Analysis of Fastener Disbond/ Delamination Arrest Mechanism for Laminated Composite Structures

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FAA Sponsored Project Information

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Industry Sponsors: The Boeing Company

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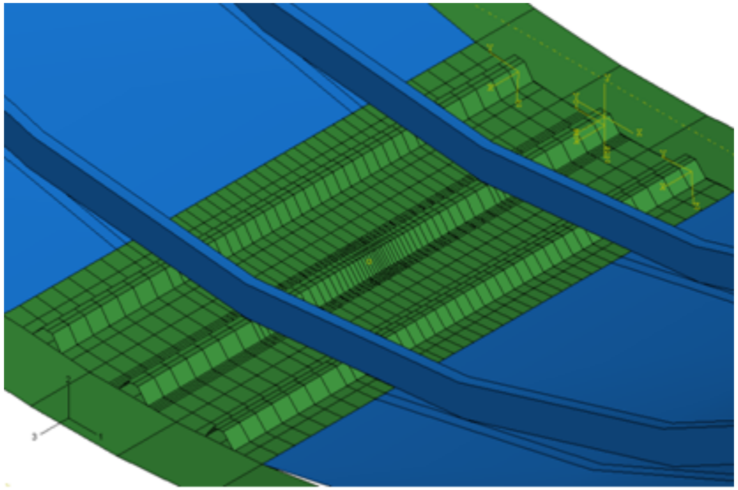
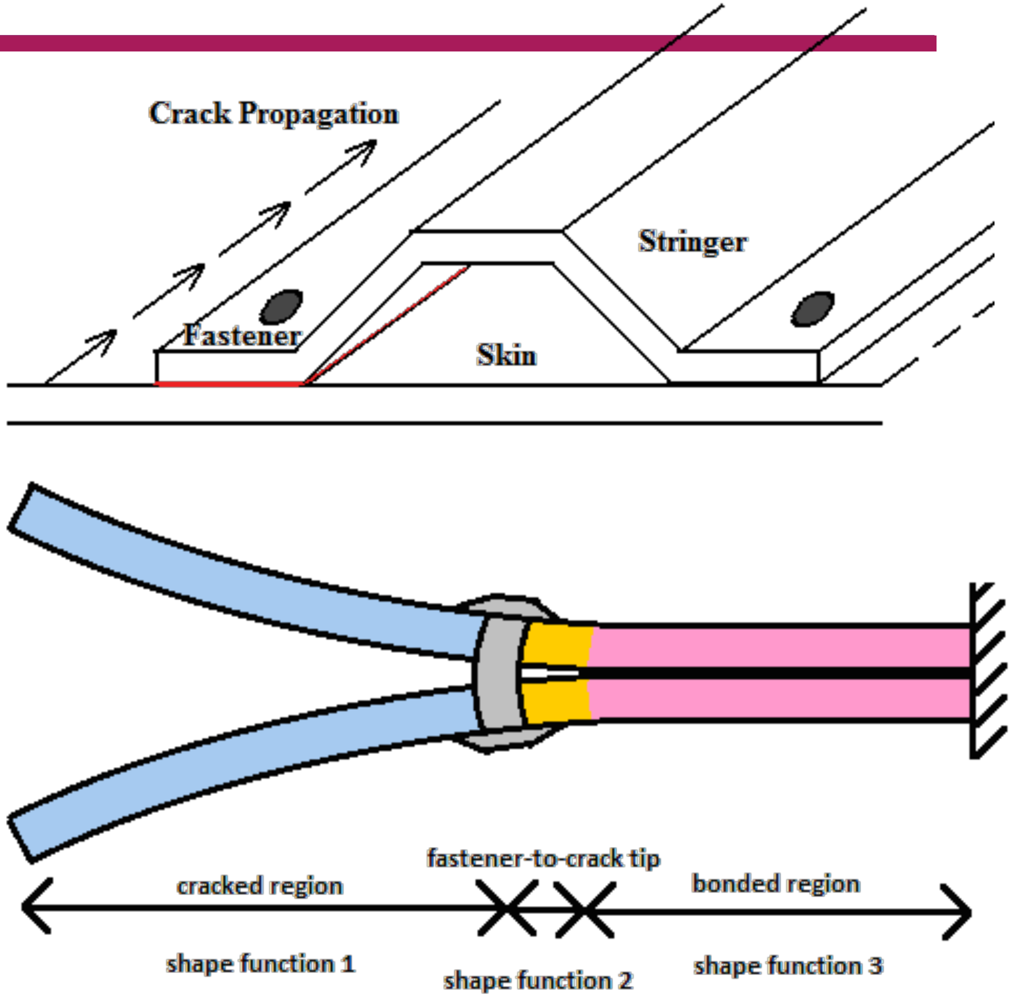
- **Objectives**
  - To understand the effectiveness of delamination/disbond arrest mechanisms
  - To develop analysis tools for design and optimization
- **Tasks**
  1. Develop Finite Element models in ABAQUS [completed]
  2. Develop 1-D (beam) [in progress] analytical solution
  3. Develop and conduct validation experiments [in progress]
  4. Conduct sensitivity studies on fastener effectiveness and stacking sequence effects [pending]
  5. Implement reliability analysis capability [pending]

