Evaluation of Additive Manufacturing for Composite Repairs

2 April 2024

Presented to: JCAMS

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Introduction

- The purpose of this project is to explore the application of AM patches for lightly loaded composite repairs.
- Possible Benefits
  - Cut down on repair time
  - Reduce costs
  - Increased reliability
- Stratasys F900 machine using ULTEM 9085 CG Filament
- Leverage distributed manufacturing capability

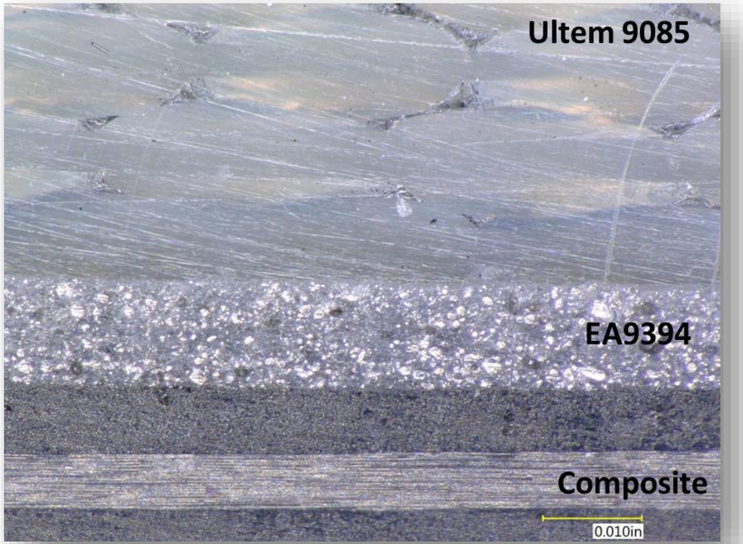
Stratasys F900

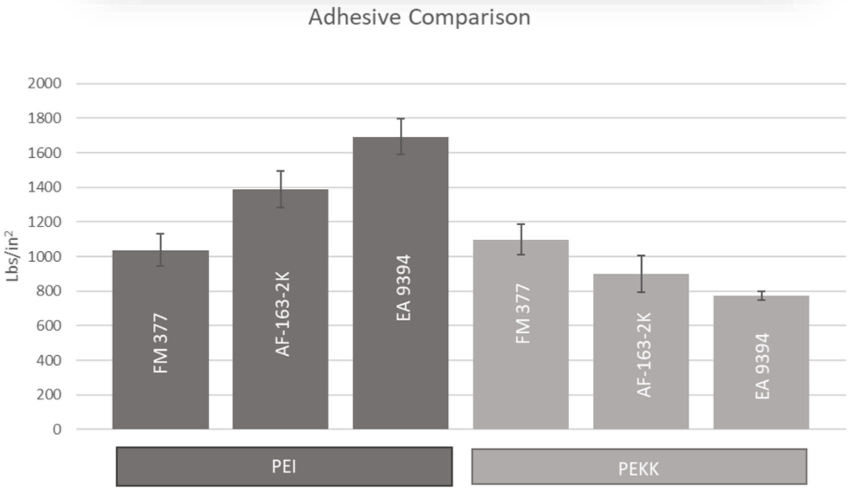
For ULTEM 9085 Layer height 0.01in (0.254 mm)

Accuracy of +/- .089 mm or +/- .0015 mm per mm whichever is greater (+/- .0035 in. or +/-.0015 in. per in. whichever is greater

Testing Outline

- Testing
  - Fracture Toughness
    - Characterize material across process settings
      - Raster angle
      - Orientation
    - Determine suitability and best process settings for repair design
  - Double Lap Shear
    - Evaluation of bonding using EA9394 to thermoset epoxy substrate
    - Bonding optimization
    - Additional characterization of bond strength
  - Demonstration/Validation
    - Demonstrate designed repair on scrap component





Fracture Toughness Test Matrix

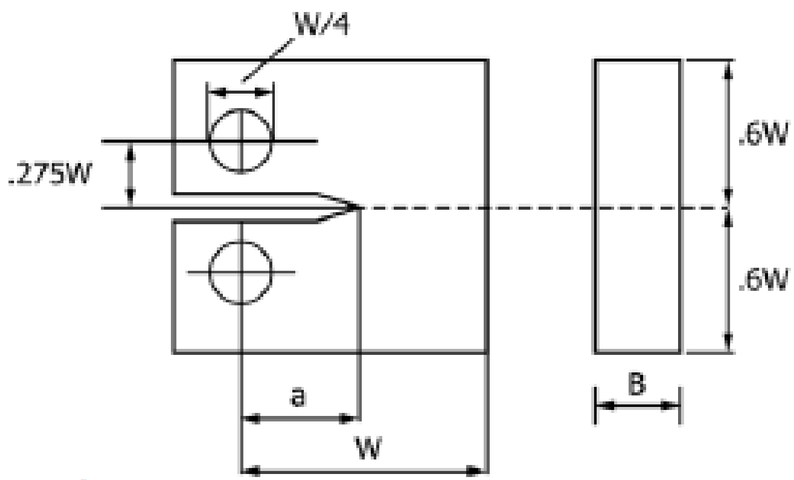
Build Direction	Flat (X)				On Edge (Y)				Upright (Z)			
Raster Angle	0/90	45/ -45	0/45/ 90	0/60/ -60	0/90	45/ -45	0/45/ 90	0/60/ -60	0/90	45/ -45	0/45 /90	0/60/ -60

Constants	
Infill	100%
Raster Width	0.508 mm (0.02 in.)
Contour Width	0.508 mm (0.02 in.)
Airgap	0 mm (0 in.)

ASTM Selection

- Based on literature reviews, ASTM 5045 was chosen. It is Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials.
- There are no ASTM AM focused test methods for Fracture Toughness.

Coupon Design



b Compact Tension Configuration (CT)

FIG. 3 Specimen Configuration as in Test Method E399

$$B,\ a,\ (W-a) > 2.5\,(K_Q/\sigma_y)^2 \qquad (1)$$

where:

K_Q = the conditional or trial K_{Ic} value (see Section 9), and
σ_y = the yield stress of the material for the temperature and loading rate of the test.

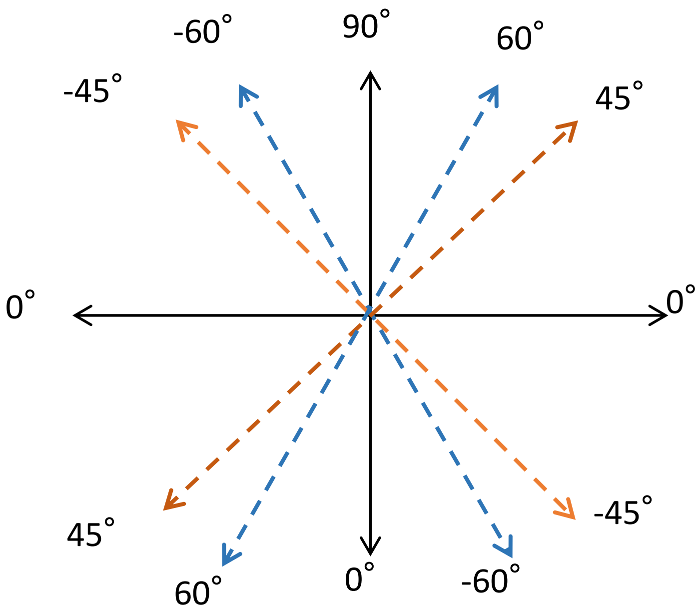
- Single End Bending versus Compact tension coupon types were allowed per the ASTM, but CT was chosen.
- We were not constrained by a specific stock material geometry.
- Based on selected dimension, the part was designed in SolidWorks.

