Fiber optic mesh for 2D strain characterization

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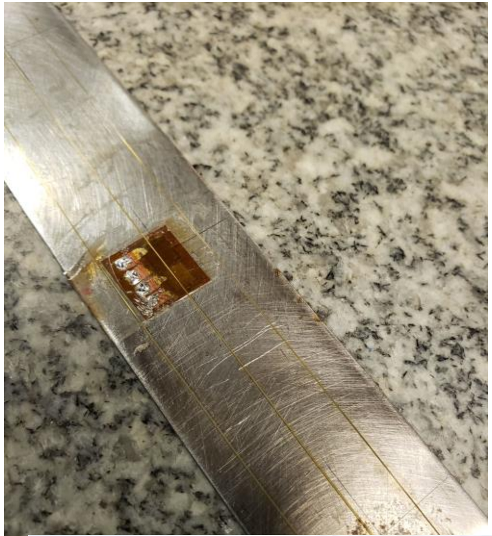
Introduction

Per the previous talk by Maria, we working on applying fiber optic strain and temperature sensors to superconducting magnets.

- **Maria was approached to see if a fiberoptic strain sensor could be used to validate a pi tape measurement of shell strain during QXFA helium vessel welding**
- **It is likely that this could have been handled well with a couple strain gages**
  - Singular strain gages are boring and prone to errors from application, interpretation or mechanical inconsistencies.
- **To be rather conservative and have a few additional measurement points, we decided to use two 10 m fibers, sampled at 0.62mm gage pitch for ~32,000 "gages" instead**
  - How much information can we squeeze out of this technology?



Killing a fly with a sledgehammer

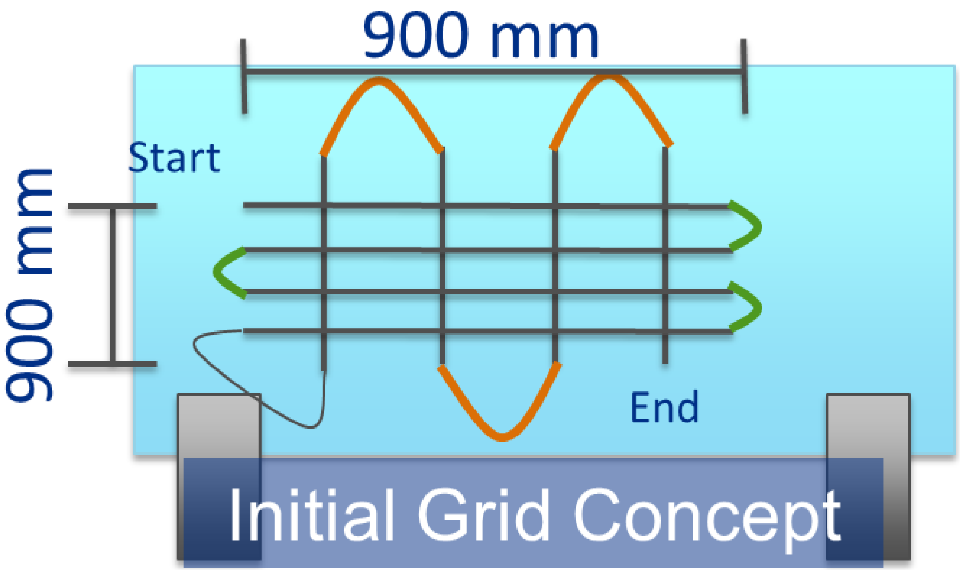
Fiber-optic sensors offer “gigantic” measurement bandwidth

- **Luna Rayleigh system will sample 32000 gages 12.5 times per second**
  - ~384000 16ish bit strain measurements per second
  - 768 KB/s/ (12Mbps, ~2 streaming movies on Netflix)
- **How can we best utilize this bandwidth?**
  - Most applications to this point have used the fibers in a 1-dimensional fashion
  - Extending to higher dimensionality better utilizes the capabilities of the system

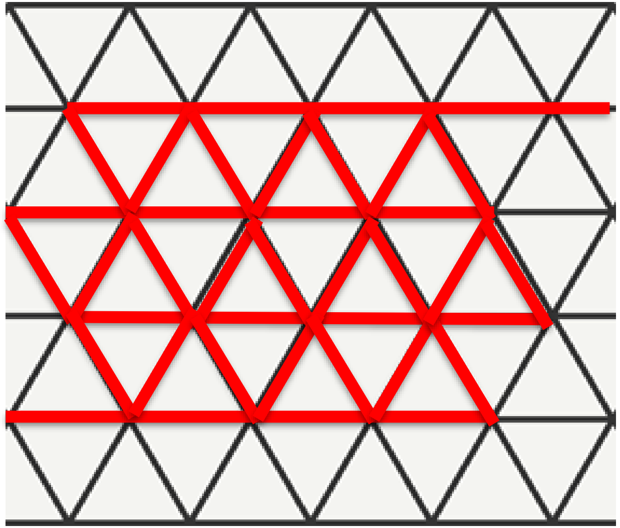
Initial Concept: Finding a bigger fly

The "goal" of the measurement is to determine the average azimuthal strain in the shell.

- **Measurements through time add an additional dimension**
- **Longitudinal strain is also likely to occur in this situation.**
  - Add an additional direction of the fiber to better characterize the strain on the surface
  - However, this is not a well-defined unidirectional load case, so we are still missing information



Isometric Generic Strain Sensing



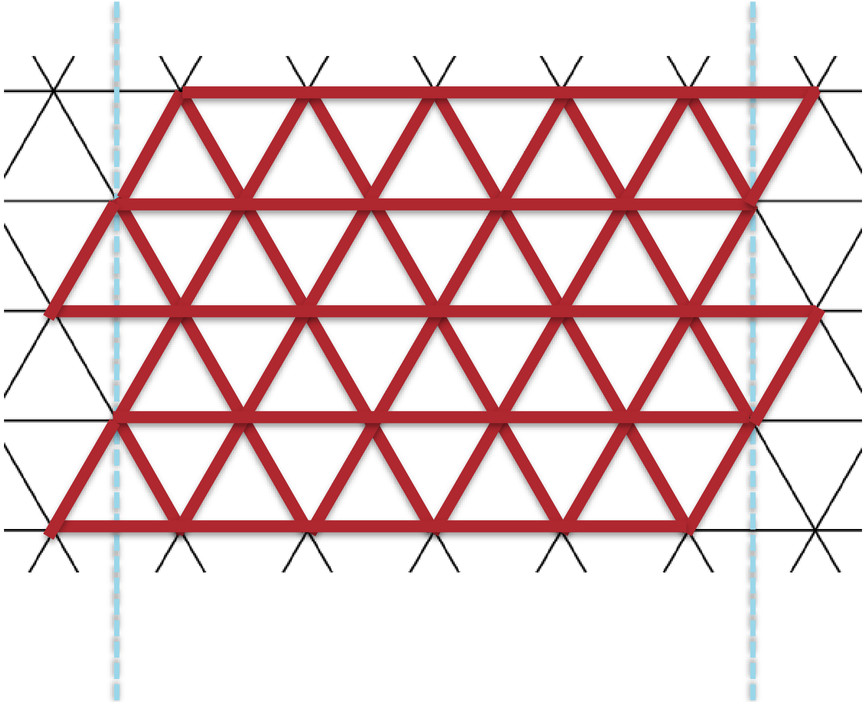
- Adding a 3rd direction of strain measurement allows full resolution of the 2D strain state of the surface. (Principle strains magnitude and orientation)