Composite Structures with Fasteners



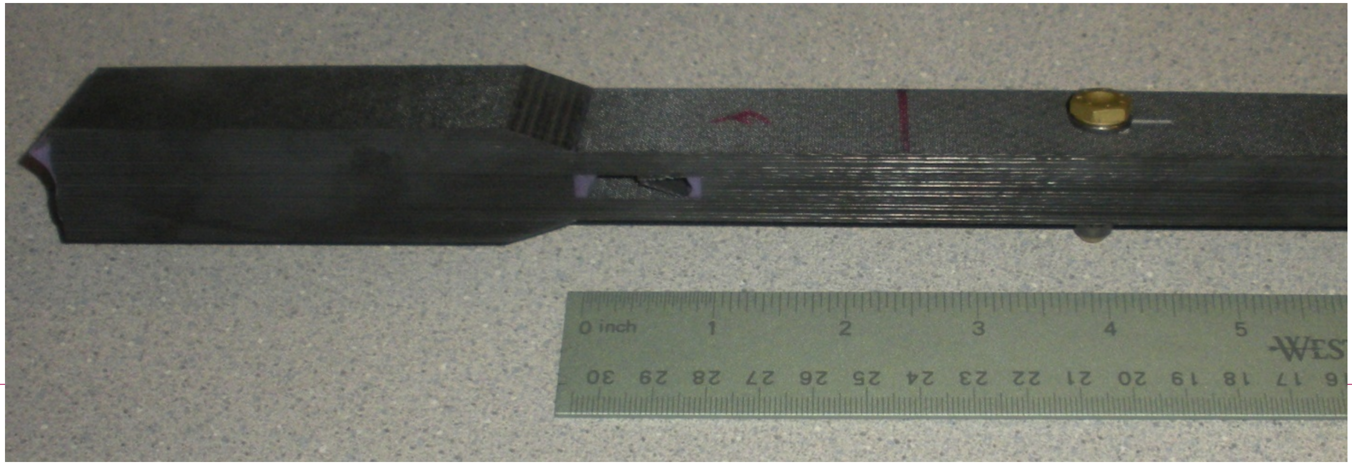


Previously

- **AMTAS 2010 -** **http://depts.washington.edu/amtas/events/amtas_10fall/Cheung_Fall_2010.pdf**
  - Design and FEA of a Novel 3-Plate Crack Propagation Specimen
  - Development of Analytical Solution to the Crack Arrest Problem
- **JAMS 2011 -** **http://www.niar.wichita.edu/NIARWorkshops/LinkClick.aspx?fileticket=gd2SsZjR360%3d&tabid=123&mid=756**
  1. Analytical Solution to the 3-Plate Crack Propagation Specimen
  2. Effect of Fastener Hole Clearance
  3. Early Testing of the 3-Plate Crack Propagation Specimen

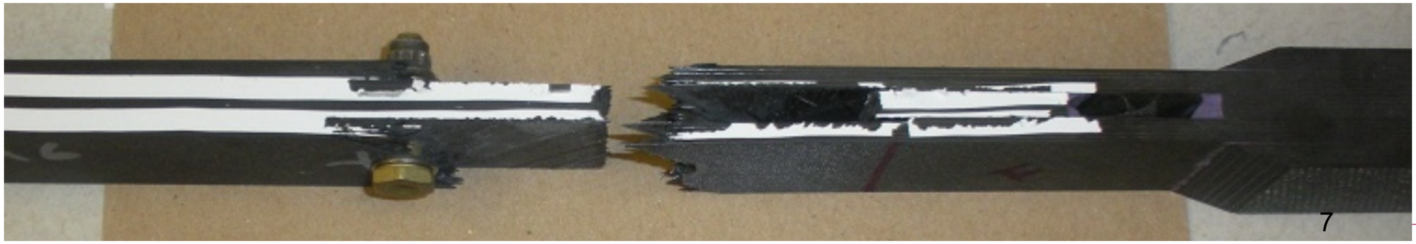
3-Plate Specimen Description

- 3 x 24-ply quasi-isotropic laminate with crack at fabric/ fabric interface; secondary bonding
- 3 x 24-ply quasi-isotropic laminate with crack at 0/0 interface; co-cured
- 0.25” Titanium fastener installed at half installation toque: 40 in-lb
- Initial cracks are implanted with Teflon inserts 1.5” from the fastener



Secondary Bonded Specimens

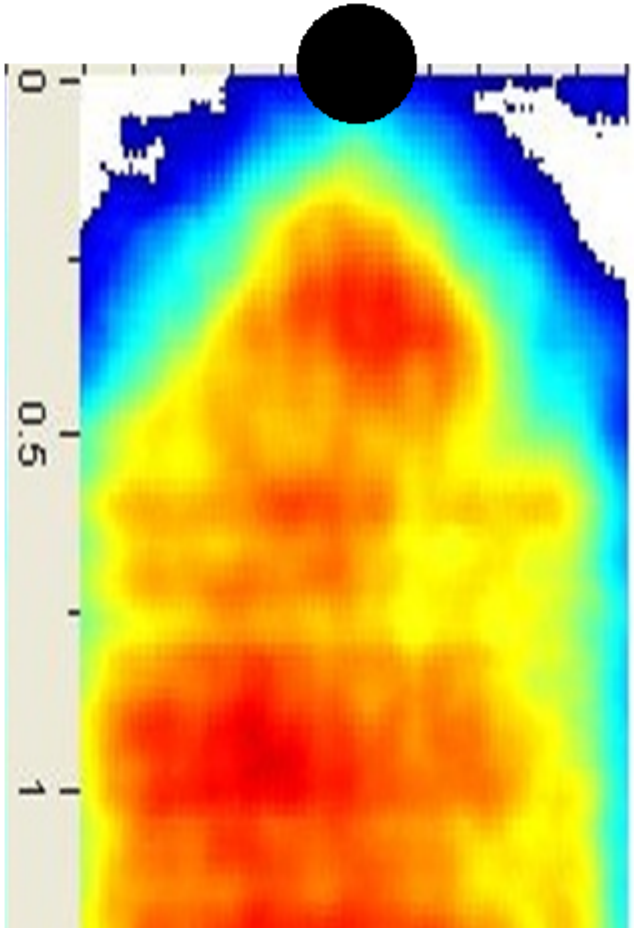
- Crack initiation is immediately followed by ultimate failure
  - Filled/Open-hole tension failure of the outer laminates
  - Crack propagation load > ultimate load in tension
- Crack jumps from the bondline to a couple plies into the outer laminates
- Fracture toughness of the secondary bond is too high