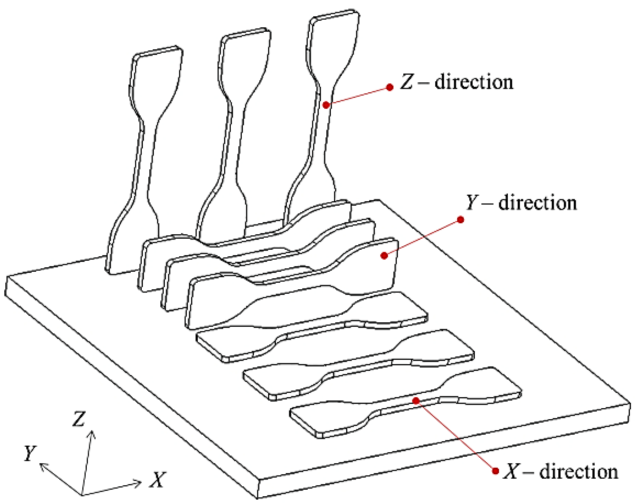
To choose the dimensions,
0.55> a/W >0.45

a= 20 mm
W= 40 mm
B= 20 mm

a is the total crack length after pre cracking, before failure

Coupon Design





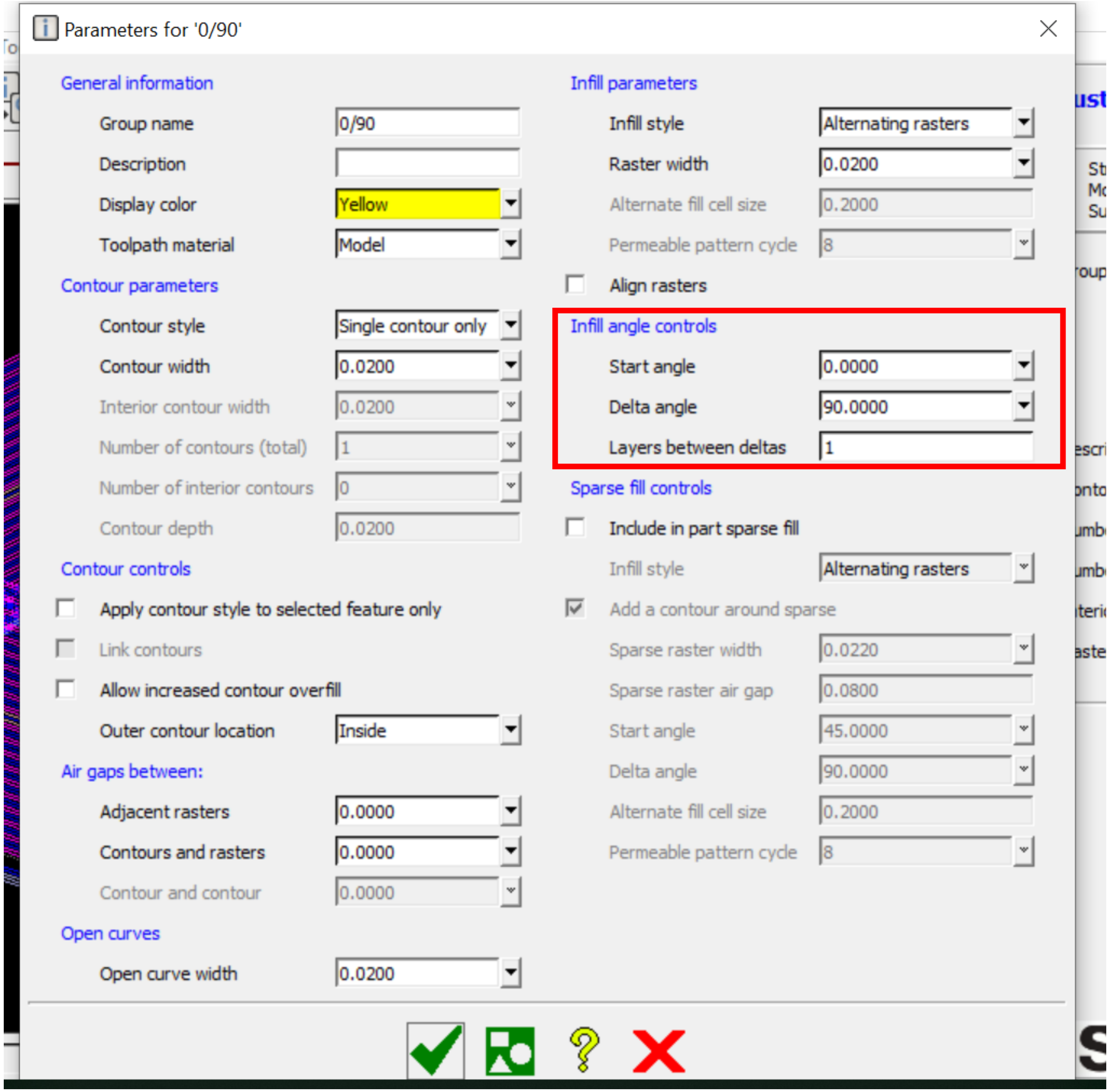
- The goal was to compare build direction and raster angle to see what would produce the highest fracture toughness.
  - Upright(Z)
  - On Edge (Y)
  - Flat (X)
- Raster Angle
  - +45/-45 degrees
  - 0/90 degrees
  - Quasi composite 0/45/90
  - Quasi composite 0/60
- Test each combination 3 times for redundancy