- For a single fiber, the system lets you map start and end points of gage sections
- Define gage segment orientation
- Interpolate X-Y grid at moderate resolution for each gage direction
- Plot each gage direction
- Calculate strain state between interpolated data

- Repeat above through time steps, either with decimation, filtering or individually as desired.

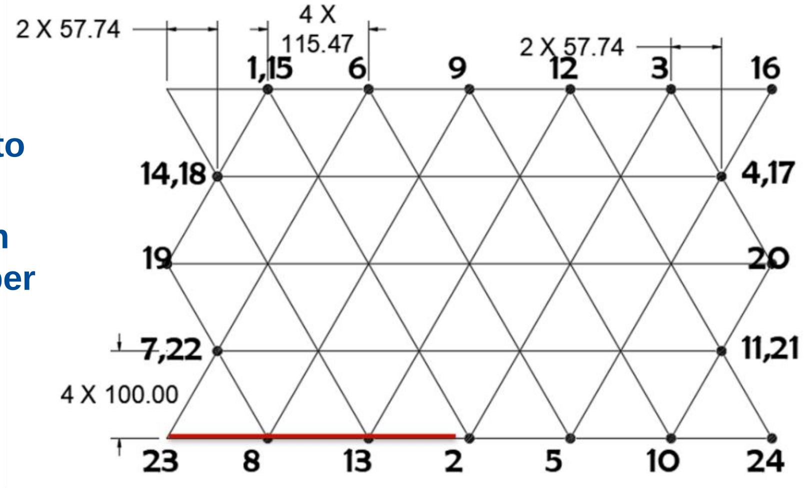
Defining a pattern

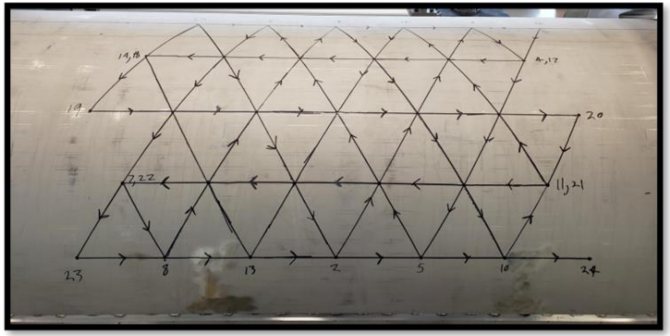
- Shell Diameter is ~620mm
  - ¼ symmetry, instrument ~486 mm of arc length
  - 4 vertical sections of 121mm, segment length of 121/(sqrt(3)/2) = 141 mm
    - 4 x 6 x '/'
    - 4 x 5 x '\'
    - (4 x 5 +1 x 6)x '-'
    - 55 total segments, 7.56m
- 115mm long segments to cover 4X18 degrees of shell
  - 6.325m
  - Maybe we can do another refinement

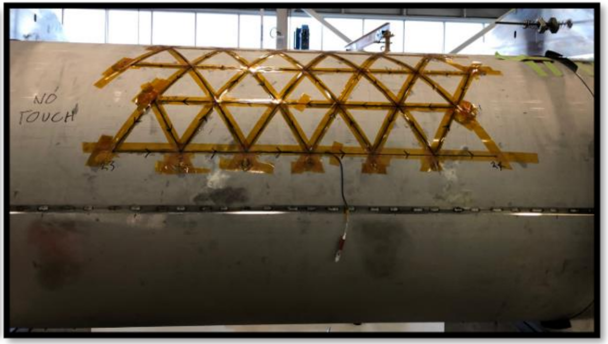


Template drawn for laying out gages

- Pattern above drawn in cad and printed 1:1 for positioning
- Holes punched at each crossover location to mark on shell
- Played a quick game of connect the dots on the shell, 1st with a marker, then with the fiber
- Fiber taped at edges, painted with araldite two part epoxy then taped along length.
- After epoxy curing, points were located by cold cotton swab