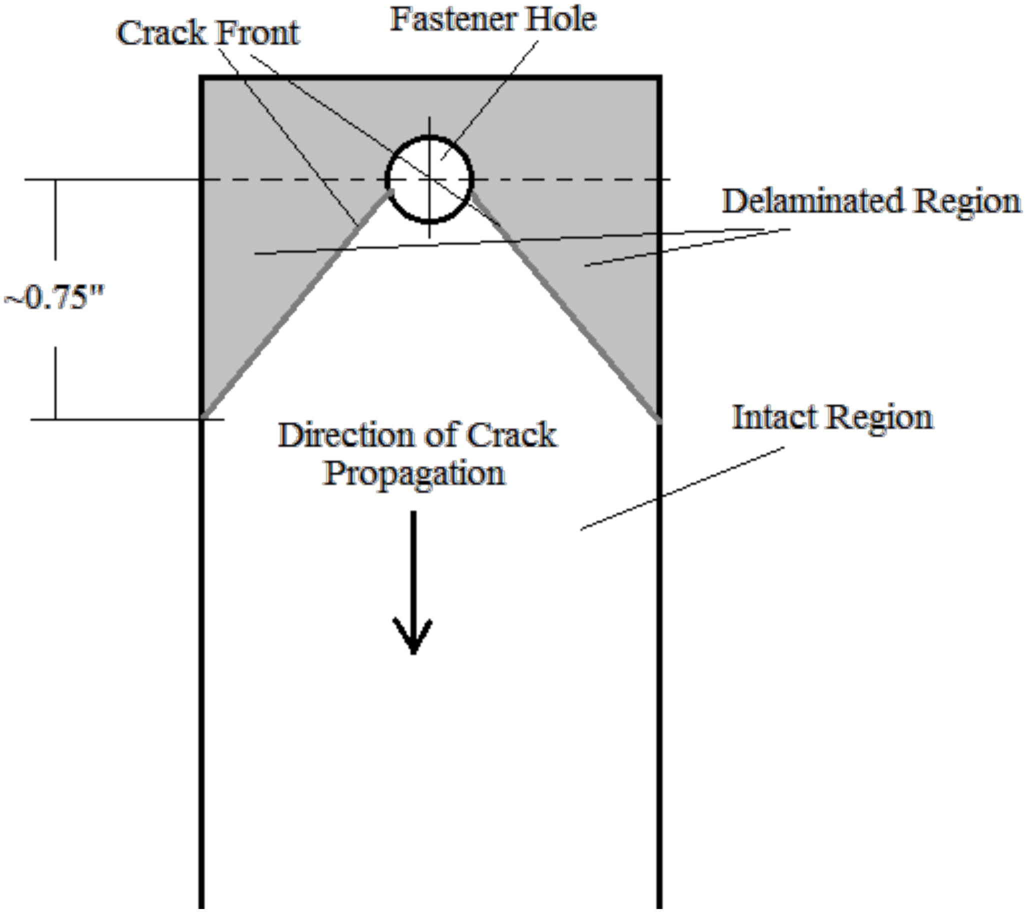


Secondary Bonded Specimens

	Fastener Installed	Initiation Load (kip)	Ultimate Failure Load (kip)	Propagation Mode	Ultimate Failure Mode
1	Yes	35.5	35.5	Disbond w/ Bridging	Net-section Failure
2 (Pre-Crack)	Yes	36.6	36.6	Disbond w/ Bridging	Net-section Failure
3	Yes	37.0	37.0	Disbond w/ Bridging	Net-section Failure
4	Yes	36.8	36.8	Disbond w/ Bridging	Net-section Failure
5	No	35.0	35.0	Disbond w/ Bridging	Net-section Failure
6	Yes	37.2	37.2	Disbond w/ Bridging	Net-section Failure
7	Yes	36.2	36.2	Disbond w/ Bridging	Net-section Failure
8	No	35.9	35.9	Disbond w/ Bridging	Net-section Failure

Secondary Bonded Specimens



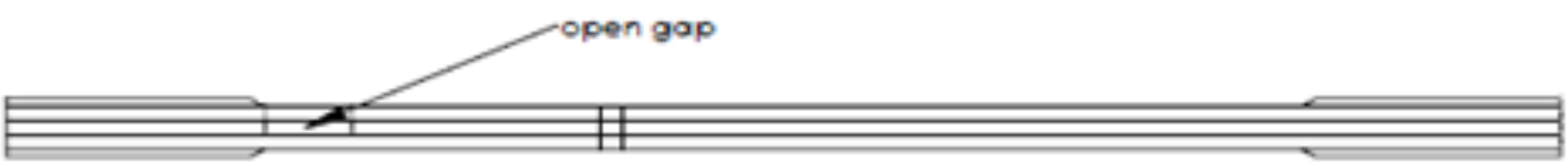


Co-Cured Specimens

- Crack initiation load occurs at ~20.6 kip
- Initial crack growth is stable
  - Fastener with significant installation torque could have stabilized crack propagation
- Cracks reach fastener at ~23.6 kip
- Crack front stays at 0°/ 0° interface
- Ultimate failure occurs at ~30.4 kip
  - Filled hole tensile failure of outer laminates
- Minor crack growth (V-shape) detected around the fastener

Co-Cured Specimens

	Initiation Load	Crack Reaches Fastener	Crack location at Test-end (NDI)	Crack front shape at Test-end	Test-end load	Tested to Ult. Failure
1	20.6 kip	23.2 kip	1.1 in	Straight	30.4 kip	Yes
2	19.4 kip	25.1 kip	0.5 to 1.1 in	Straight, but at an angle	29.7 kip	Yes
3	21.2 kip	23.6 kip	0.6 in	V-shape	29.5 kip	No
4	24.3 kip	24.3 kip	0.6 in	V-shape	29.3 kip	No