45
-45
90
0
90
-45
45

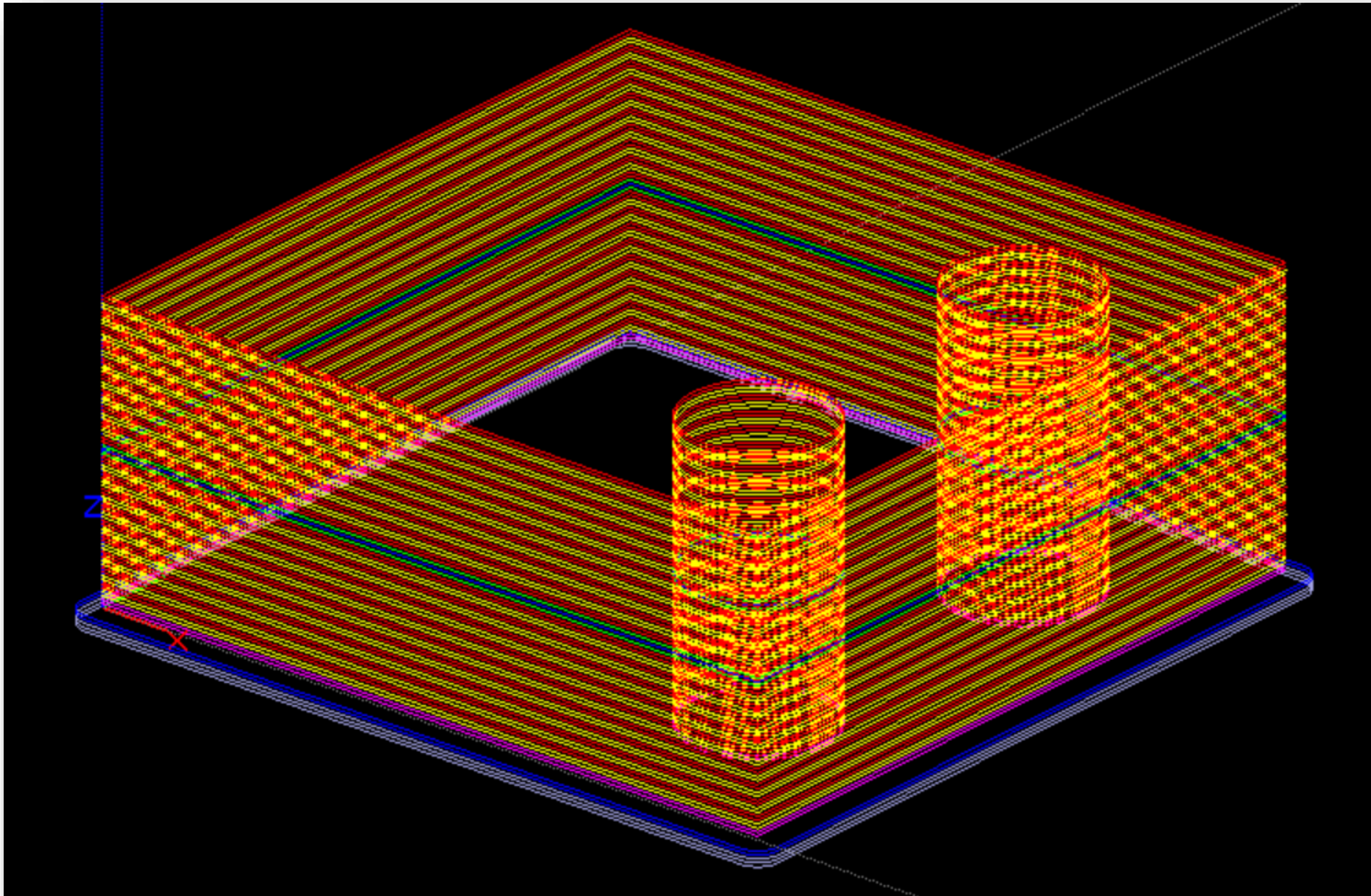
-60
0
60
-60
60
0
-60

Layer patterns

Coupon Design

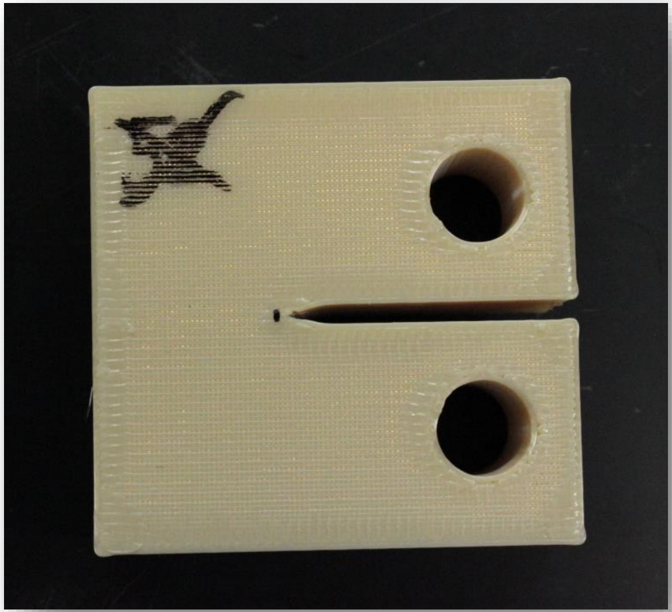


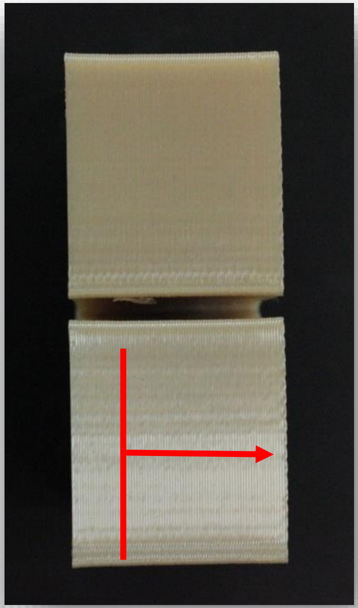
Coupon Design

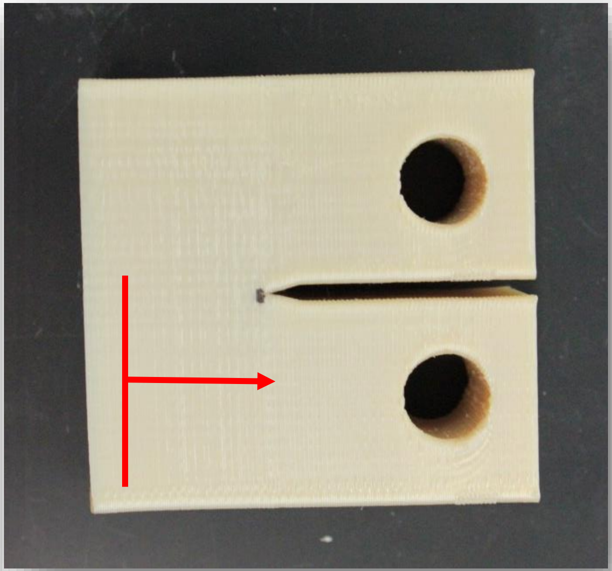


Quasi 0/45/90 Flat(X) No crack, compliance coupon

Coupon Design

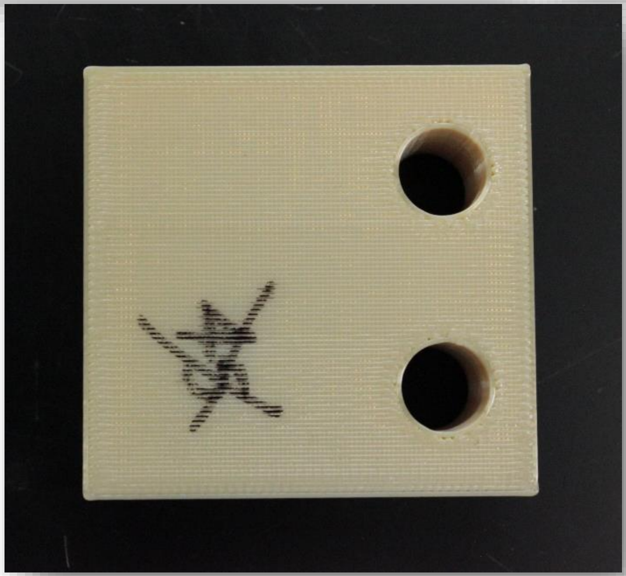




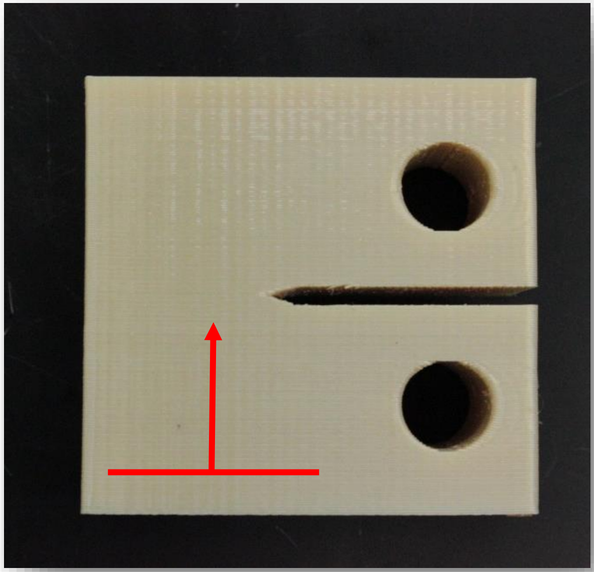


On Edge Specimen

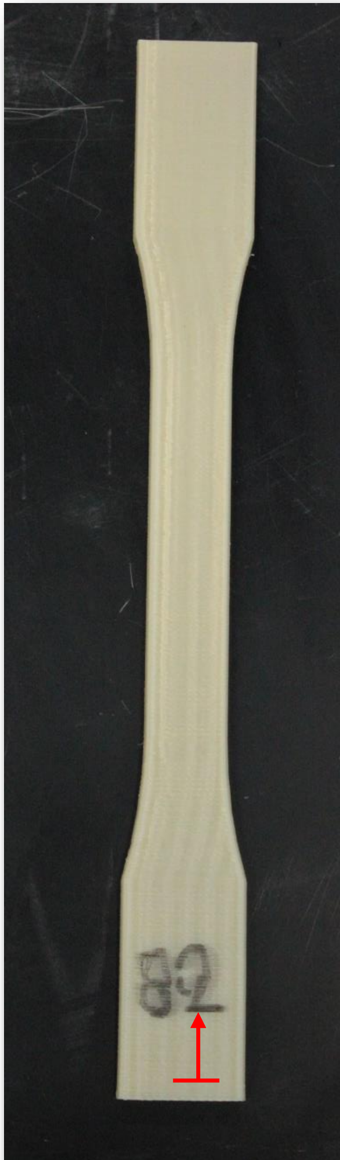
Flat
Specimens



Upright
Specimen



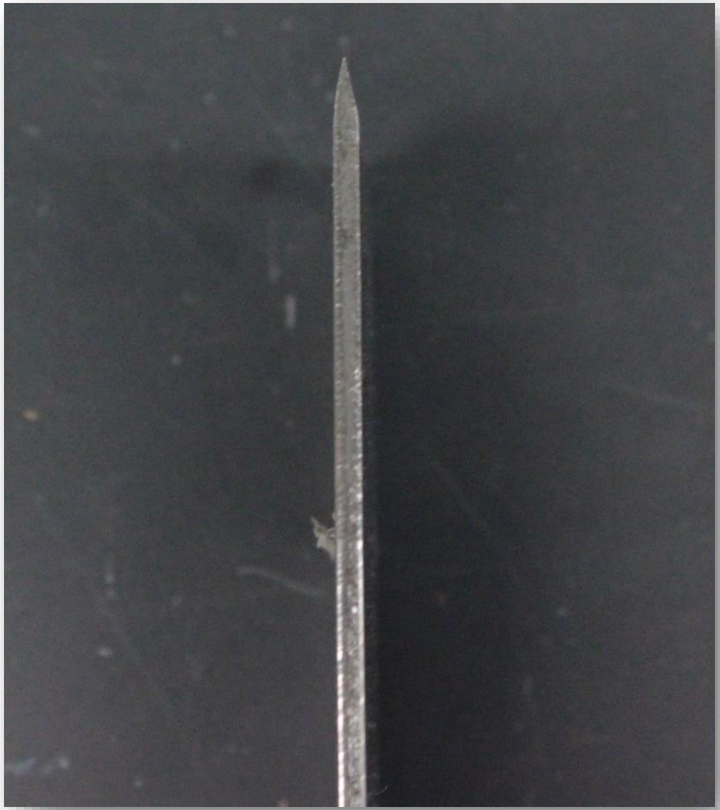
Tension Coupons



Test Procedure

1. Pre-crack the FT coupons
