2 = 0.18$ in., diameter d=0.25 in., E_x= laminate stiffness
  - Single Lap, bolted graphite/epoxy joint, constants taken as; a=2/3, b=4.2, n=1
- Fastener joint stiffness $k_{slide} = \frac{1}{C}$, Fastener tensile stiffness $k_{clamp} = \frac{AE}{(t_1 + t_2)}$
- Fracture parameters, G_{IC}=1.6 lb/in, G_{IIC}=G_{IIC}=14 lb/in.
- Power Law fracture criterion $\left(\frac{G_I}{G_{IC}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIC}}\right)^\beta + \left(\frac{G_{III}}{G_{IIIC}}\right)^\delta \leq 1$

  $\alpha = \beta = \delta = 1$, linear mode mixture assumed
- Fixed boundary condition similar to test; grips not modeled

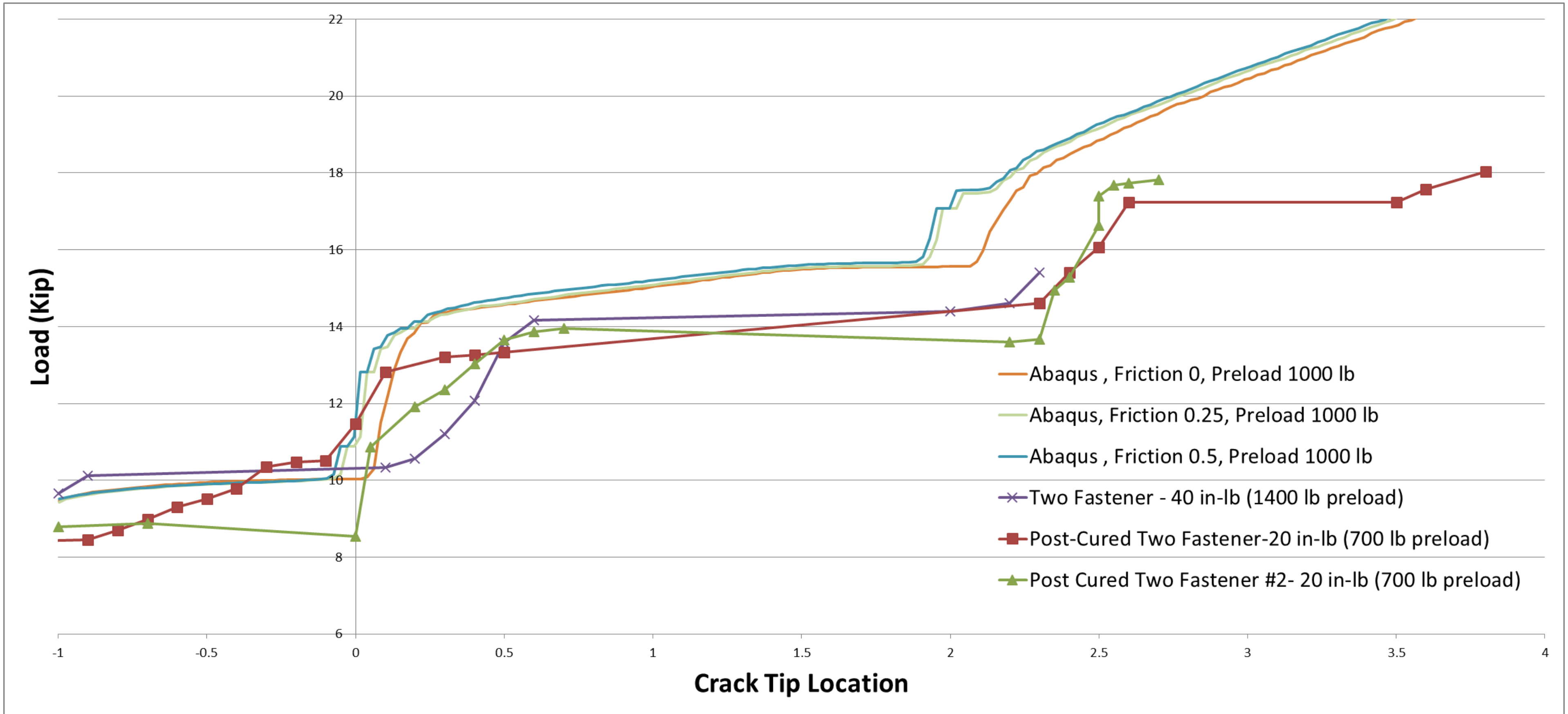


Arrest Effectiveness vs. Friction Modeling

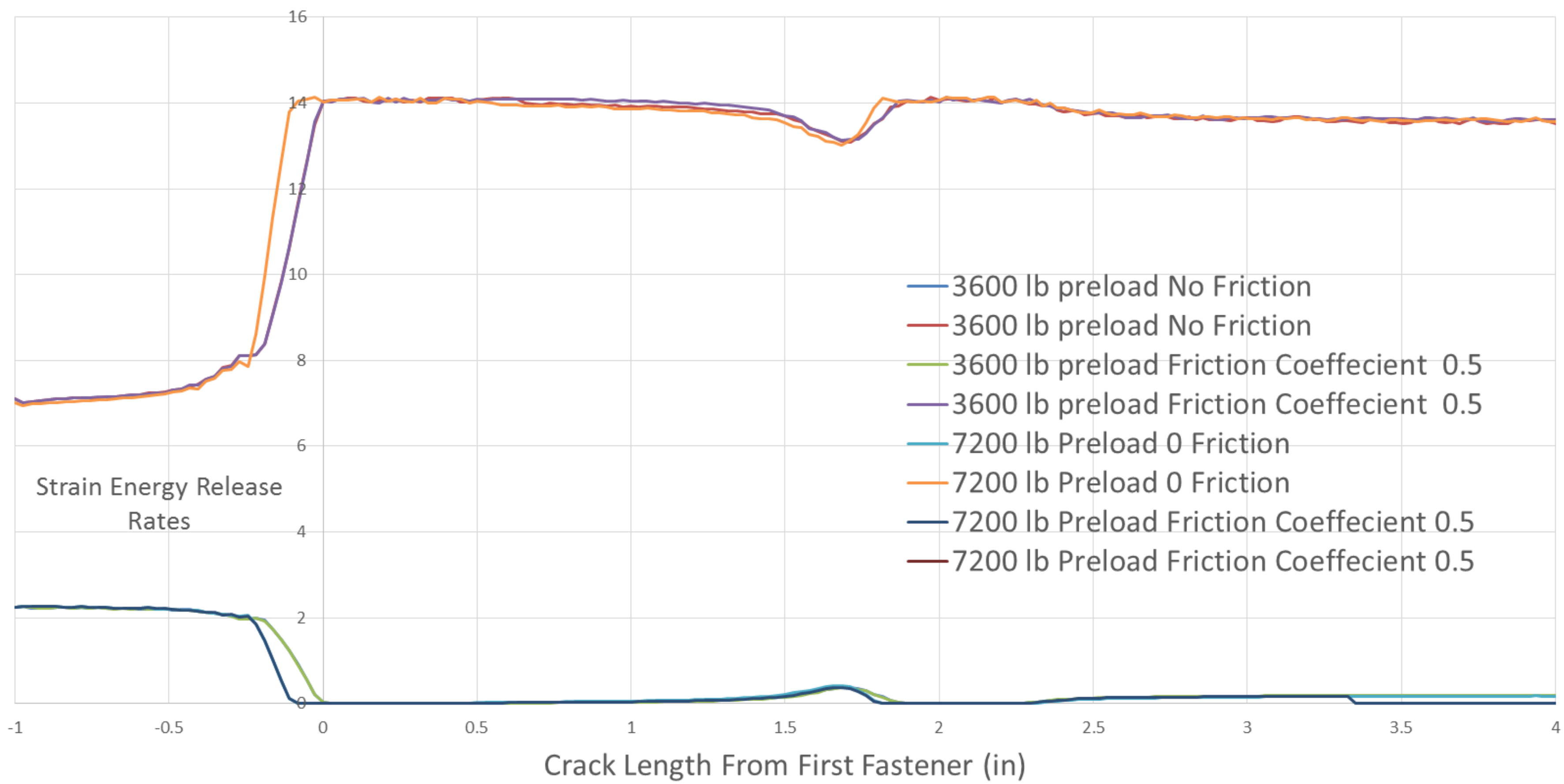
- Inclusion of friction increases arrest capability by 10% for constant coefficient of 0.5, preload of 1000 lbs (40 in-lb installation torque)
- Reduction of friction to 0.25 reduces arrest capability by 3%, 300 lbs of load for a 1.25 inch specimen
- Increase in friction coefficient provides diminishing returns



