Strength Measurement of Tracker Detector Composite and Titanium Structures

ITk Global Mechanics Structural Prototypes

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  - FE Analysis
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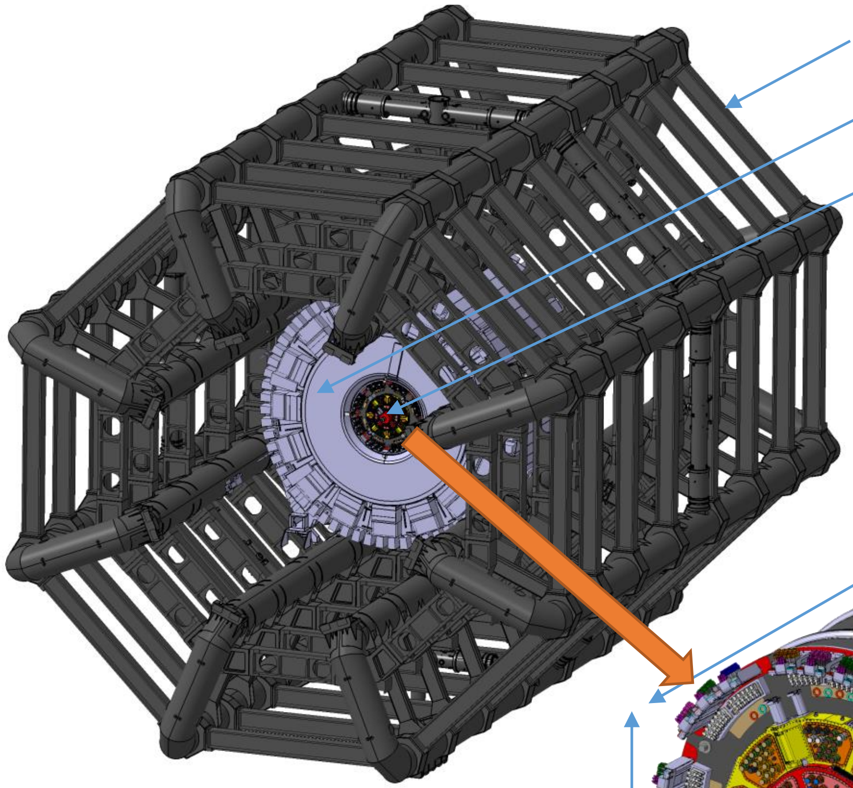
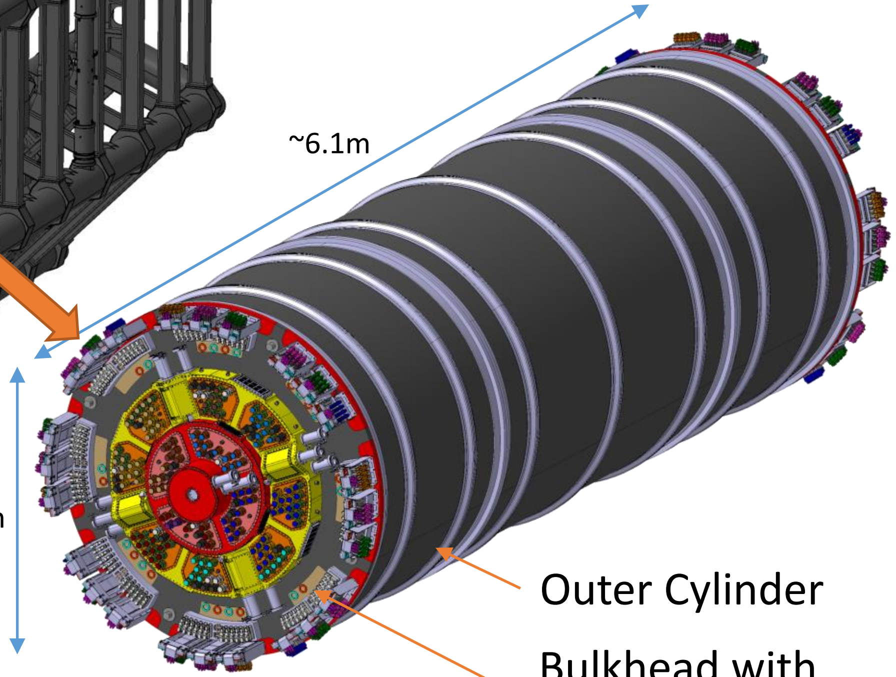
Introduction