2. Perform tension test on tension coupons
3. Get time to failure and max load
4. Determine yield stress via ASTM E399
5. Load the FT coupons at a rate such that crack extension occurs within ± 20% of the time to max load of the tension coupons
6. Perform compliance CT test, reach same load within ± 20% of time of tension coupons
7. If any coupons fell outside the time, they were invalidated
8. Perform calculations and numerical checks to confirm validity of data

Coupon Preparation



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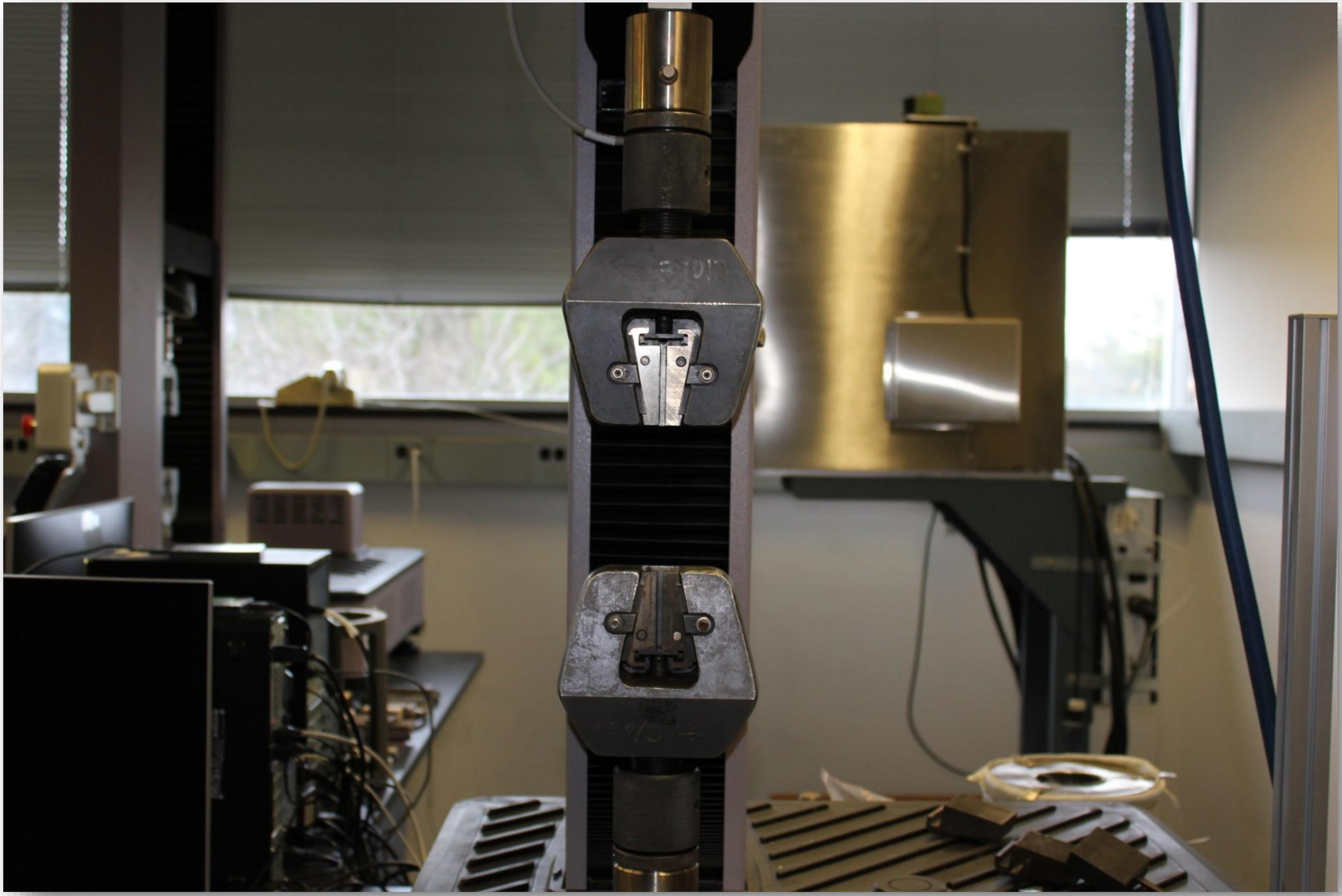
Tension Test Procedure