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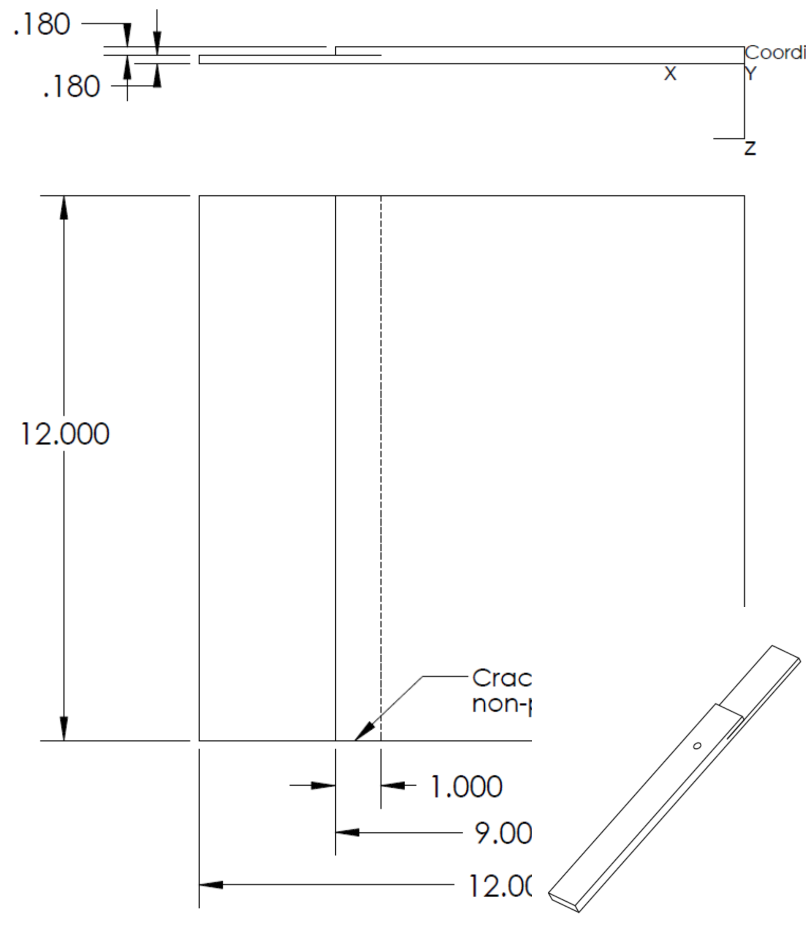
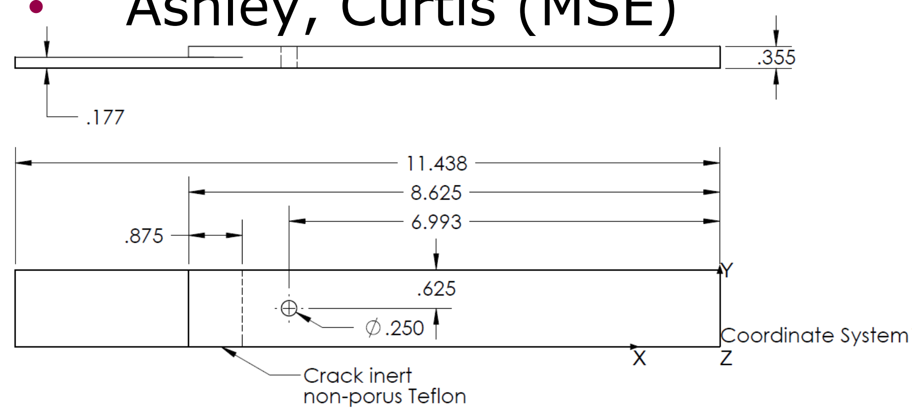
Future of the 3-Plate Specimen

- Competing failure mode is a major hurdle
  - The fastener definitively arrested the crack, but unable to determine the maximum capability
- Specimen can be optimized for higher G_{II} available
  - Increase stiffness of the center plate; decrease stiffness of outer plate
  - Increase total thickness
  - But loses flexibility in choosing lay-up
- G_{IIC} could be reduced by using a different material system or manufacturing technique
- Arrest capability could be reduced by using a smaller fastener and reducing the installation torque