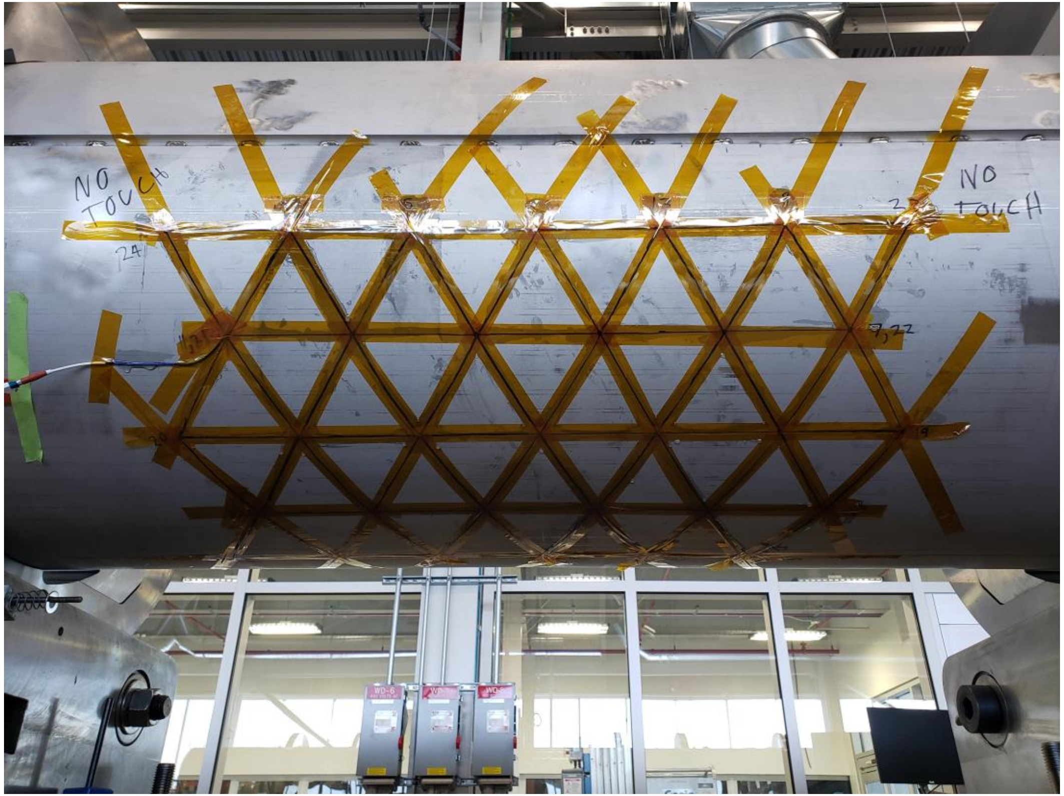






Fiber Installation on Shell

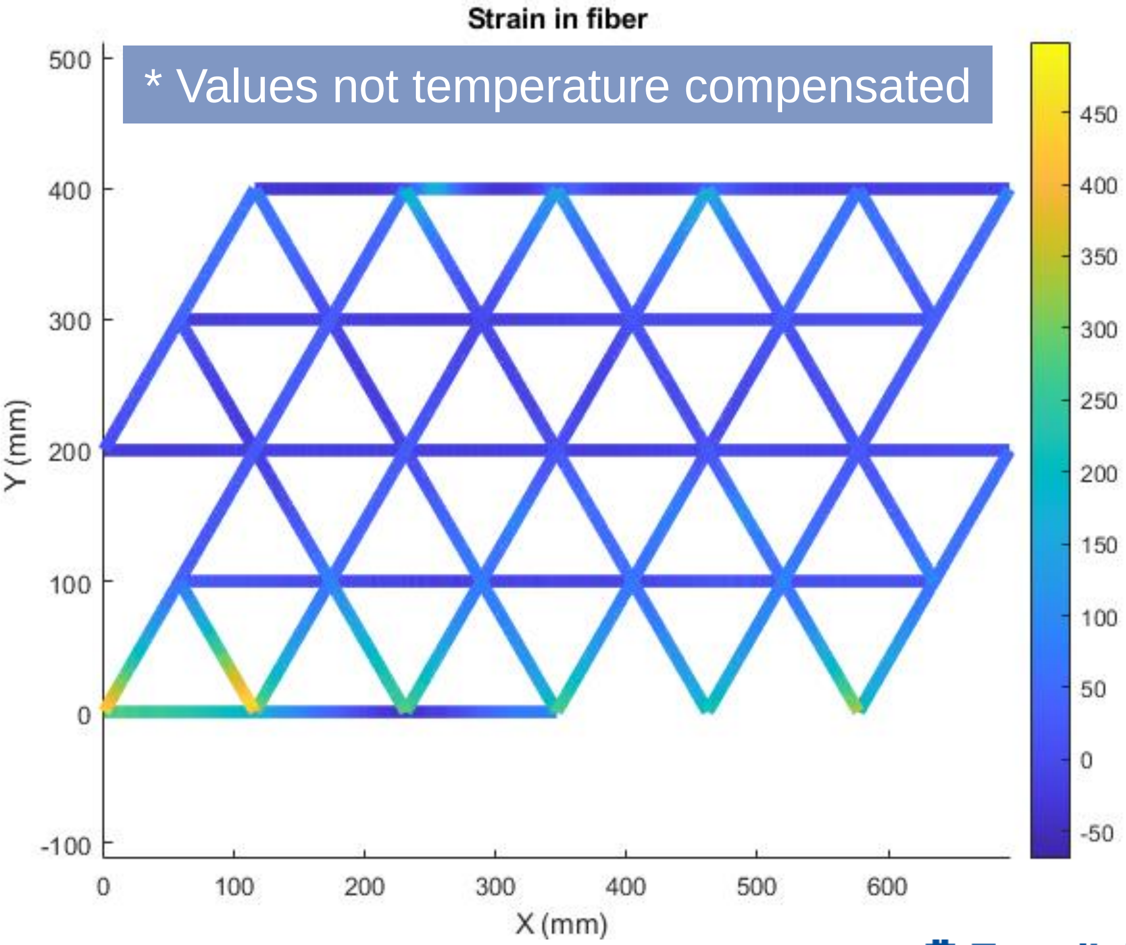
- **Fibers were installed on both upper and lower shell halves**
- **Installation went smoothly, perhaps 8 hours labor after template provided**
  - Not bad considering usually around 1 hour per individual gage
- **Broke lower fiber on insertion into welding tooling**
- **As far as instrumentation goes, fibers are quick to install and mostly noninvasive**
- **There was a concern voiced about strain at crossover regions, but our data has no evidence of discontinuities.**



Preview of a dataset

- There are lots of ways to present the data from these sensors, hopefully we can present it in an easy to interpret fashion
- Data a short time after the 1st pass is shown.
- Weld is at roughly -100 mm
- Note: We ran out of fiber just before the end so we didn't have longitudinal coverage from ~350 to 600mm on the Y=0 segment

- Tare data from this pass is used to normalize later plots

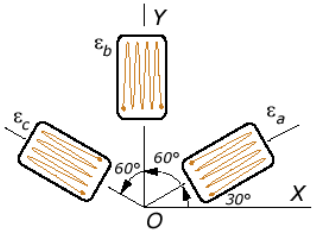


After obtaining strain measurements in 3 directions, each direction is interpolated onto a rectangular grid