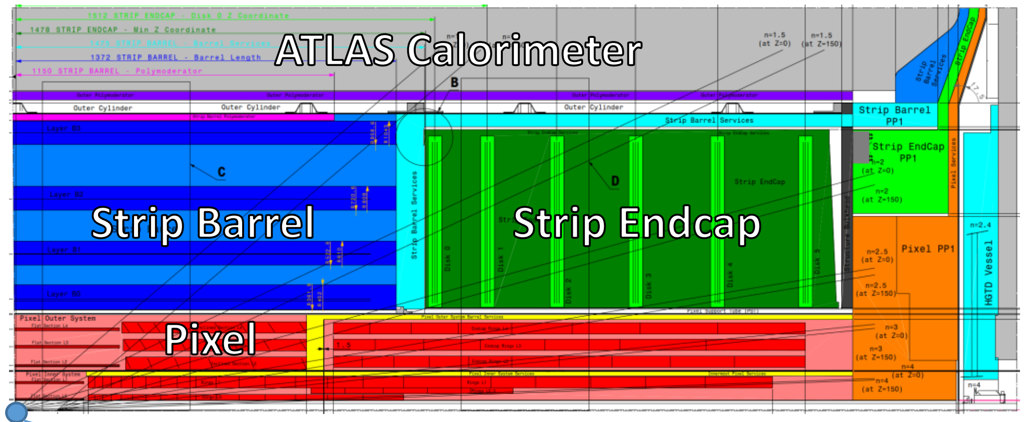
New ATLAS **I**nner **D**etektor = **I**nner **T**ra**k**cer

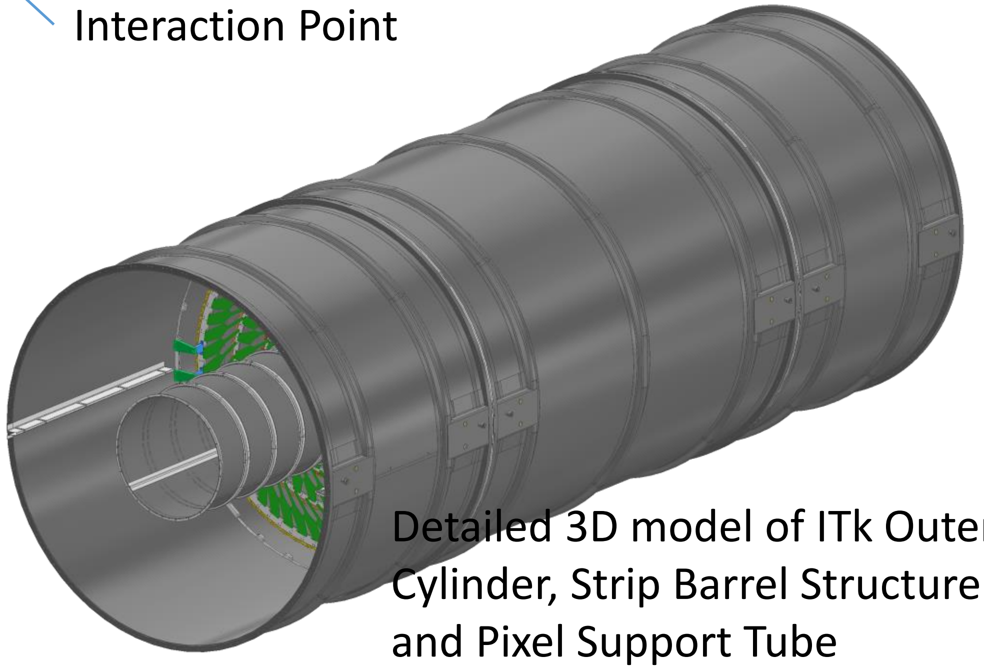


Simplified 3D model of ATLAS Experiment



Inner Tracker 3D model





Detailed 3D model of ITk Outer Cylinder, Strip Barrel Structure and Pixel Support Tube