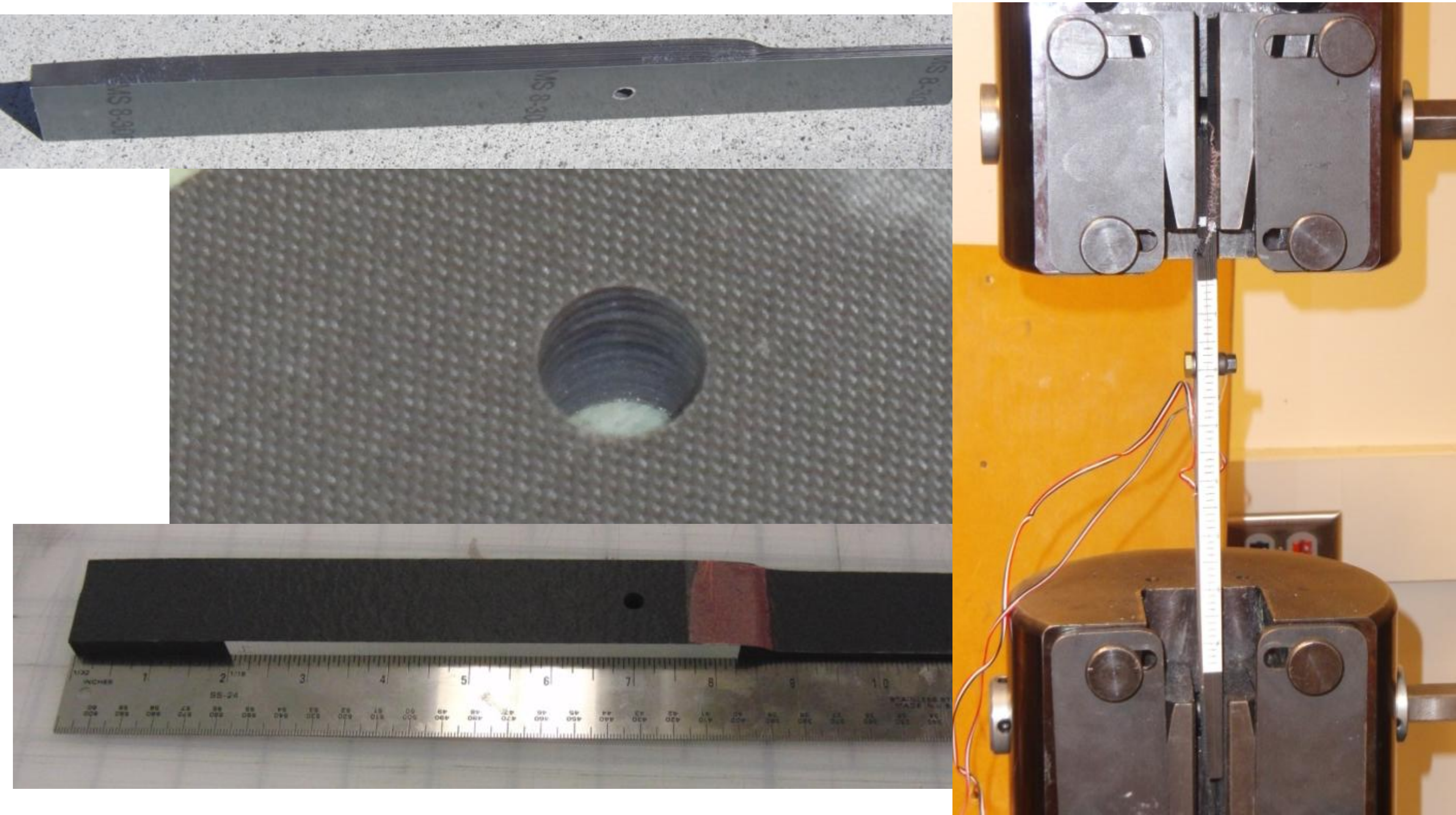
2-Plate Specimen Description



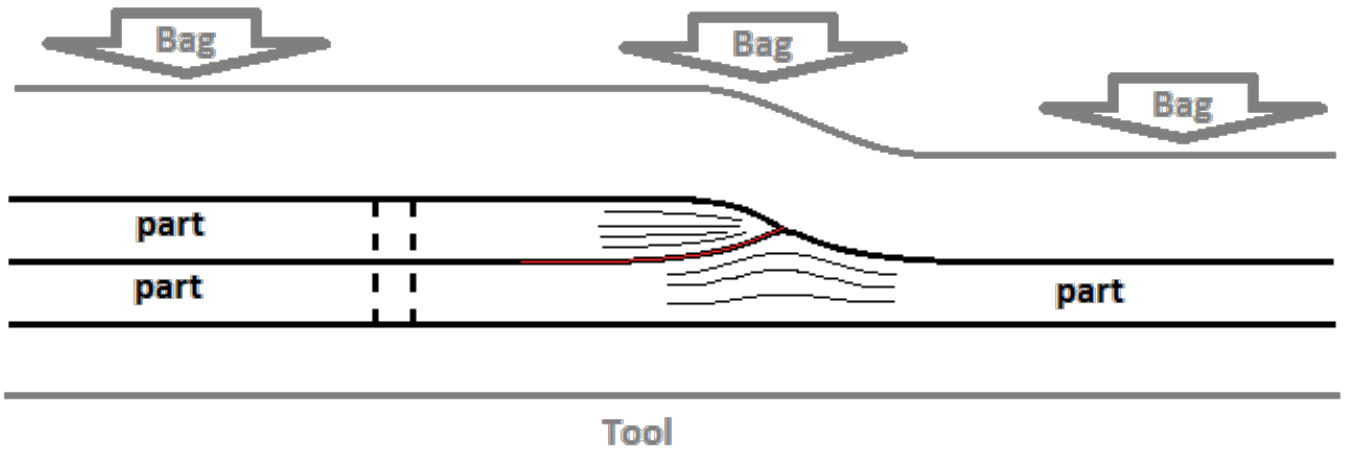
- BMS 8-276 unidirectional pre-preg tape
- BMS 8-308 peel ply
- Titanium Fasteners
- $(0/45/90/-45)_{3S}$
- $(0/-45/02/90/45/02/-45/90/45/0)_S$
- Ashley, Curtis (MSE)