Experimental vs. Analytical Results



Two-Fastener Analysis of SERR vs. Crack Tip Location



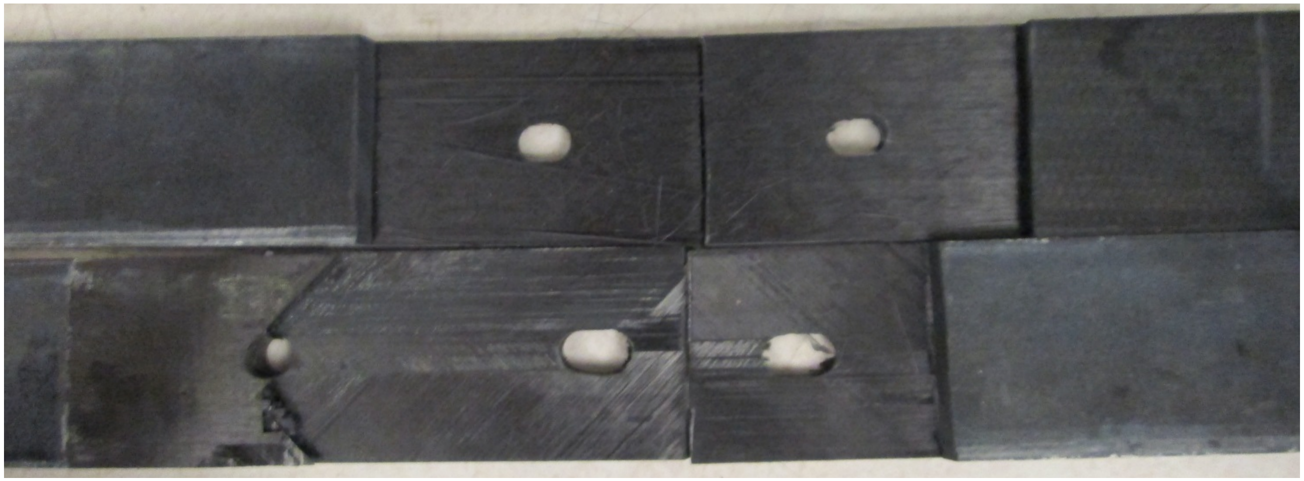
Results

- Delamination Arrest Mechanism
  - Mode I suppression
    - Propagation load increases as $G_{IIC} > G_{IC}$
  - Fastener flexibility is a major driver of arrest
  - Crack-face friction slows propagation
    - Crack Arrest fastener becomes effective before crack passes bolt
- Limitations
  - Crack-face friction is poorly understood and rarely studied, difficult to model
  - Delamination could steer around the fastener's grip
  - Crack front advances faster at sample edges
    - Results in offset of experimental vs. FEM results

Current Tasks

- Further Develop Analysis for Multiple Fasteners
  - Expand modeling capability
    - Accurately model propagation of varied configurations
  - Understand possible sources of modeling error
    - Model sensitive to shear spring placement
- Experimental Studies of Fracture Surface Friction
  - Manufacture specimens and conduct tests to understand limits
    - Determine minimum coefficient
  - Understand coefficient variance under different testing conditions
    - ASTM standards vs. fastened structures in service

Friction Testing Using Delaminated Specimens



- Previously delaminated 2 fastener test article utilized
- New samples created for friction testing
- Samples delaminated in Mode I (DCB) and Mode II (ENF)
- Two distinct crack face surfaces based on delamination mode were tested

Interfaces Tested

- Interfaces chosen to represent likely and bounding cases
- Ply orientation influences roughness of delamination interface