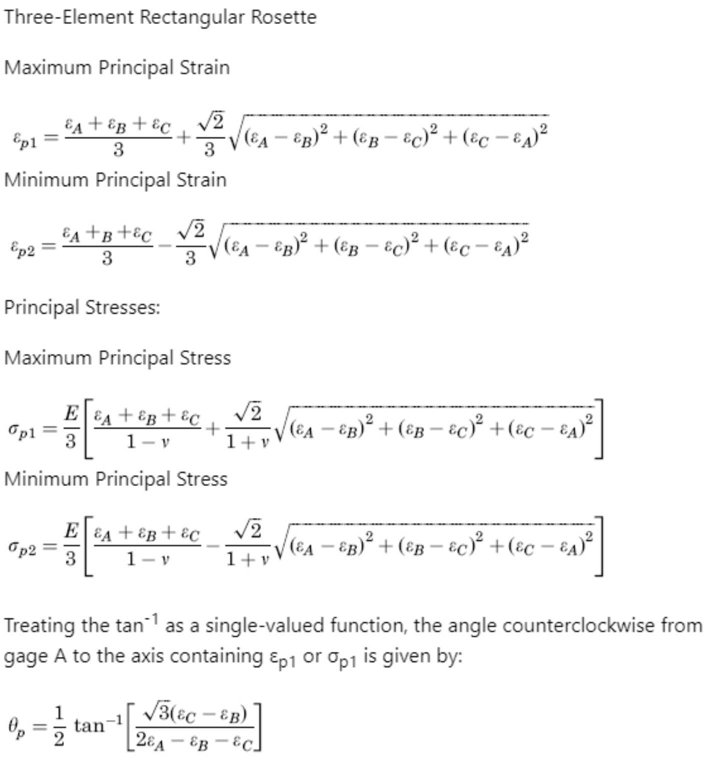
- **Interpolation only valid within area bounded by points with all directions measured**
- **Principal strain calculated on grid**
- **X strain is the 0° orientation fiber**
- **Y strain is calculated as $\frac{2}{3}$(60° + 120° - 0.5 * 0°)**

After loading the dataset, most operations are linear and calculate very quickly. (sub ms per sample)

Case 2: 60º strain rosette, the middle of which is aligned with the *y*-axis, i.e., α = 30º, β = γ = 60º.



$$\begin{cases} \varepsilon_x = \frac{2}{3}\left(\varepsilon_a - \frac{1}{2}\varepsilon_b + \varepsilon_c\right) \\ \varepsilon_y = \varepsilon_b \\ \varepsilon_{xy} = \frac{1}{\sqrt{3}}(\varepsilon_a - \varepsilon_c) \end{cases}$$



Three-Element Rectangular Rosette

Maximum Principal Strain

$$\varepsilon_{p1} = \frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{3} + \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2}$$

Minimum Principal Strain

$$\varepsilon_{p2} = \frac{\varepsilon_A +_B + \varepsilon_C}{3} - \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2}$$

Principal Stresses:

Maximum Principal Stress

$$\sigma_{p1} = \frac{E}{3}\left[\frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{1 - v} + \frac{\sqrt{2}}{1 + v}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2}\right]$$

Minimum Principal Stress

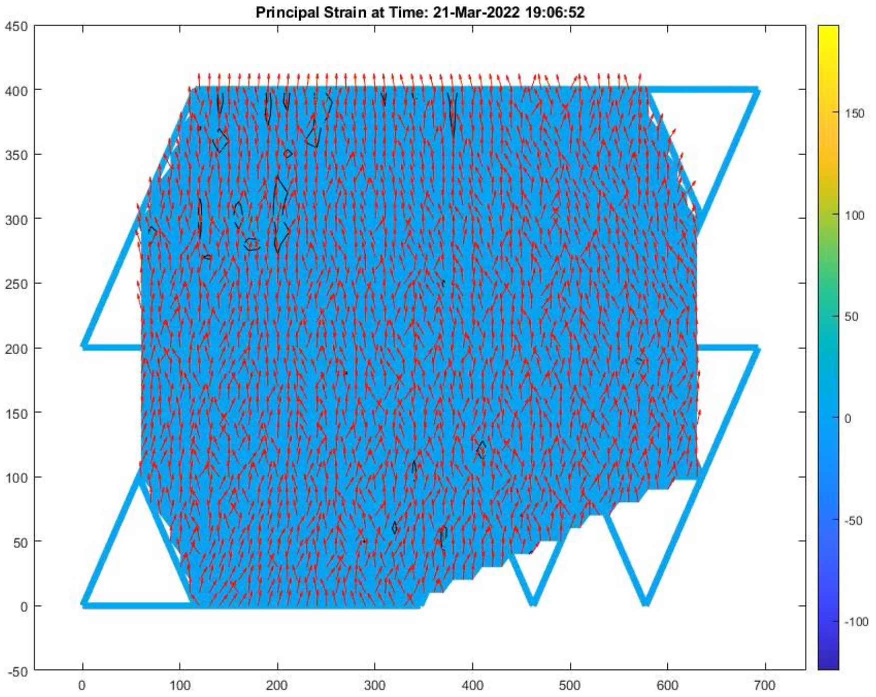
$$\sigma_{p2} = \frac{E}{3}\left[\frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{1 - v} - \frac{\sqrt{2}}{1 + v}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2}\right]$$

Treating the $\tan^{-1}$ as a single-valued function, the angle counterclockwise from gage A to the axis containing ε_{p1} or σ_{p1} is given by:

$$\theta_p = \frac{1}{2}\tan^{-1}\left[\frac{\sqrt{3}(\varepsilon_C - \varepsilon_B)}{2\varepsilon_A - \varepsilon_B - \varepsilon_C}\right]$$

Pass 1 Video Principal

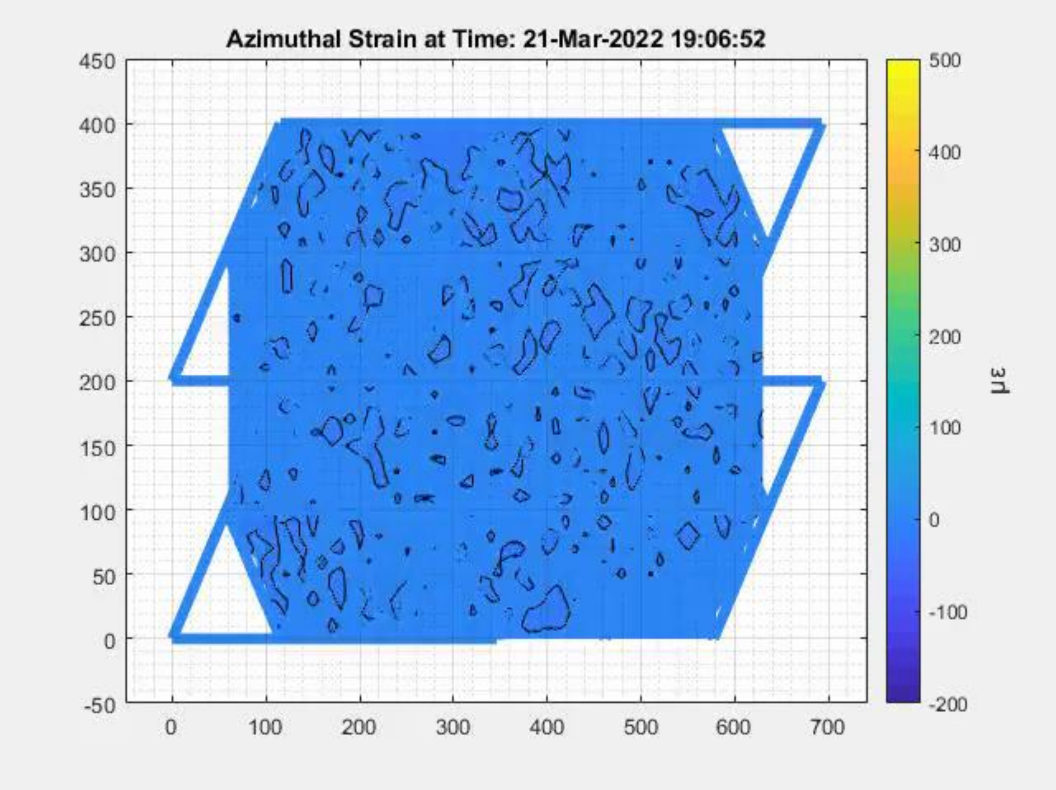
- Fiber strain shown by colored lines following layout.
- Principal Stress calculated as a function of all 3 strain directions.
- Vectors indicate direction of principal stress, which is primarily azimuthal
- Welding occurs from left to right, and strain map reflects this.
- After an initial strain wave (from the welder passing the gage area, high azimuthal strain is measured, especially near the weld location at ~ -100 in Y. as the shell cools, this redistributes around the skin. The 2nd pass animation shows this more clearly as this dataset was interrupted.
- Note: The actual sample rate was 0.52 Samples/Second for all data