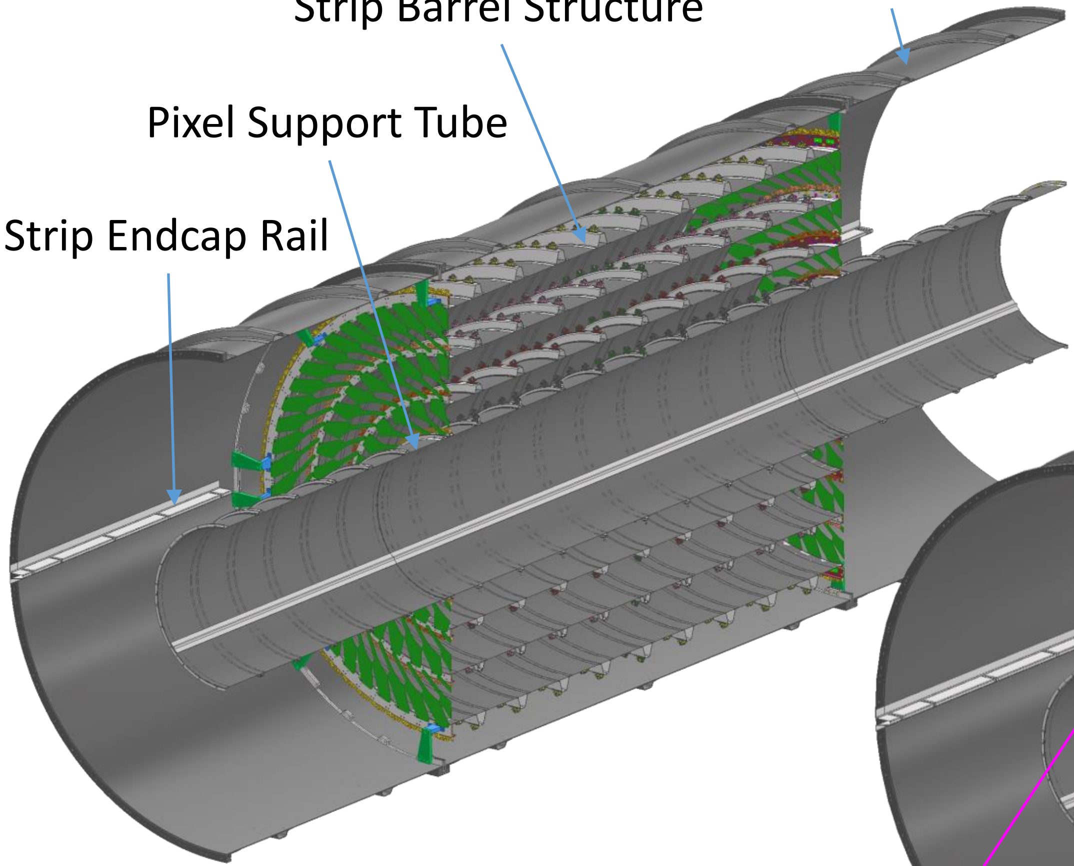
Introduction

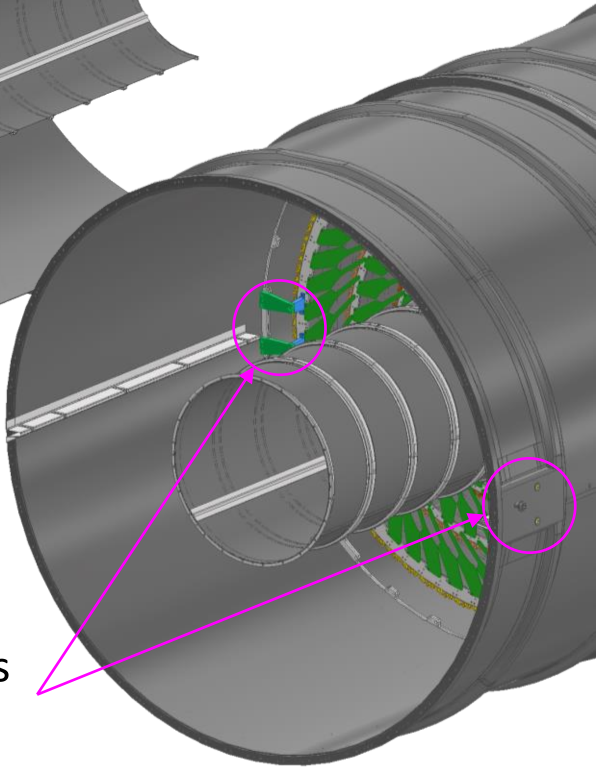
Outer Cylinder

Strip Barrel Structure