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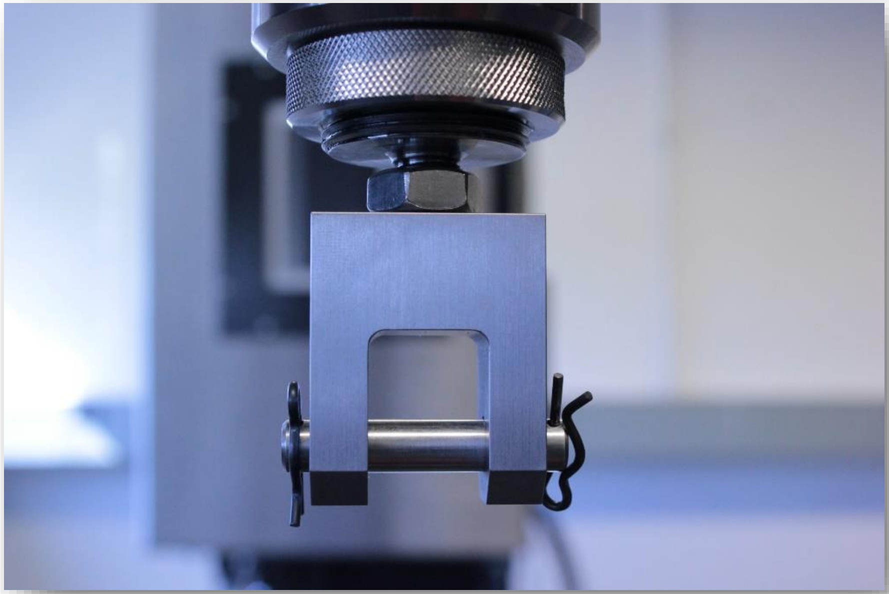
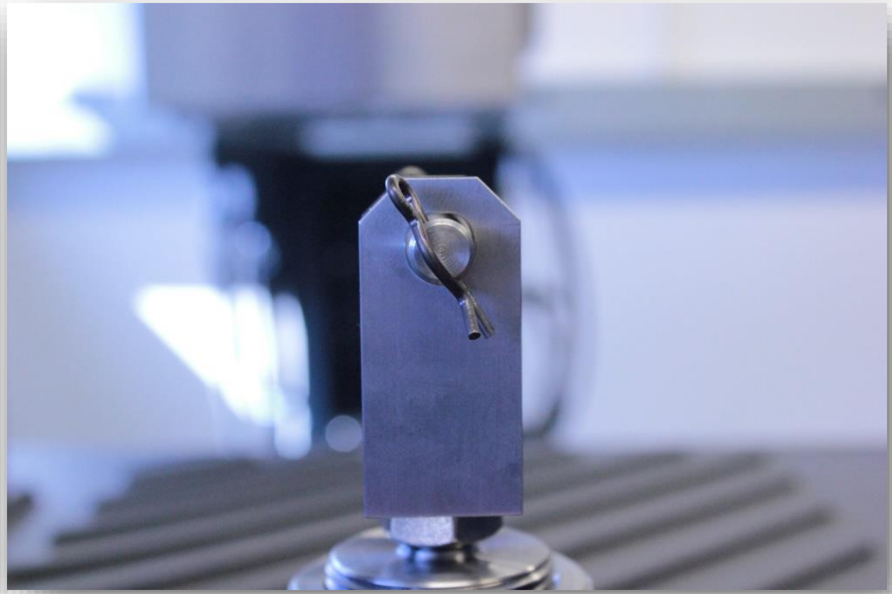
Custom Clevis





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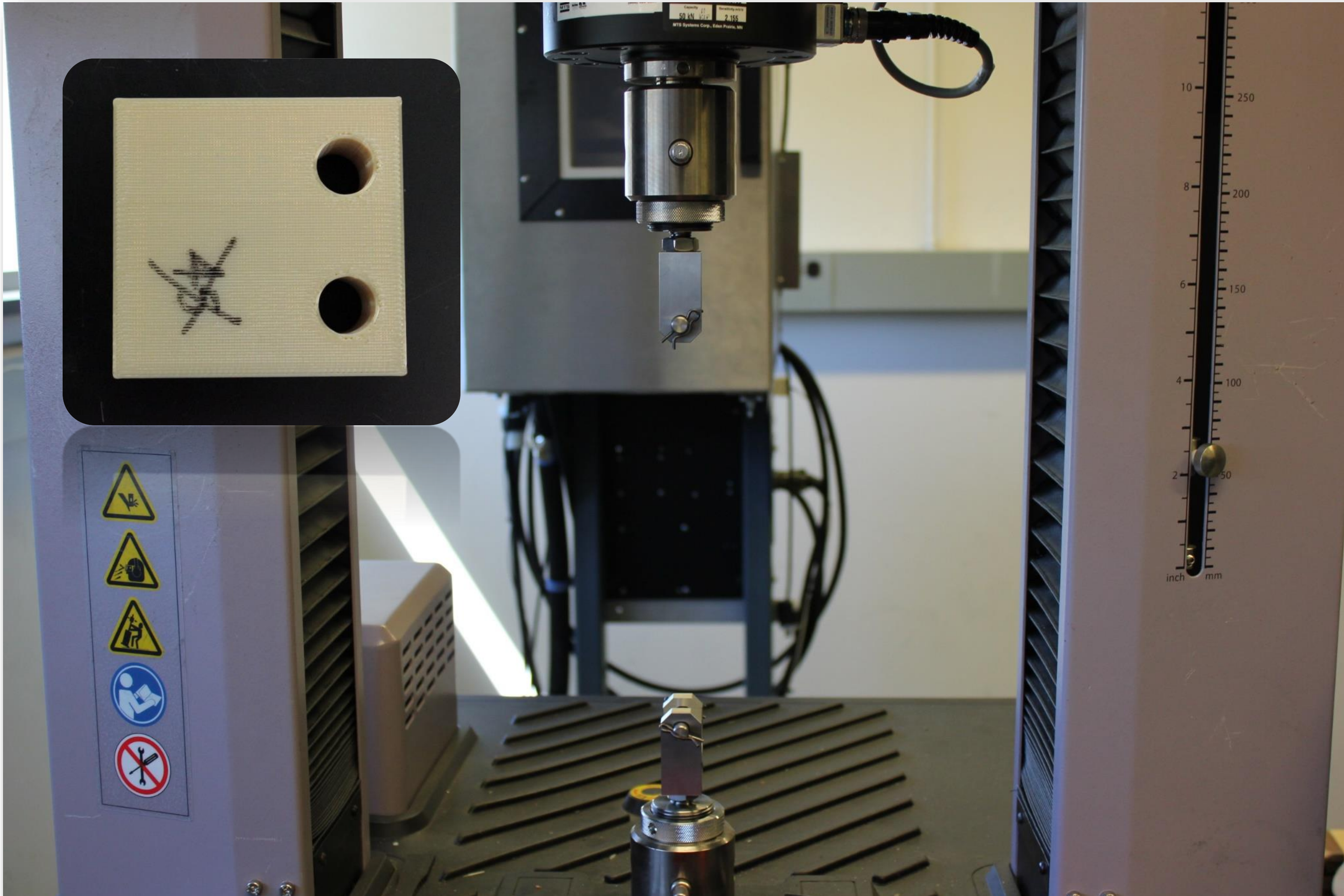