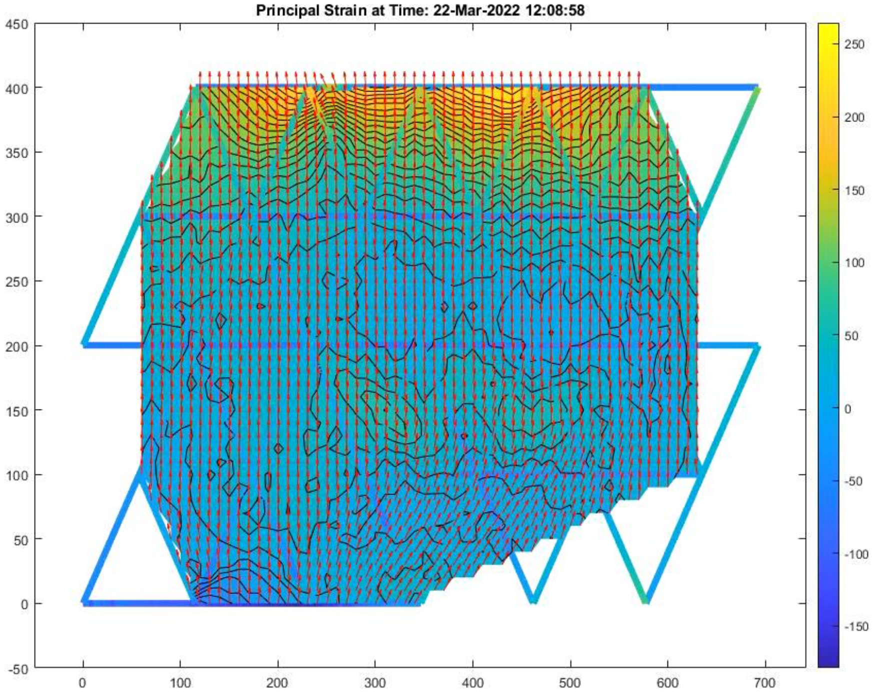
Principal Strain, Fast Video

Pass 1 Video Azimuthal

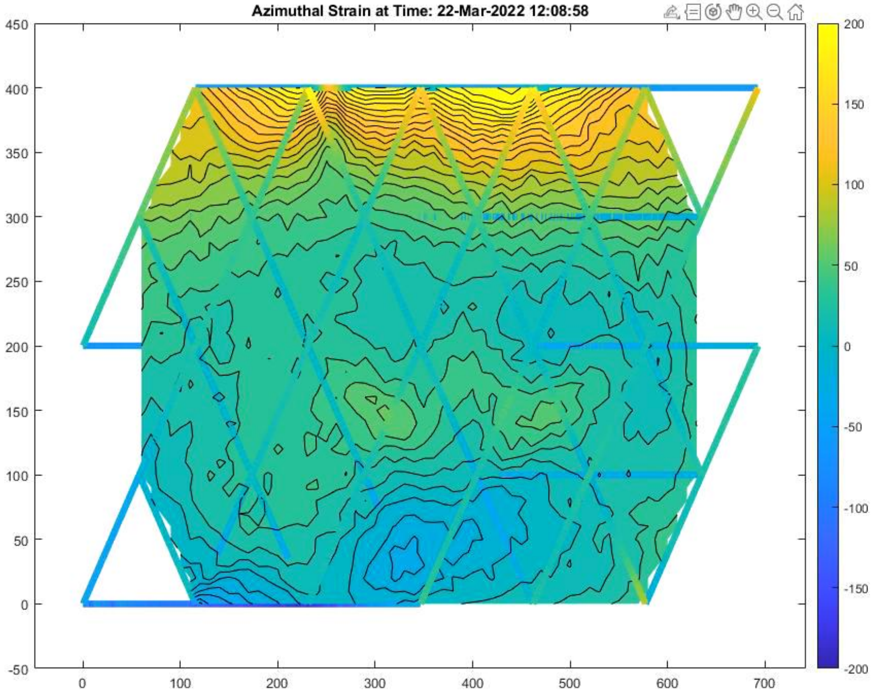
- **Azimuthal stress is calculated from 60° and 120° fibers**