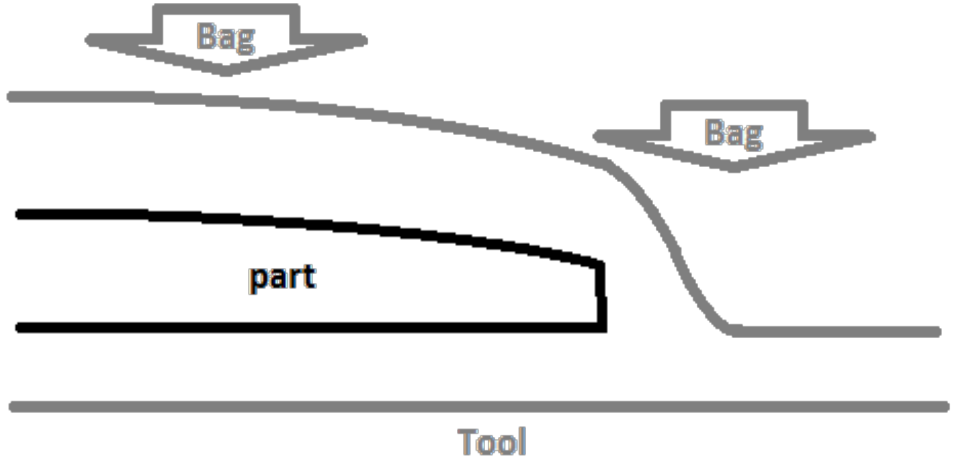


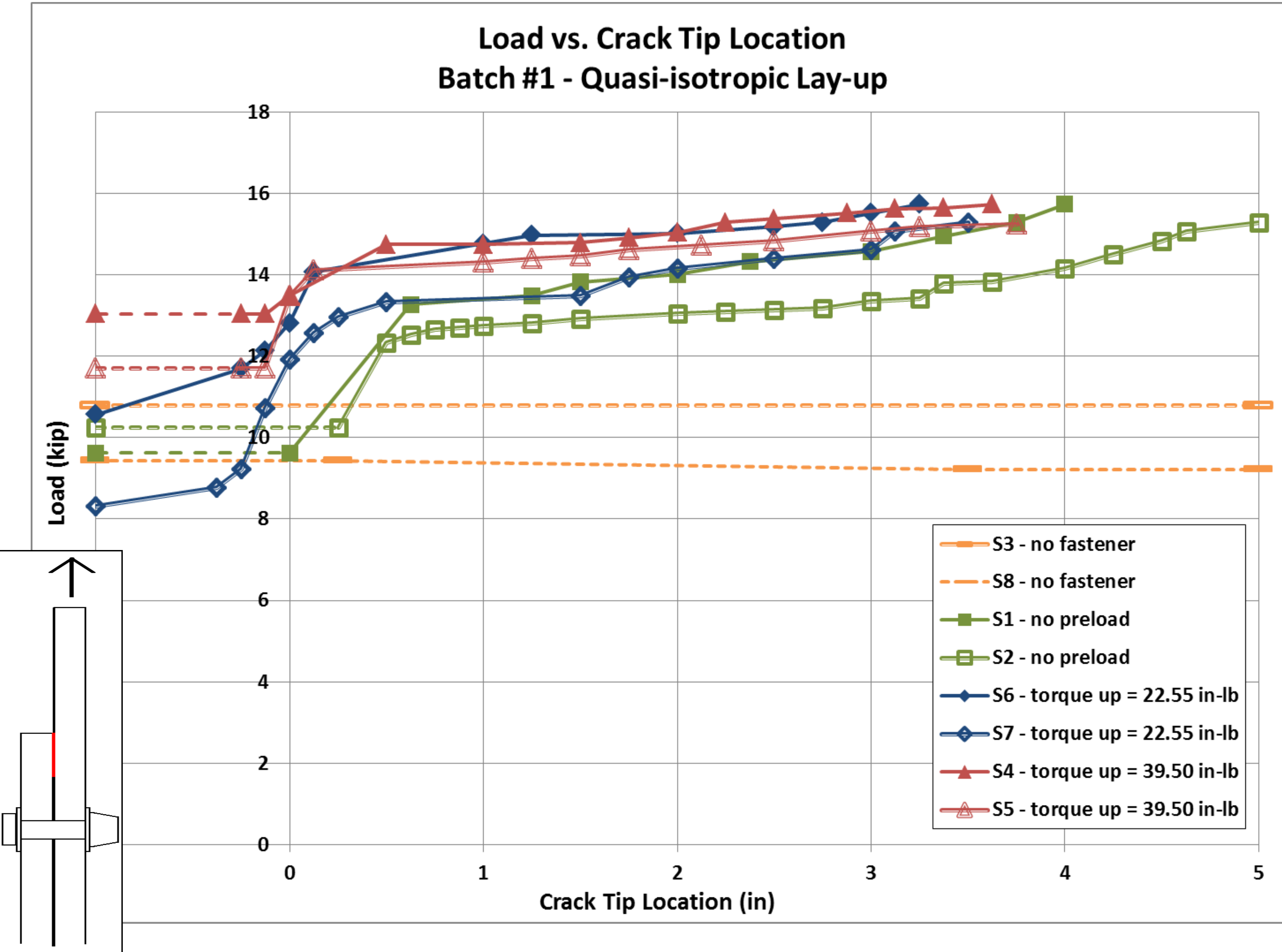
2-Plate Specimen Photo Collage



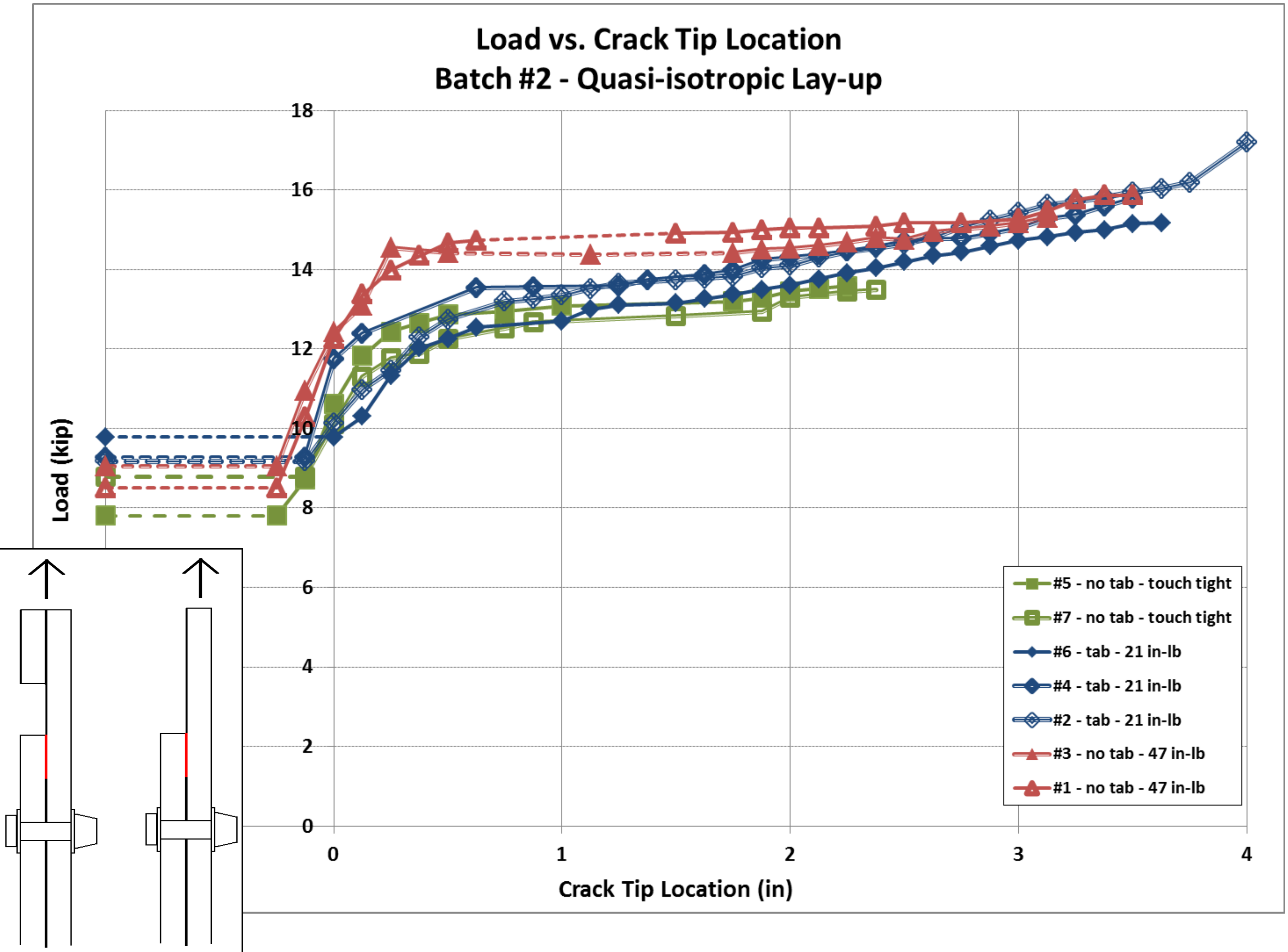
Manufacturing Issues



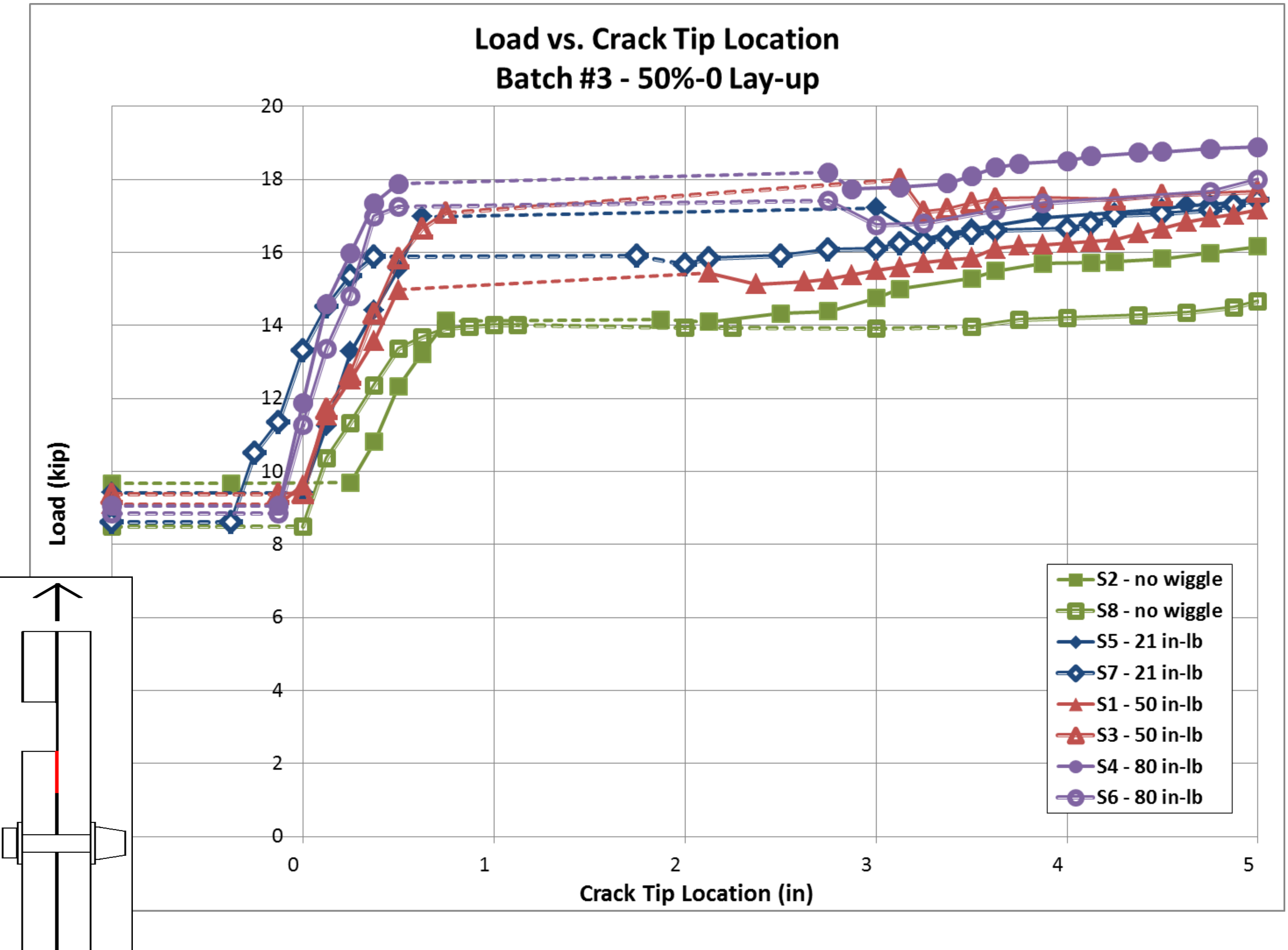


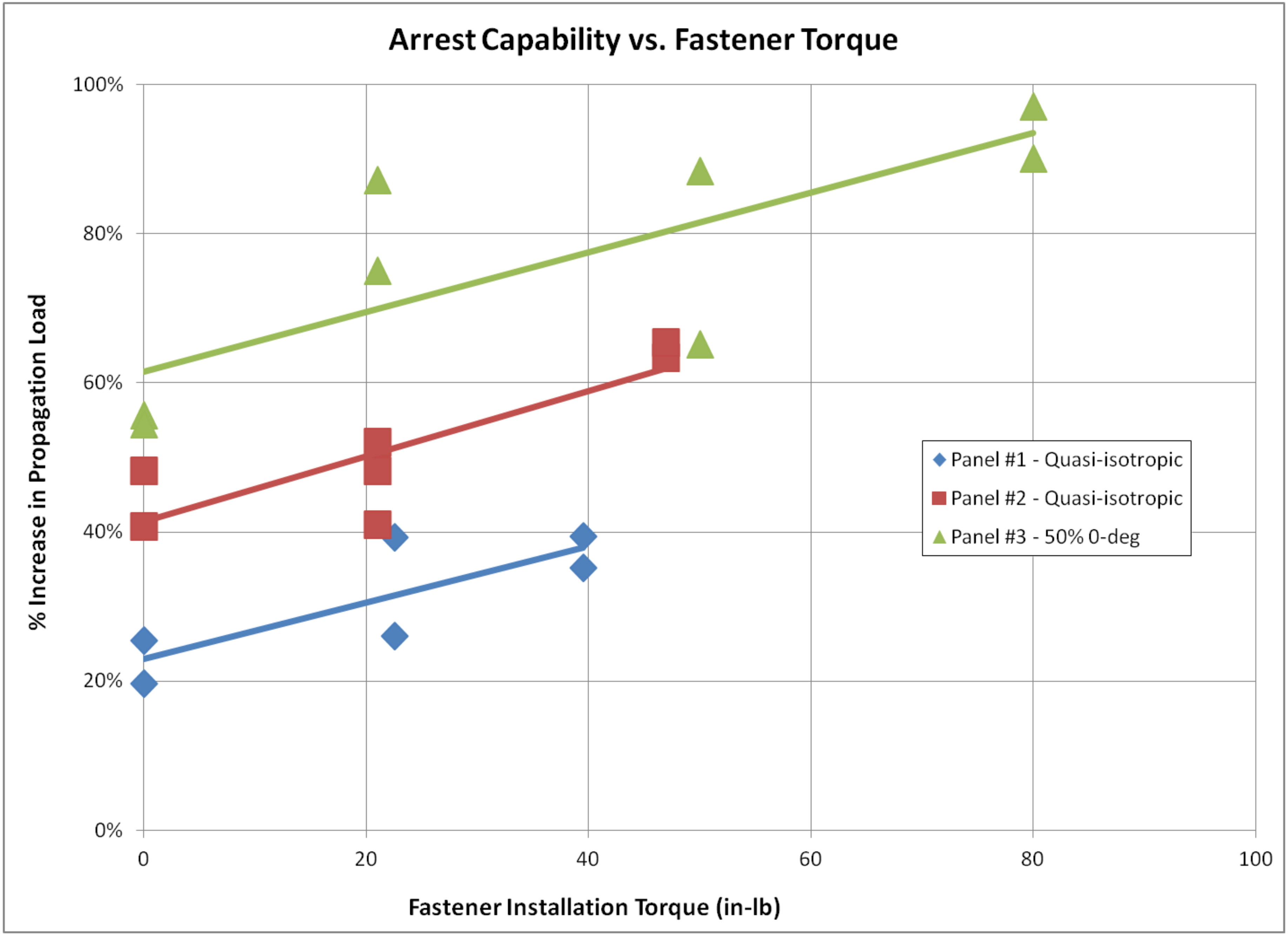


Load vs. Crack Tip Location
Batch #1 - Quasi-isotropic Lay-up
Load (kip)
Crack Tip Location (in)
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
S3 - no fastener
S8 - no fastener
S1 - no preload
S2 - no preload
S6 - torque up = 22.55 in-lb
S7 - torque up = 22.55 in-lb
S4 - torque up = 39.50 in-lb
S5 - torque up = 39.50 in-lb



Load vs. Crack Tip Location
Batch #2 - Quasi-isotropic Lay-up
Load (kip)
Crack Tip Location (in)
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
#5 - no tab - touch tight
#7 - no tab - touch tight
#6 - tab - 21 in-lb
#4 - tab - 21 in-lb
#2 - tab - 21 in-lb
#3 - no tab - 47 in-lb
#1 - no tab - 47 in-lb


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

2-Plate Specimen Summary

- 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 issues persist
  - Use heat press
- Crack propagation is not symmetric across the width of the specimen, especially near the fastener

Future Work

3-Plate Specimen

- Optimize thickness and lay-up
- Pre-cracking

2-Plate Specimen

- Improve manufacturing quality
- Different thicknesses and lay-ups
- Different fastener sizes
- Analytical solution