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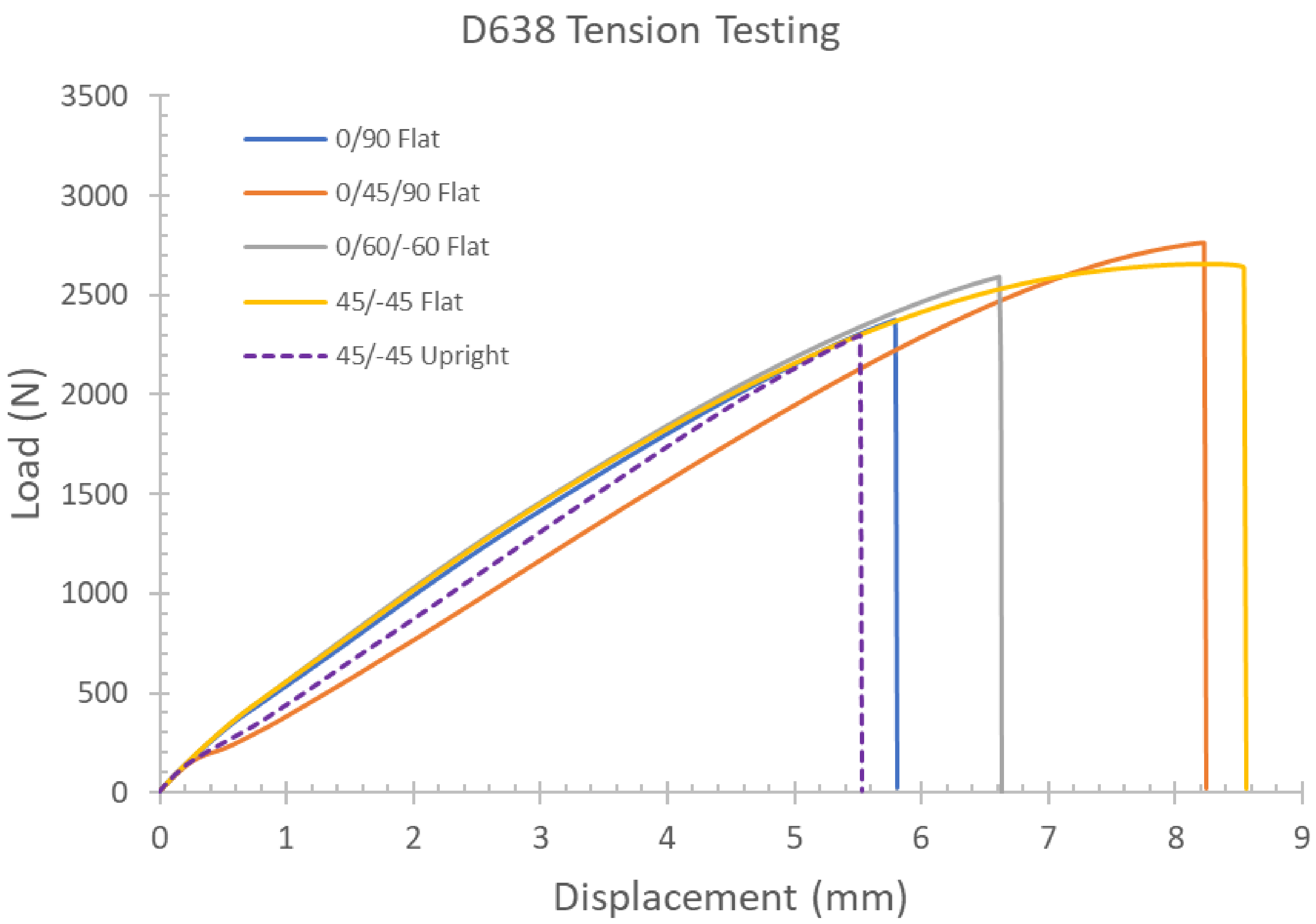
Tension Results

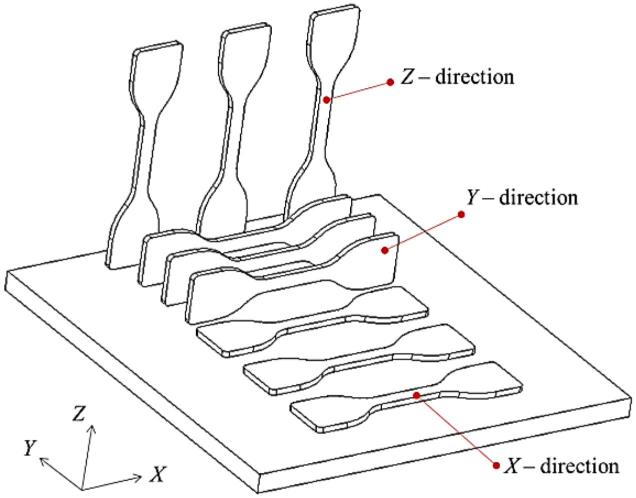


Tension Results

Yield Strength (MPa)

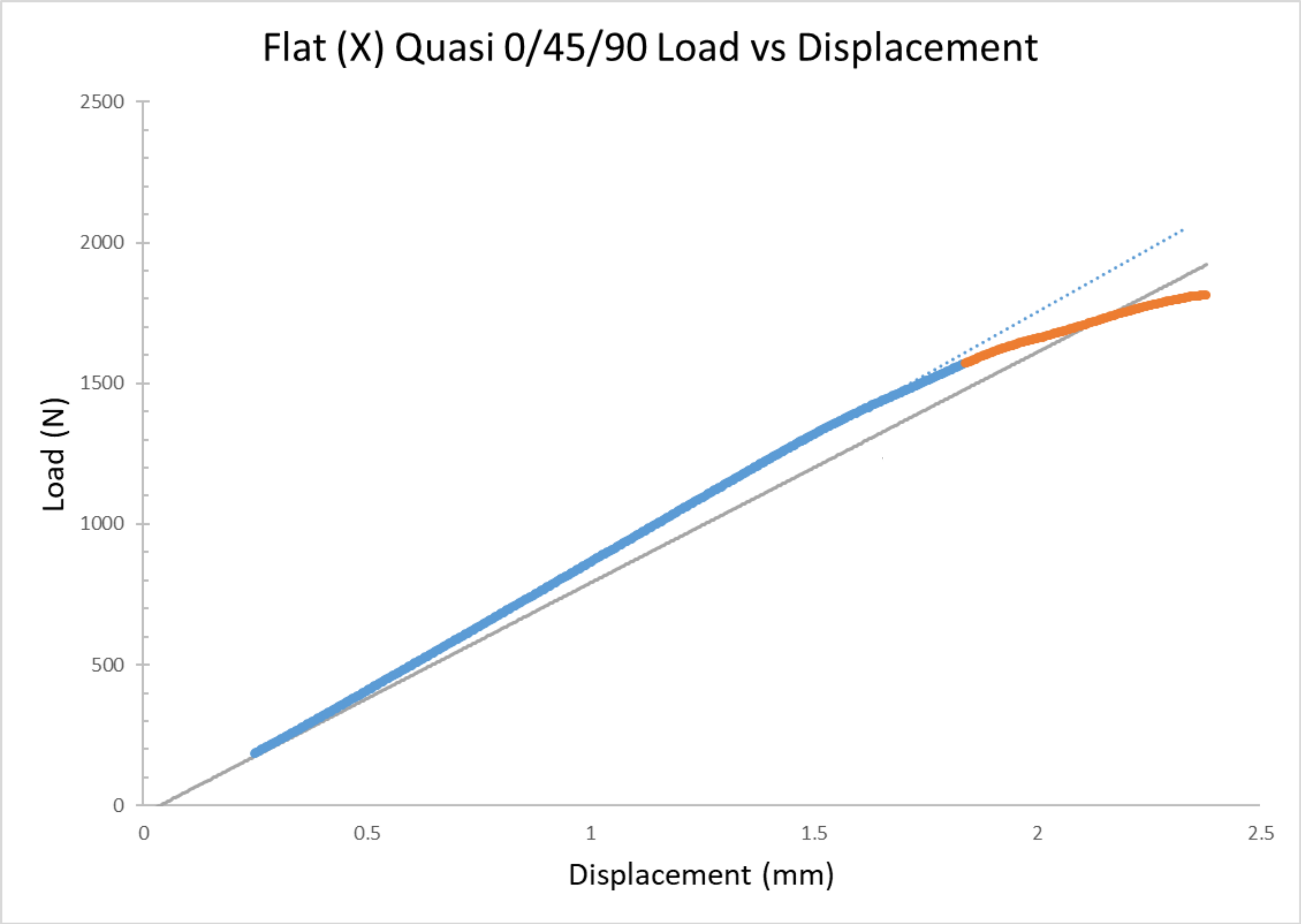
Raster	Orientation	Average	Std Dev
0/45/90	Flat (X)	63.1	1.3
45/-45	Flat (X)	62.3	0.4
60/-60	Flat (X)	59.7	2.0
0/90	Flat (X)	54.9	1.5
45/-45	Upright (Z)	54.6	2.4