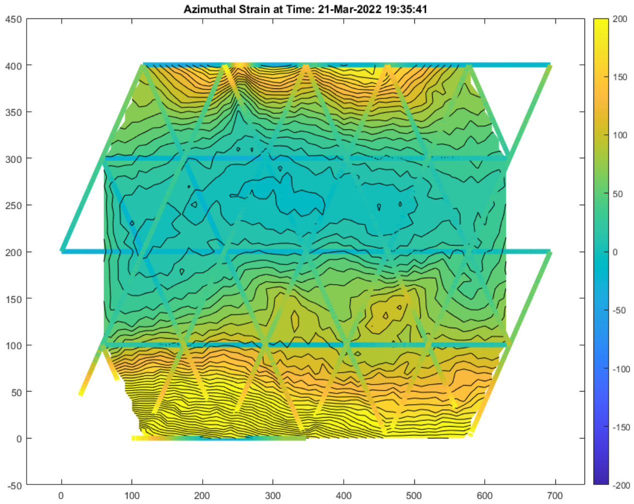
Pass 2 Video Principal

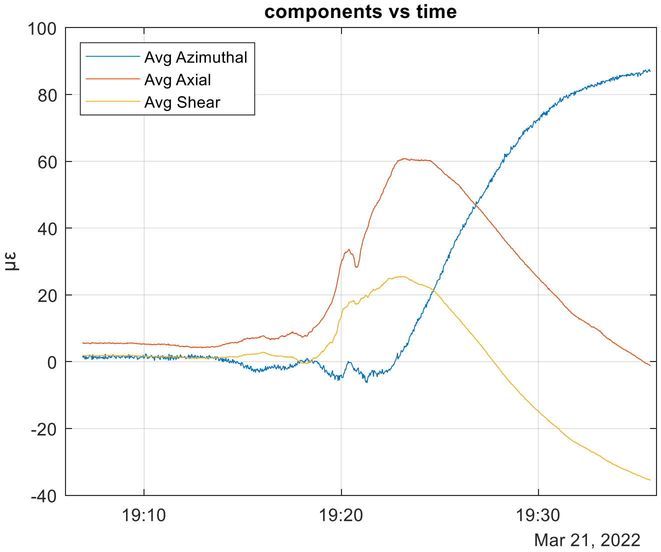


Pass 2 Video Azimuthal



1st Pass



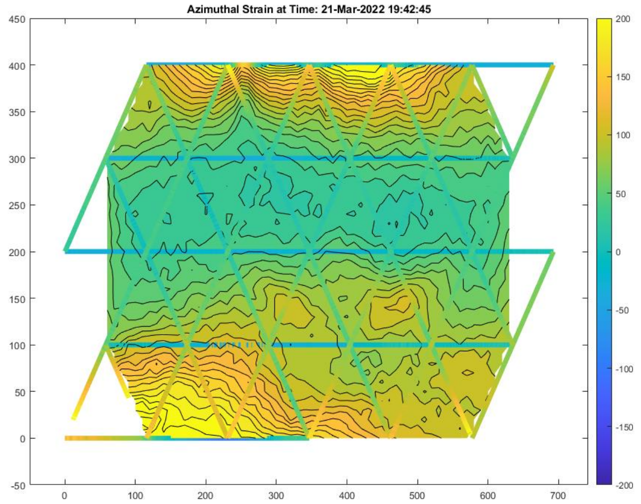


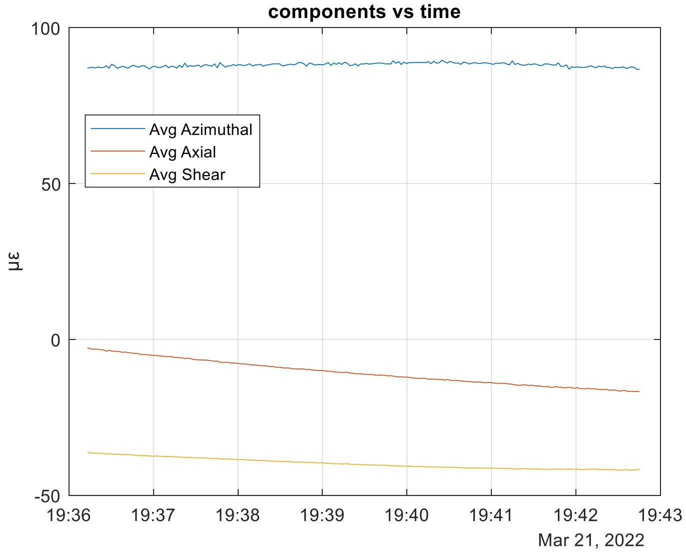
End of weld Azimuthal

Time vs average Azimuthal.

- **Azimuthal strain calculated by all points shown in grid**

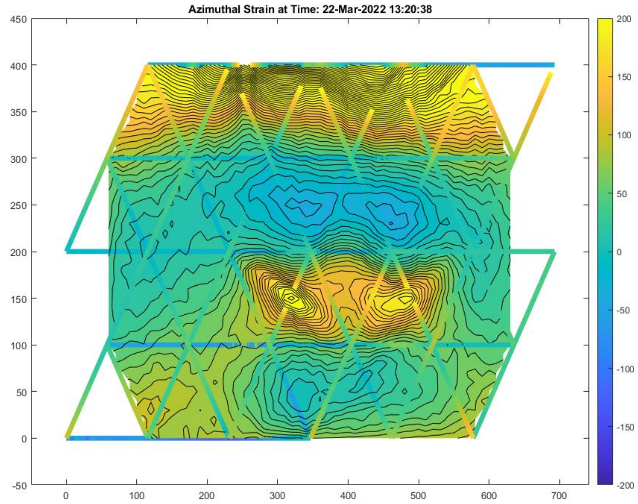
1st Pass after cooling some more

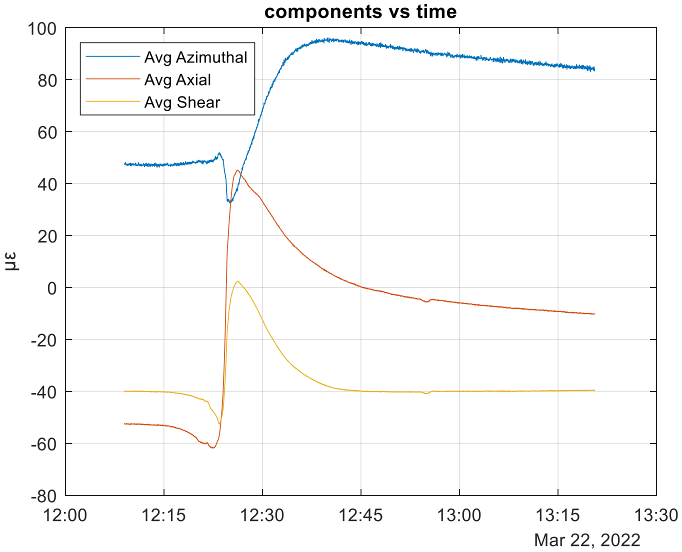




Recording was paused briefly after pass 1 but resumed to capture some of the cooling