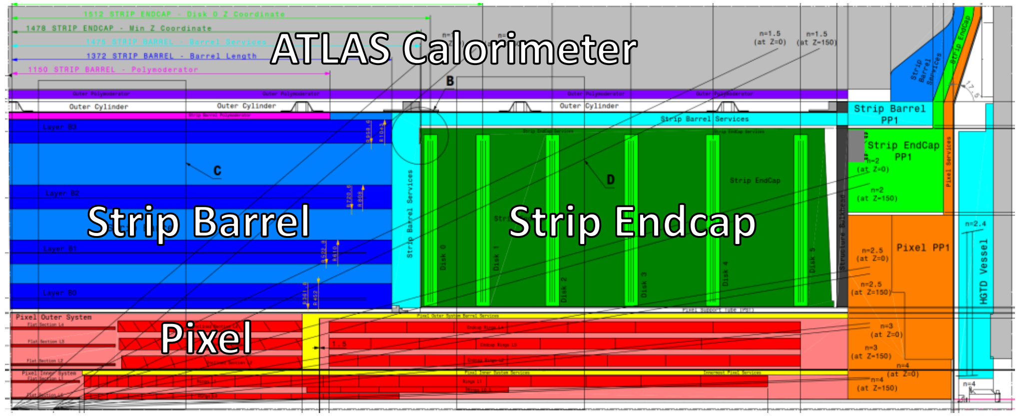
Pixel Support Tube

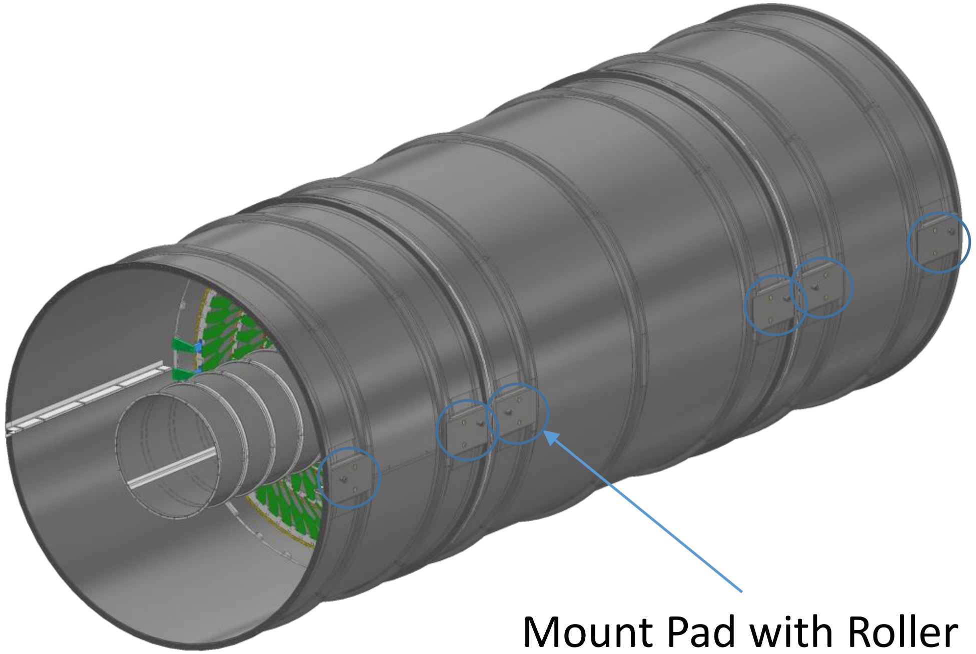
Strip Endcap Rail





Selected critical locations along load path.