0 Degrees

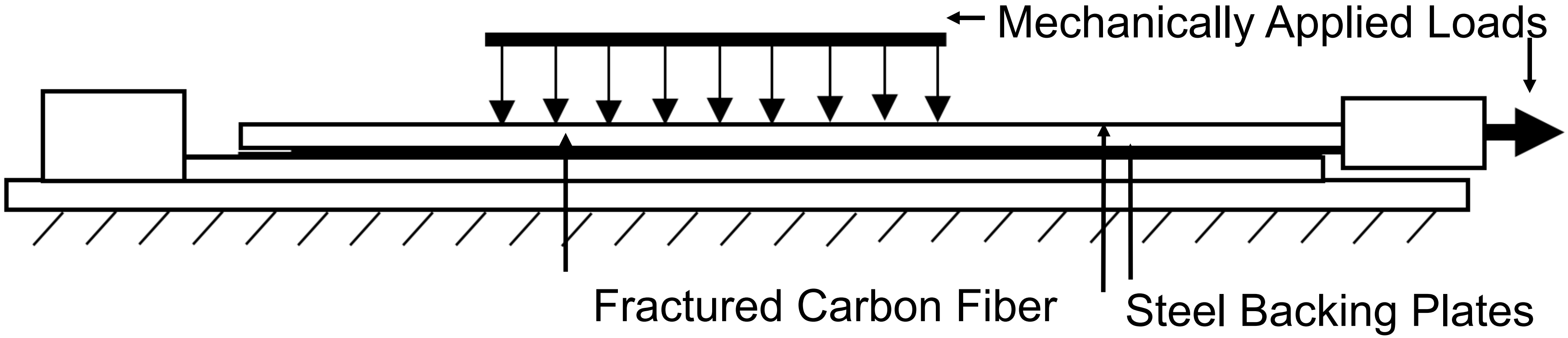
90 Degrees

45 Degrees

-45 Degrees

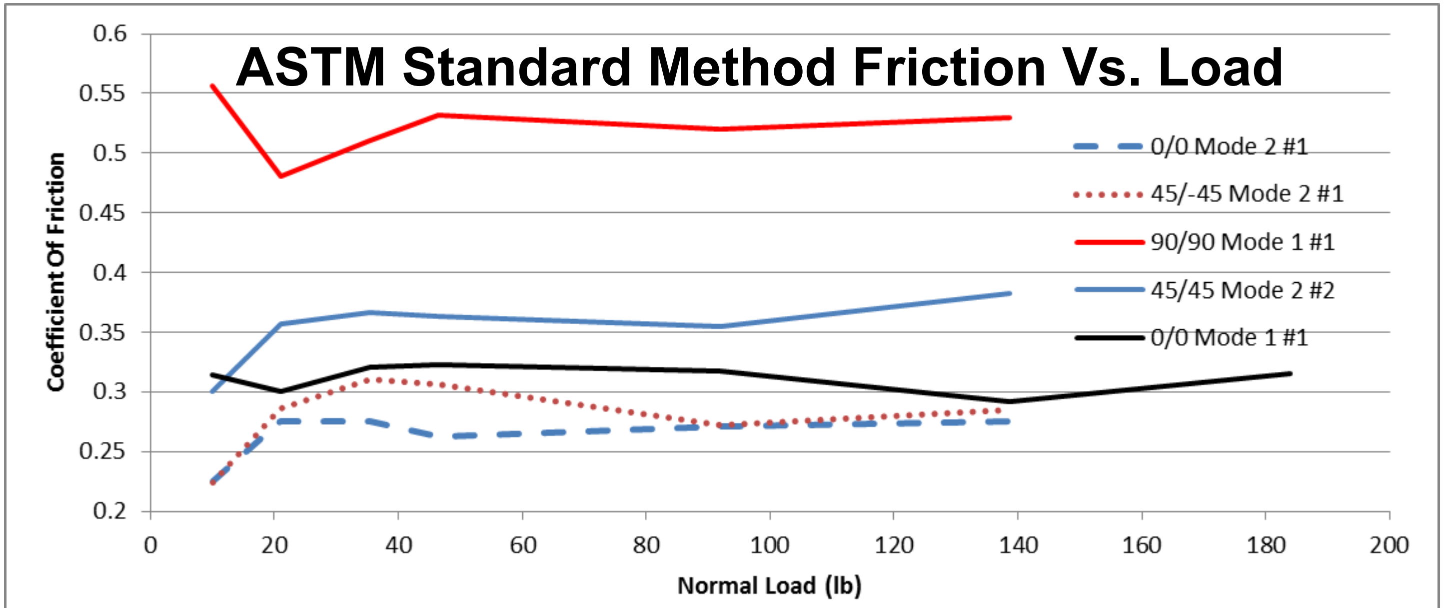
Testing Methods

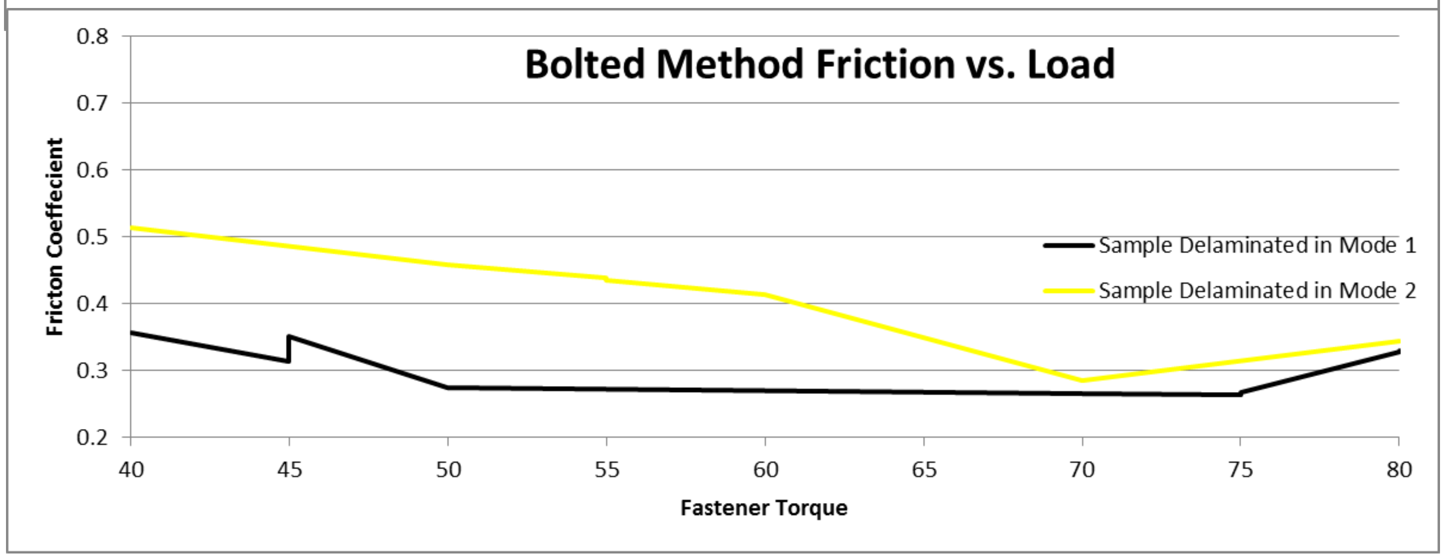
- **ASTM Standard**
  - Load is approximately evenly distributed over larger area of sample
  - Higher normal force requires mechanically applied load
  - Friction force between loading system and sample subtracted out
    - Rollers being implemented to minimize effect



- **Bolting Method**
  - Load is distributed over small area under bolt head
  - Better approximates loading method of fastened structures