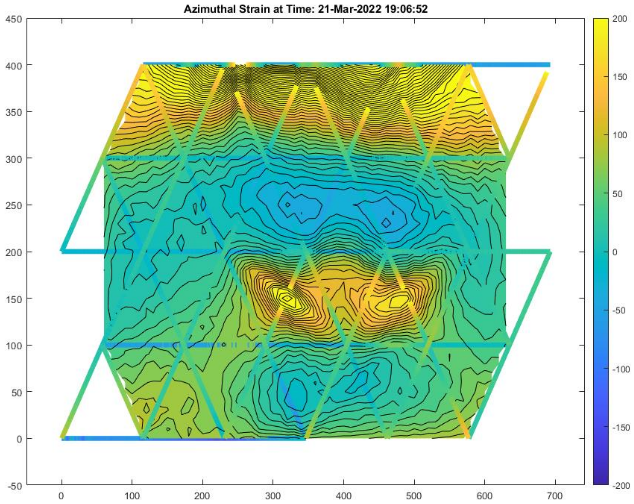
2nd Pass





2ns pass recorded following day

Before Pass 3, ignore timestamp, had to patch data together



- Avgy = 79.7379 με
- avgX = -14.3207 με
- avgXY = -39.1052 με

3rd pass recorded later same day as pass 2

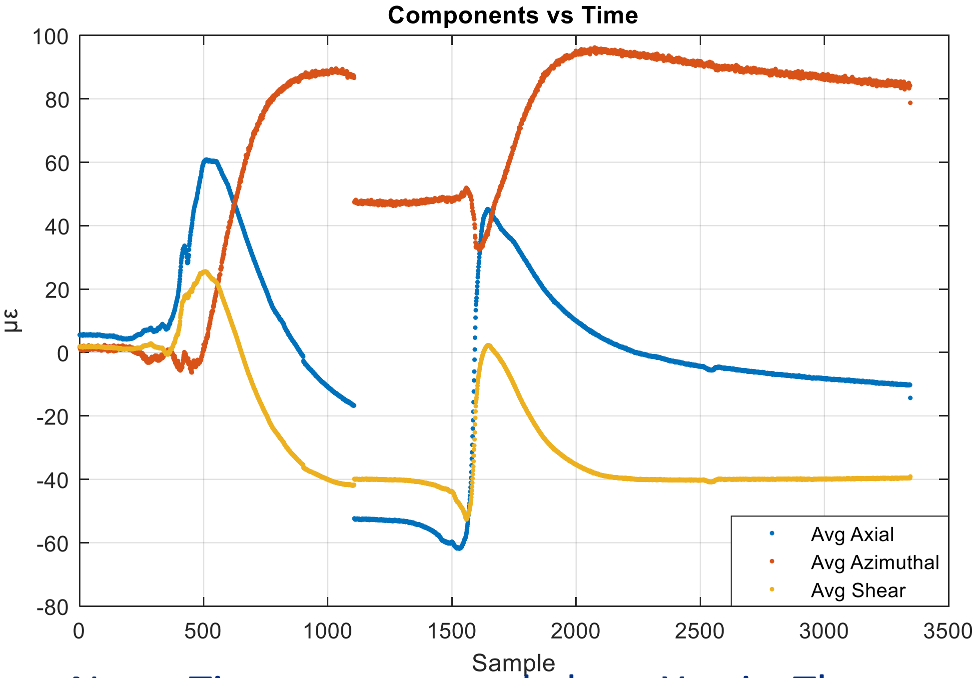
Measured values agree with calculated values.

Average Strains

All samples stitched together

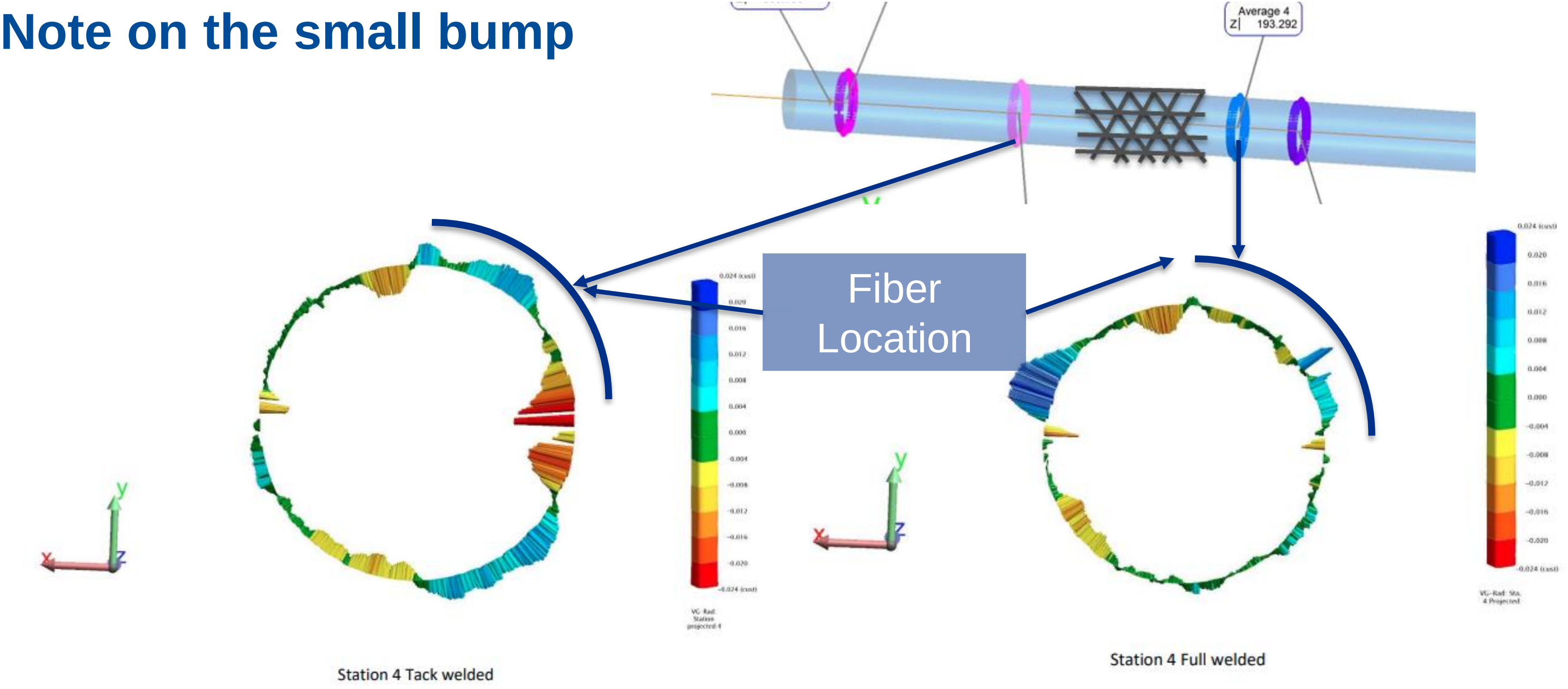
- Missing 3rd pass as fiber broke after taking tare
- Tare value from 3rd pass normalized to pre-weld tare included as final point
- Axial Strain = -14.3207
- Azimuthal Strain = 78.7379
- Shear Strain = -39.1052