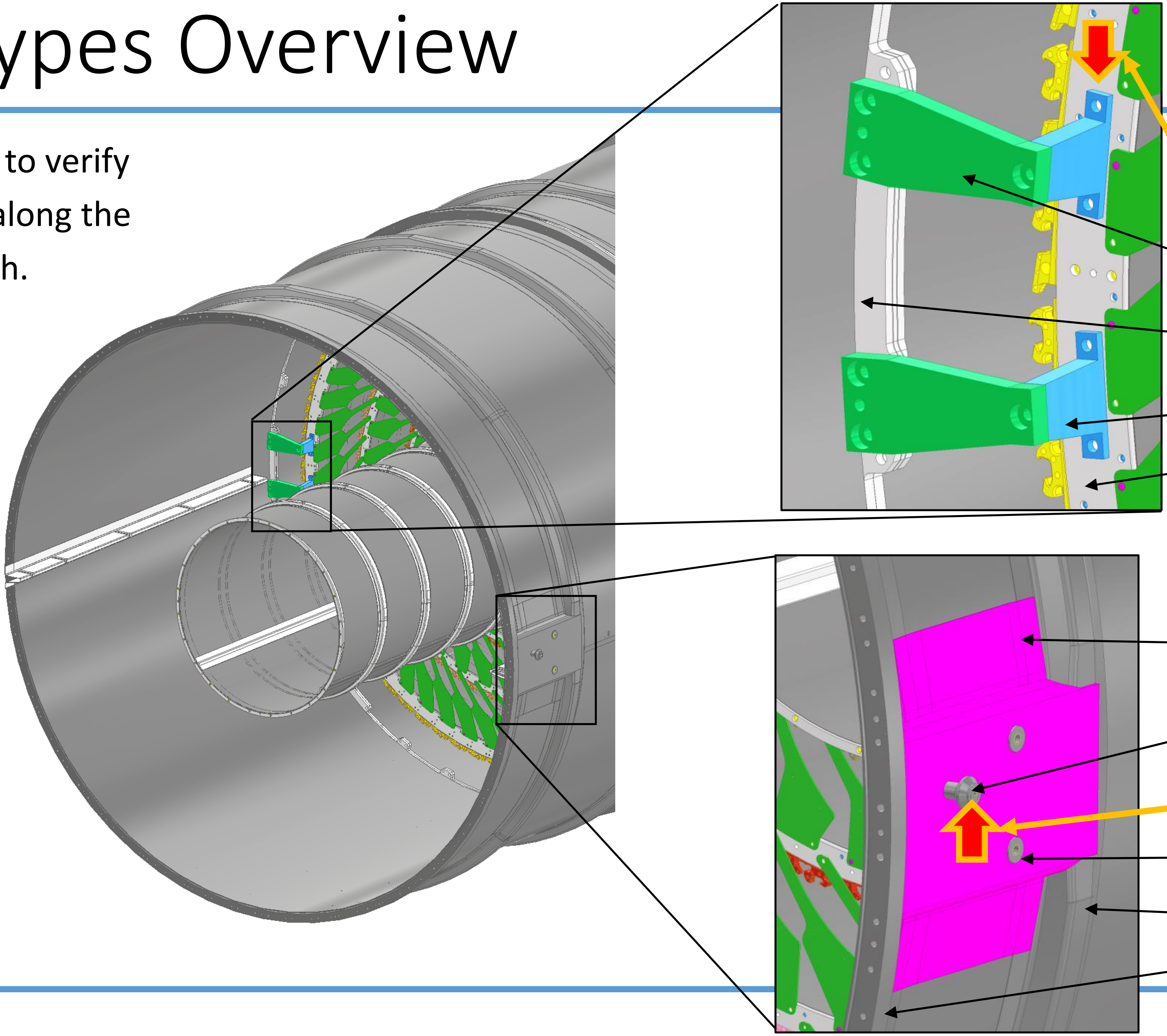




Mount Pad with Roller

Prototypes Overview

Prototypes used to verify critical location along the 'critical' load path.