***n=3**



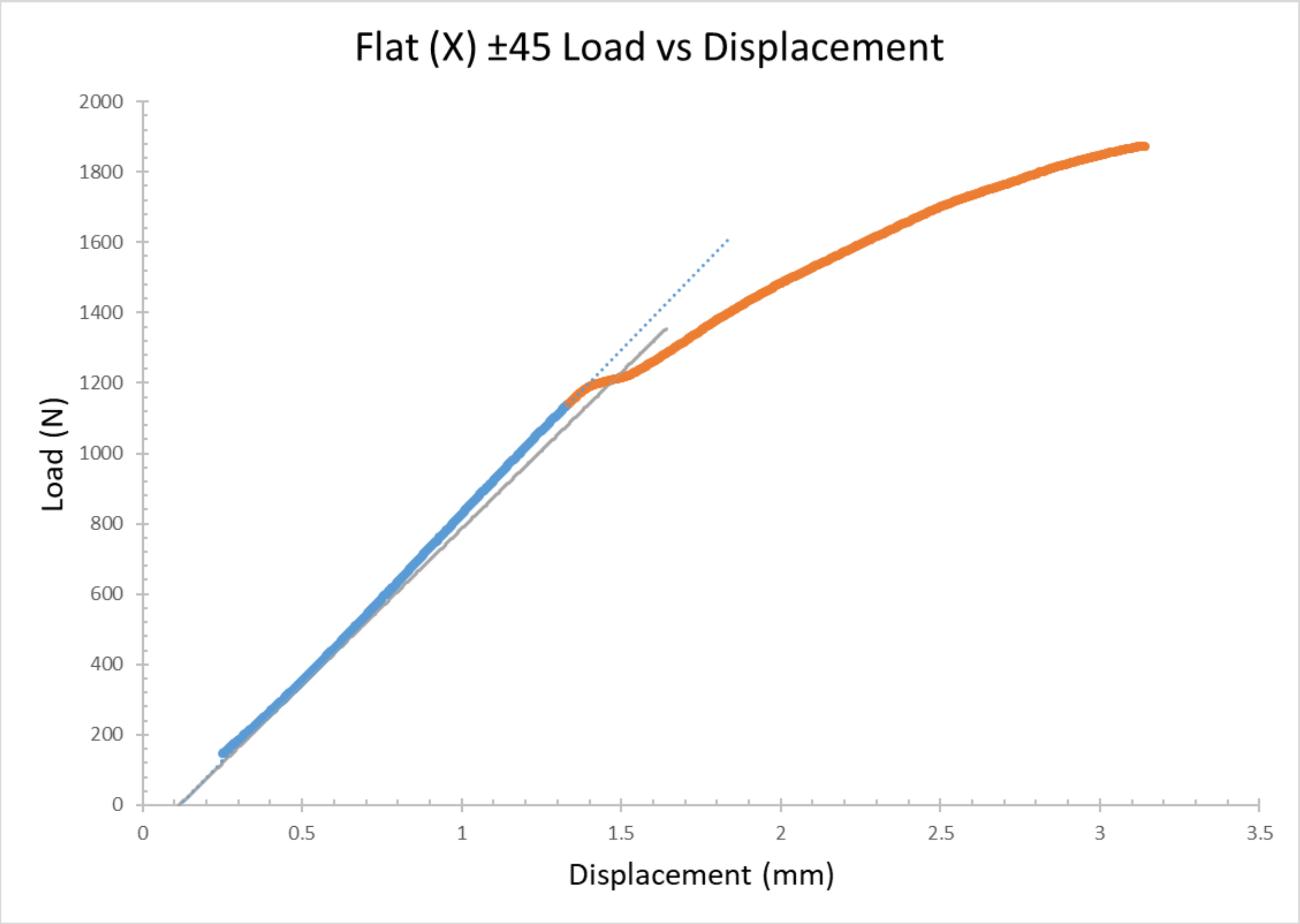
- ASTM D638 Type 1 tensile coupons
- Testing followed ASTM standard requirements
- Differences in raster orientation and build orientation impacted yield strength