Results

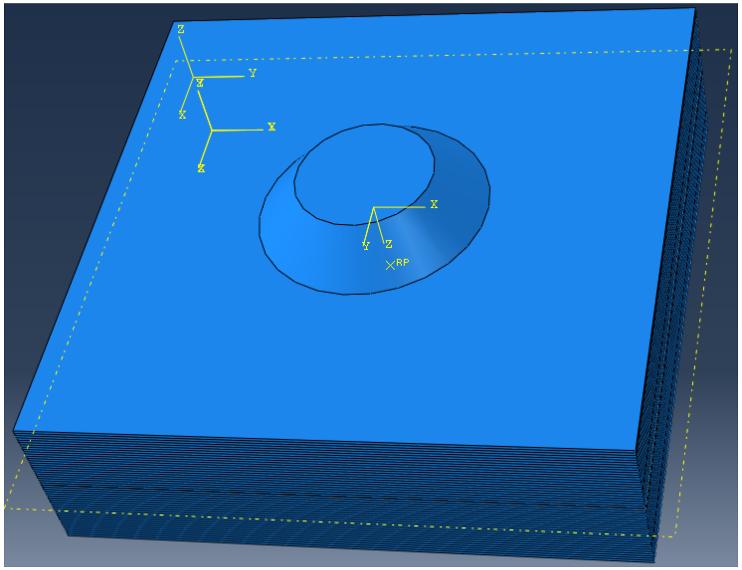

ASTM Standard Method Friction Vs. Load
Coefficient Of Friction
Normal Load (lb)
0/0 Mode 2 #1
45/-45 Mode 2 #1
90/90 Mode 1 #1
45/45 Mode 2 #2
0/0 Mode 1 #1
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0
20
40
60
80
100
120
140
160
180
200

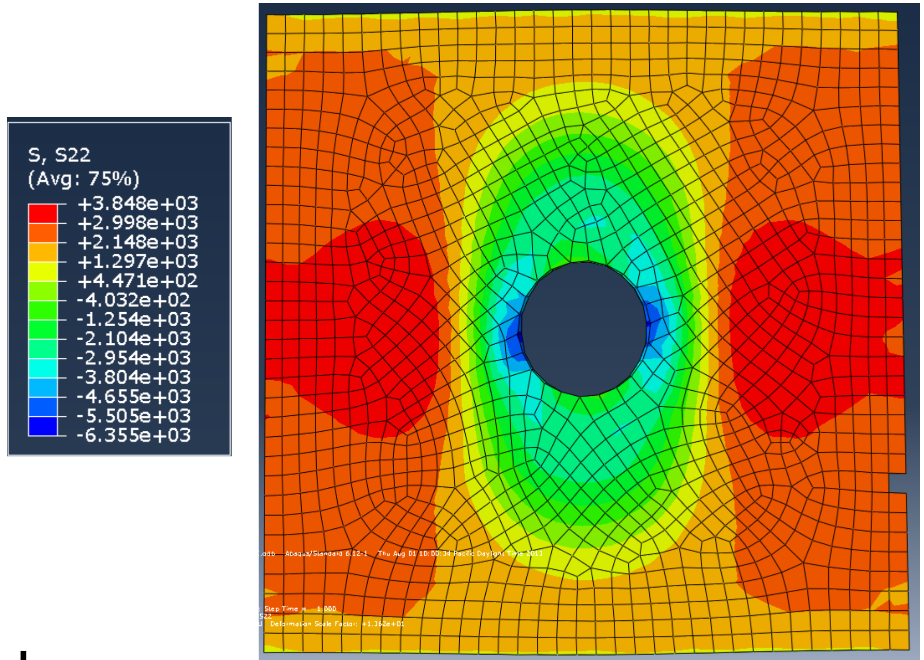

Bolted Method Friction vs. Load
Fricton Coeffecient
Fastener Torque
Sample Delaminated in Mode 1
Sample Delaminated in Mode 2
0.8
0.7
0.6
0.5
0.4
0.3
0.2
40
45
50
55
60
65
70
75
80

Results

- Bolted Method Produced Higher Friction Coefficients
  - Approximately 75% difference between methods
    - More exploration of discrepancies is required
  - Higher local pressure may have induced “locking” between rough surfaces
- 0/0 interface under ASTM standards had lowest measured level of friction (0.26) while 90/90 had highest (0.52)
- ASTM standard more sensitive to how fracture surface was created compared to bolted method
  - 15% difference when testing 0/0 interface