- Prototype #2

Applied Load Reaction of 5kN

Titanium Bracket

Carbon Fiber Service Module Support Ring

Titanium Standoff

Strip Barrel Layer Shell

- Prototype #1

Carbon Fiber Mount Pad with CF PEEK stiffener

Titanium Roller Stud with Roller

Applied Load Reaction of 5kN

Titanium Lifting Point Insert

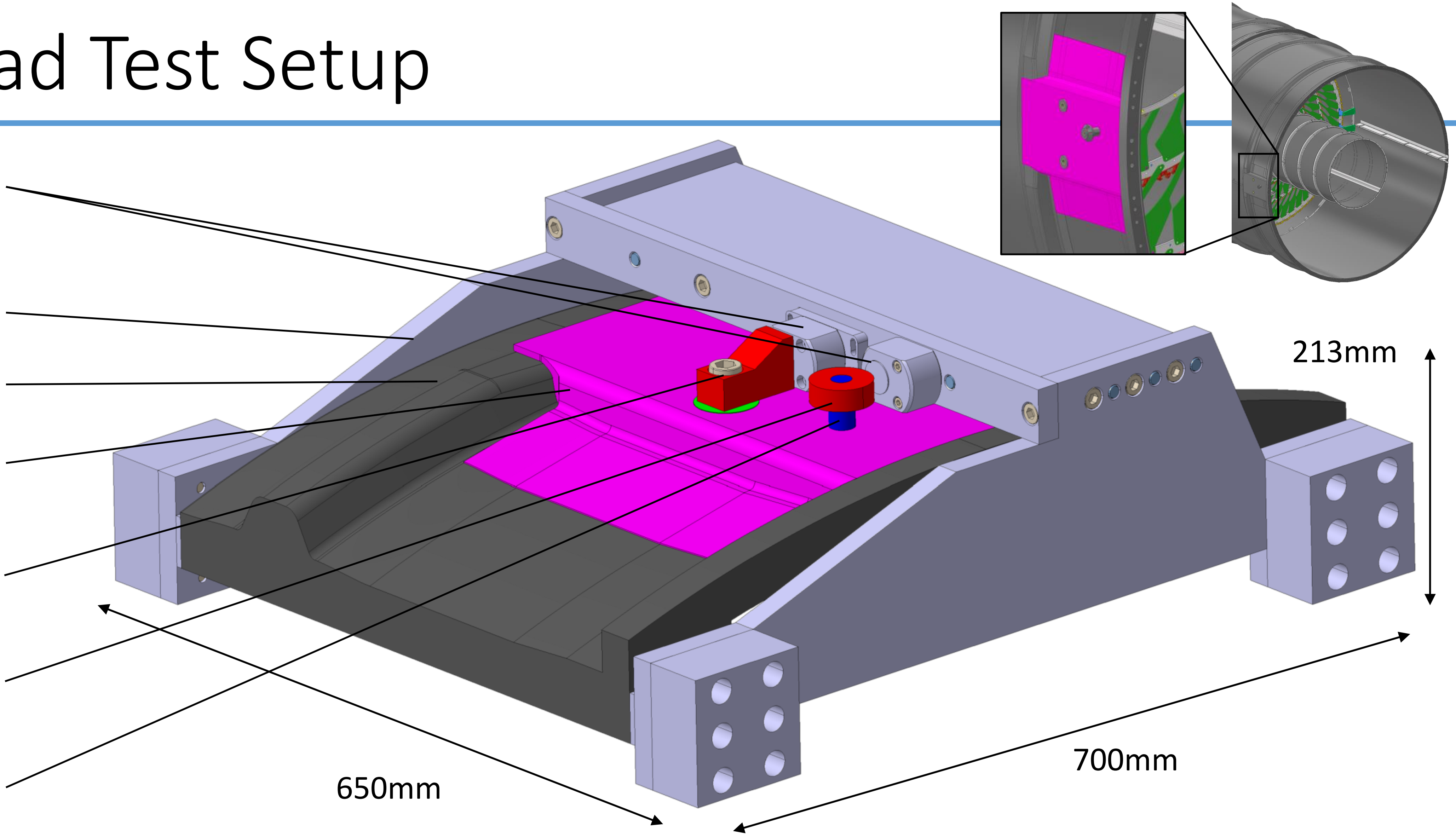
Head stiffener

Bulkhead Flange

Scope of the Experiments

- Validate the FE analysis of these critical components
  - Are our predictions for mechanical stability correct?
- Measure the failure load:
  - Difficult to predict with models – this is why we use safety factors…
  - Minimize any risk on the critical components
- Identify measurement locations for Structural Health Monitoring (SHM):
  - The aim is to use strain gauges to monitor loads (and health) of the structure during the ITk assembly:
    - Can we find a measuring spot that can give as a good indication of the load level on these critical components?
    - Can we correlate the measurements with a ‘real-time safety margin’?