Preliminary Results



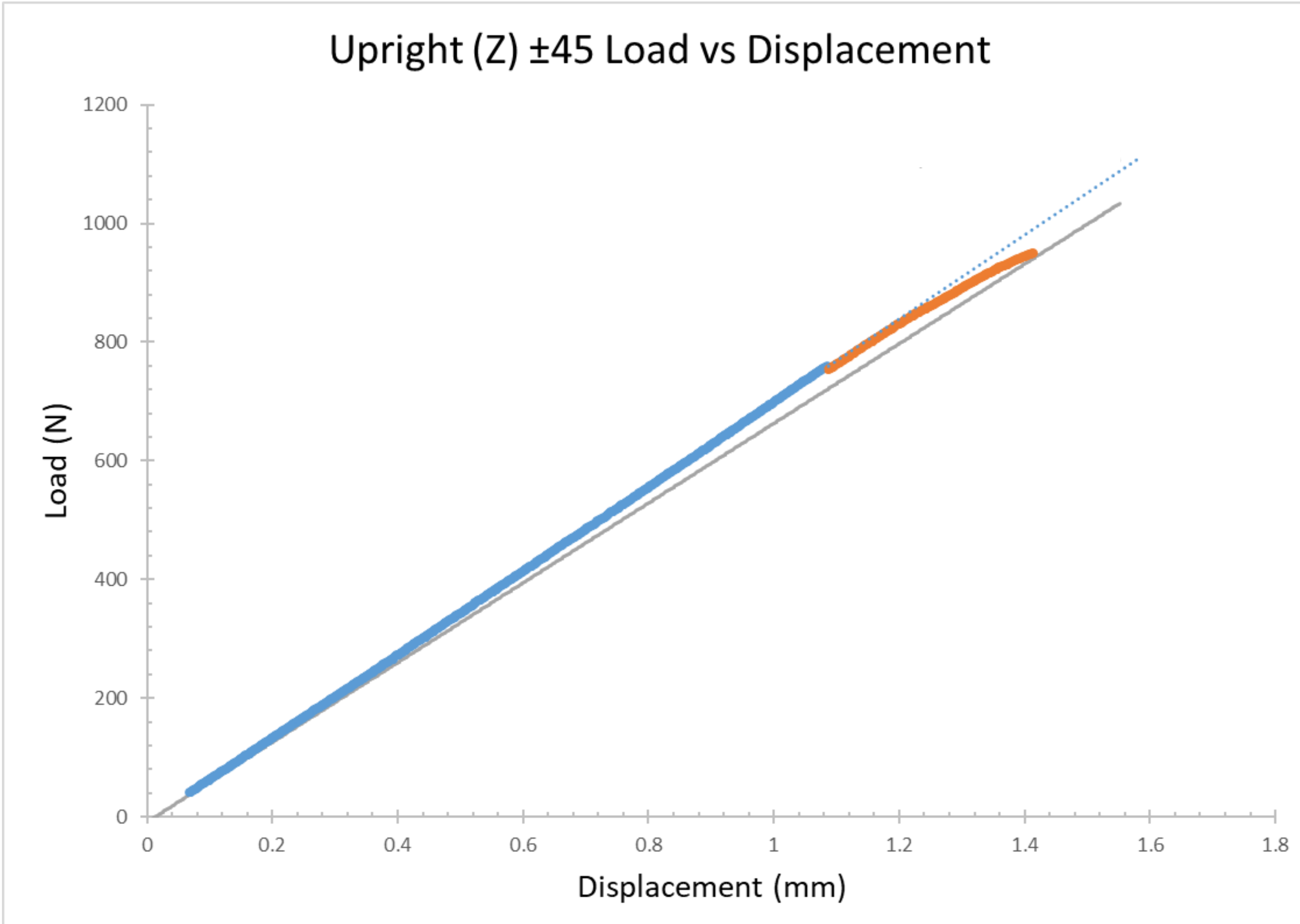
$$K_{I_C} = 4.46\ {}^{MPa}/_{m^2}$$

Preliminary Results



Invalid Test

Preliminary Results



$$K_{I_C} = 2.59\ {}^{MPa}/_{m^2}$$

Evaluation of Test Method Suitability

- Originally tried to get the crack using a scraper with a plastic handle but that broke from the hammer, switched to one with a metal tang through the handle
- Before we fixed the crack issue, there was too much yielding in the parts, invalidating the max load according to the spec

Recommendations

Lessons learned

- Getting the proper natural crack before testing was important
- Dial in the loading rate to get the proper time to crack
- Print more coupons
- The extras allow you to dial in the loading rate
- Adjust testing rate outside of ASTM D638 requirements

Continuing Work

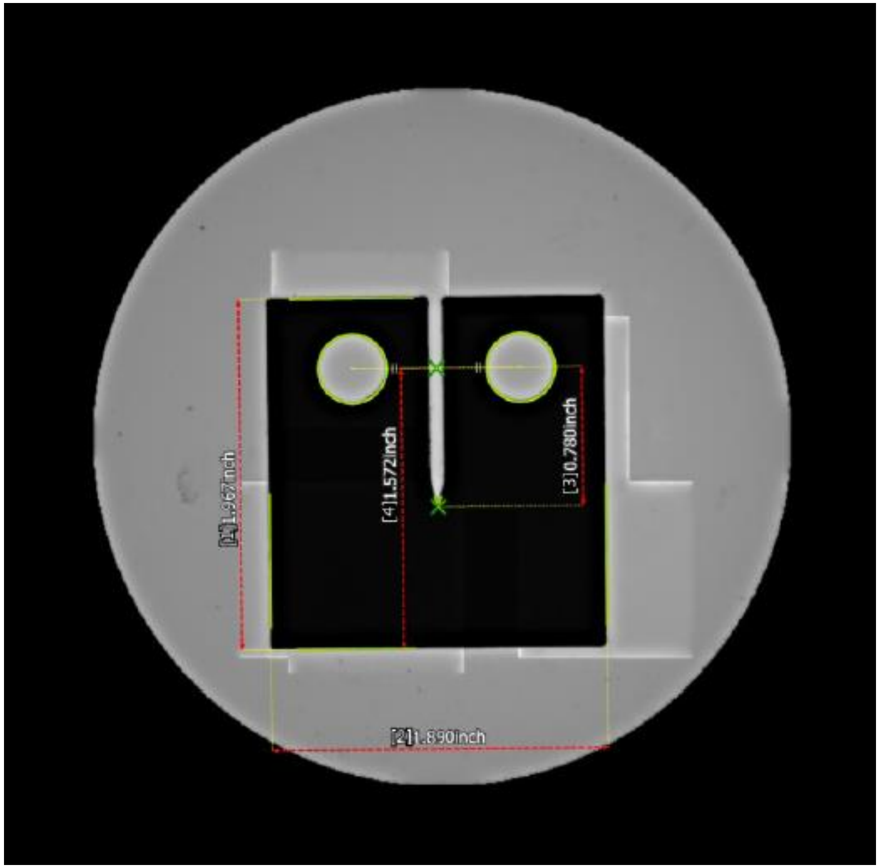
- Continuing testing to complete matrix
  - Making modifications as needed
  - Repeat any testing with optimized test conditions
- Double lap shear testing
- Repair design development
- Demonstration/Validation of repair concepts

Questions?

Back-up

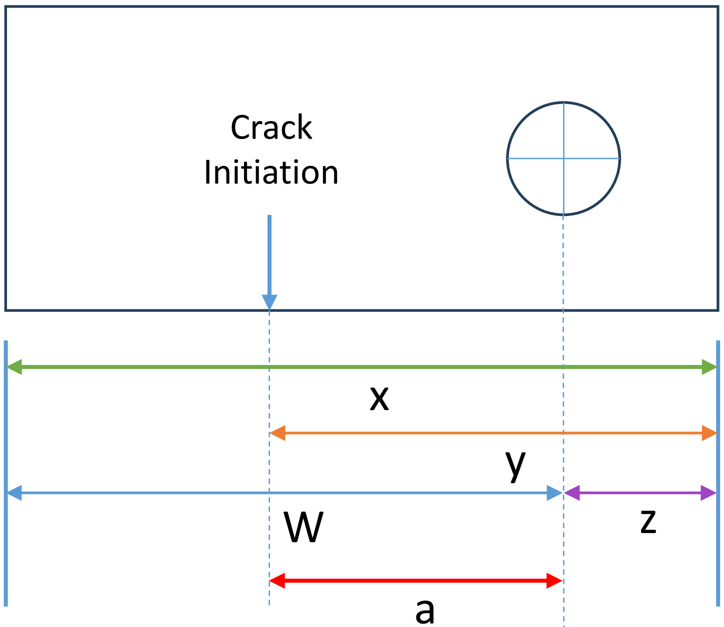
Measurement Technique

- An optical comparator was used to get the measurement of the W for all the specimens



Measurement Technique

- The measurement of a was easier to get after breaking the coupons. So, it was measured with calipers.



$$x - W = z$$

$$y - z = a$$

References

ASTM International. *Standard Test Method for Tensile Properties of Plastics*; ASTM D638-22; West Conshohocken, PA, 2022. DOI: 10.1520/D0638-22

ASTM International. *Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials*; ASTM D638-22; West Conshohocken, PA, 2022. DOI: 10.1520/D5045-14R22.

ASTM International. *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials*; ASTM E399-23; West Conshohocken, PA, 2023. DOI: 10.1520/E0399-23