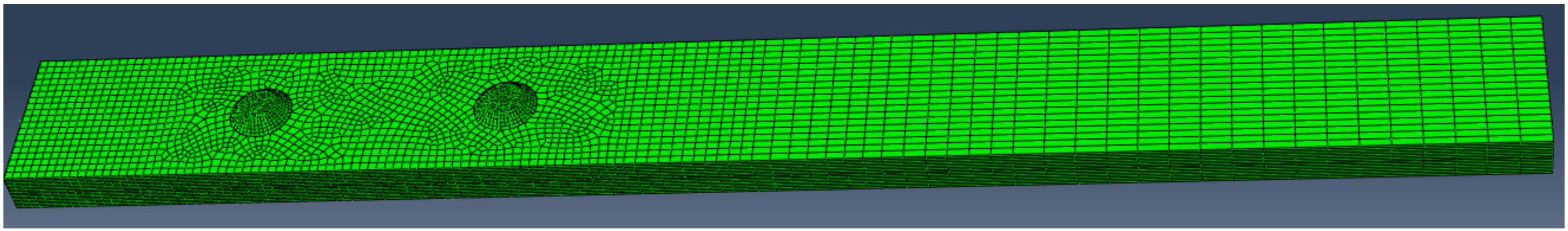
Local Preload Effects





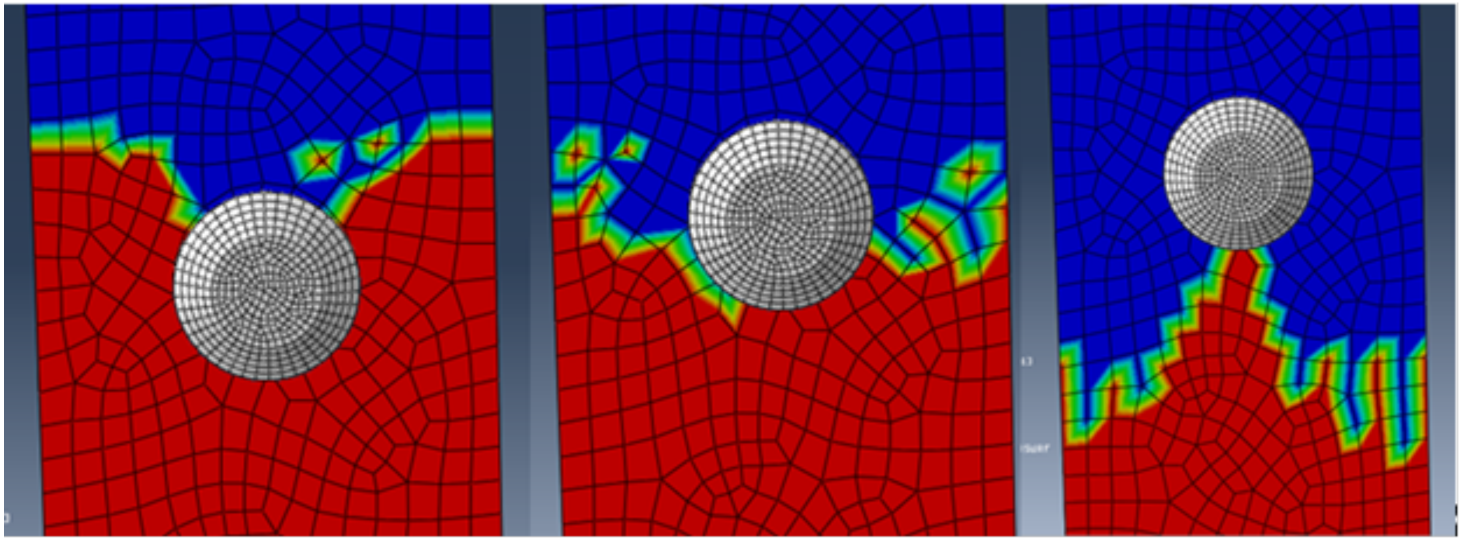
- 1.25 Inch square modeled
- Fastener simplified for computational simplicity
  - Multiple head shapes tested with very similar results
- Load is spreads asymmetrically under fastener head

Full 3D Finite Element Model



- Mirrors 2D models in scale
- Fastener VCCT results reasonably agree with 2D modeling approach
- Crack curvature is observed

Crack Curvature



- Crack curves in and reaches fastener first
- Crack front flattens out around the fastener as crack is arrested
- Once crack passes fastener, curvature reverses and shape observed in 3 plate testing is recovered
- Removal of fastener removes crack curvature

Work in Progress

- Continue testing of friction coefficient
  - Analyze discrepancies between testing methods
  - Determine coefficient limits
- Develop predictive method for friction coefficient
  - Estimate effective coefficient based on test parameters
- Verify effectiveness of fasteners in series
  - Crack propagation past second fastener is difficult
  - Determine scenarios where two fasteners in series may be insufficient

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

Thank you for Attending!

Questions?

Suggestions?

Comments?