- All gages together give a gage area of
  - .2246 m^2 Azimuthal
  - .2119 m^2 for Principal and others
- Compare to standard 062 gage of $3*10^{-6}$ m^2 or ~100,000 times large gage area



Note: Time compressed along X axis. The dataset spanned 2 days. Note discontinues in data

Note on the small bump



Fiber Location

Station 4 Tack welded

Station 4 Full welded

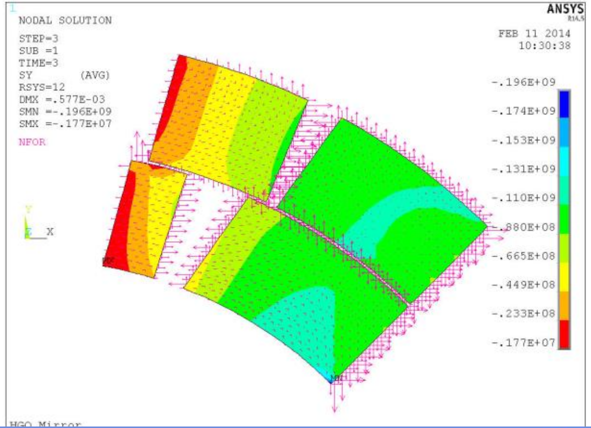
Before welding. None of these contours would be visible as we zeroed data before welding

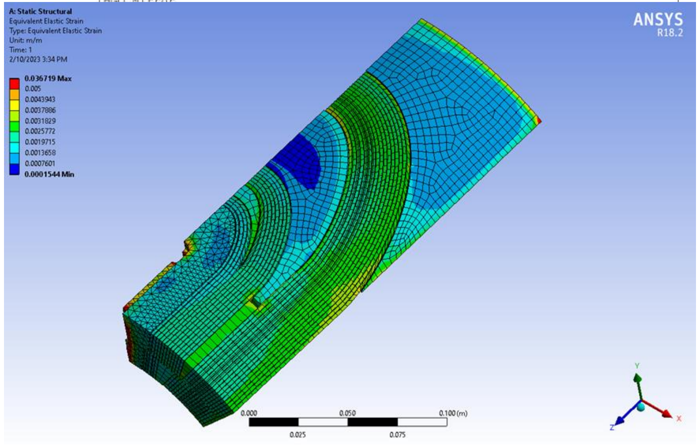
After welding, a noticeable bump can be seen on the station 4 inspection location at the same azimuthal position of the bump in the strain map.

Moving Forward: Gauges on Magnets

Can we Validate FEA in mid-section?

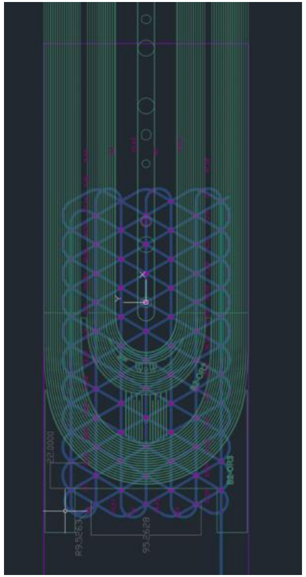
- **Fiber installation was fairly easy**
- **Visualize strain distribution in coil end**
- **Choose fiber size to allow at least some quenches to be captured at high sample rate >50 Hz, potentially at reduced N channels**
- **Can we see problems form in real time?**
  - Pole Debonding
  - Wedge discontinunity





Distributed fiber sensors: azimuthal strain map

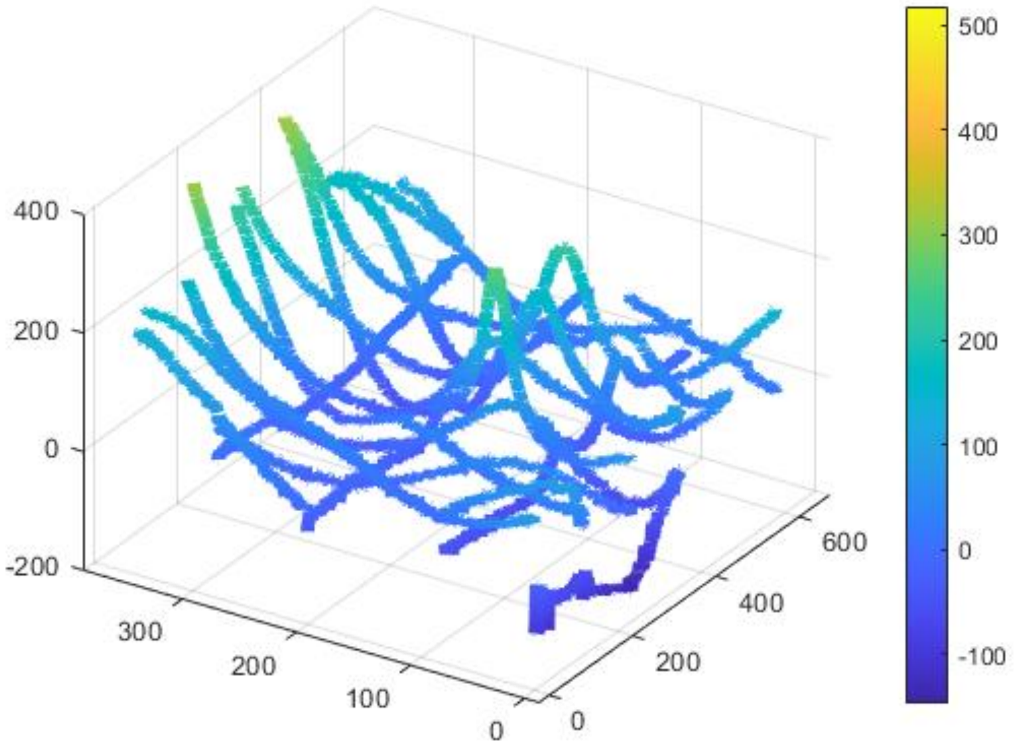
Sensors have been installed on a short QXF coil (along with other piles of diagnostics). Will be tested sometime after the AUP magnet



Fibers Installed On QXFSM03 waiting for magnet assembly

Fiber Grid Conclusions and notes

- Fiber sensors are easy to install with a low profile
- The fiber grid is an extremely powerful tool for characterizing strain on surfaces
- Fairly large fiber datasets can be represented in a clear and intuitive fashion
- Computation and analysis of datasets can be reasonably fast with some optimization (easily over 1000 samples/second) at maximum sample rate



Thank you!