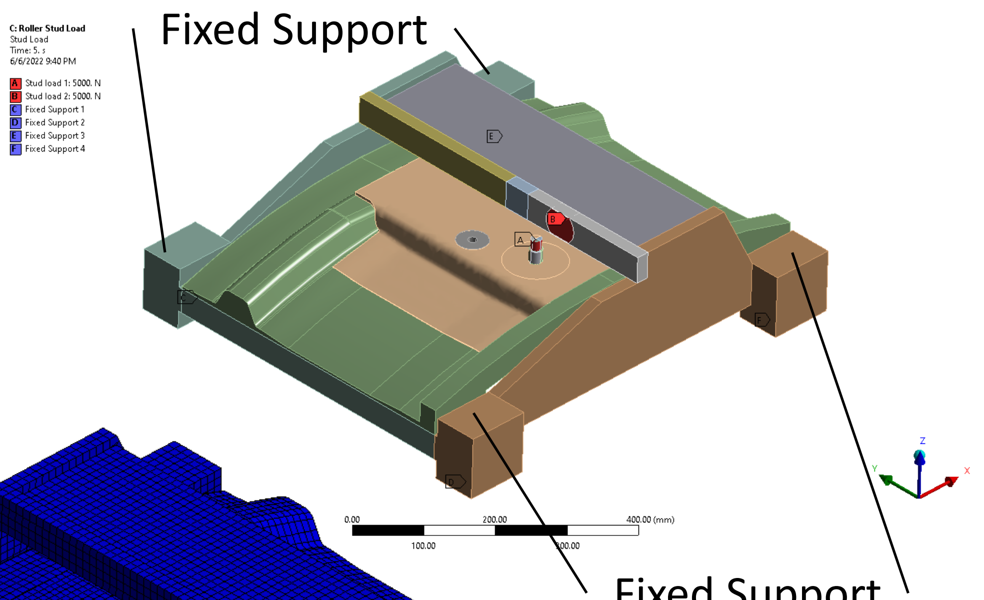
Mount Pad Test Setup

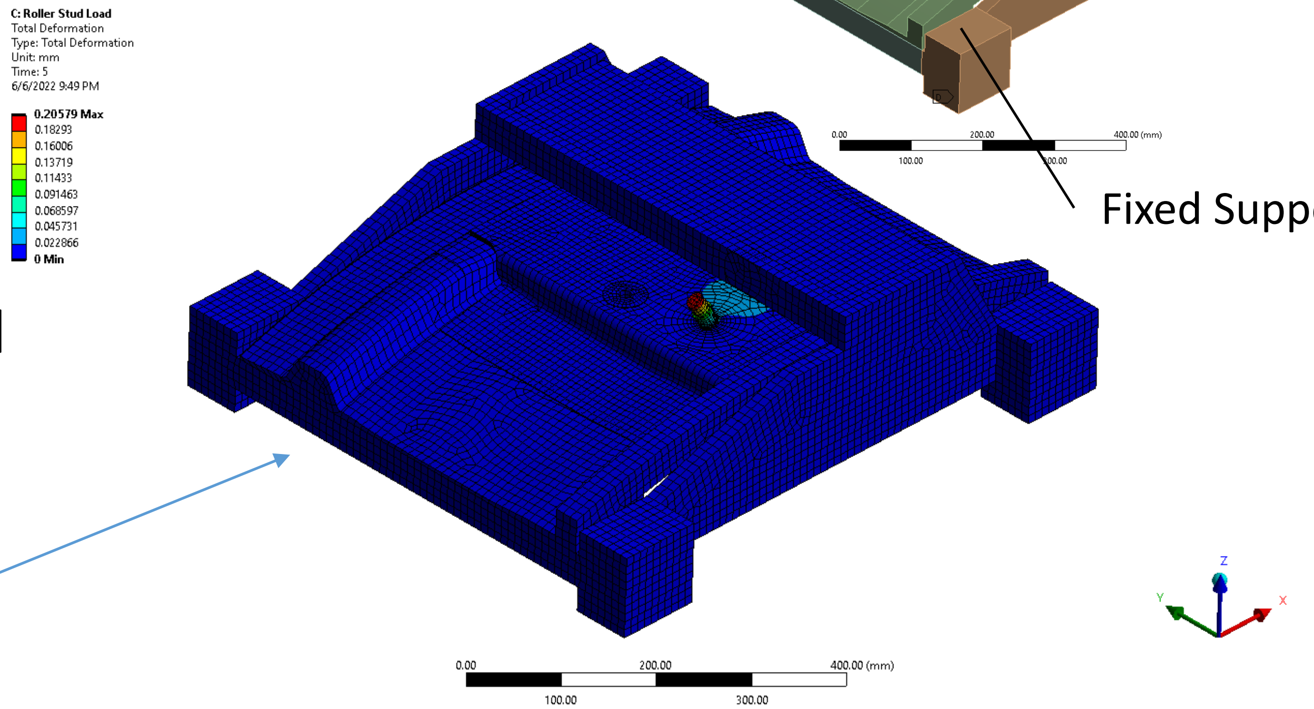


Approx. mass = 58kg

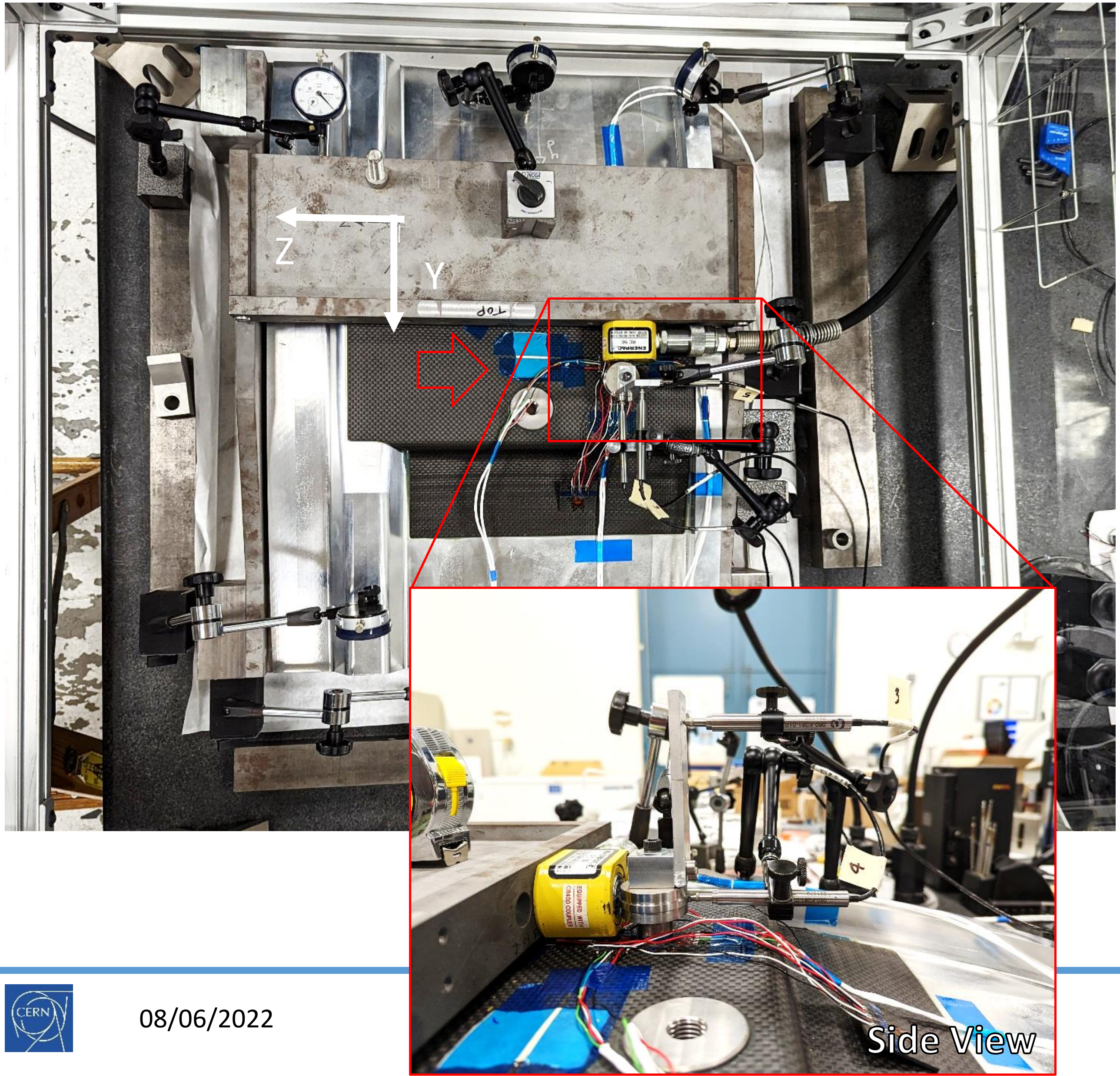
FE Model Description – Stud Load

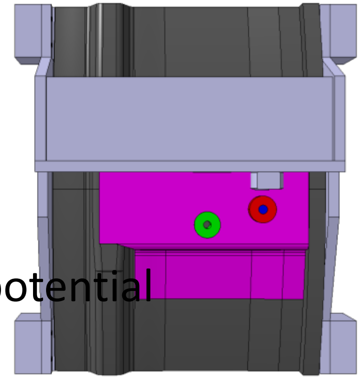
- Mesh
  - Everything modeled with solid elements
  - Carbon fiber components modeled with ACP
- Boundary conditions:
  - Fixed Supports on the Support Frame
  - Assembly connected with bonded contacts
- Load steps:
  1. Load to nominal load (5kN)
  2. Cycling around nominal load





Mount Pad Test Set-Up – Stud Load





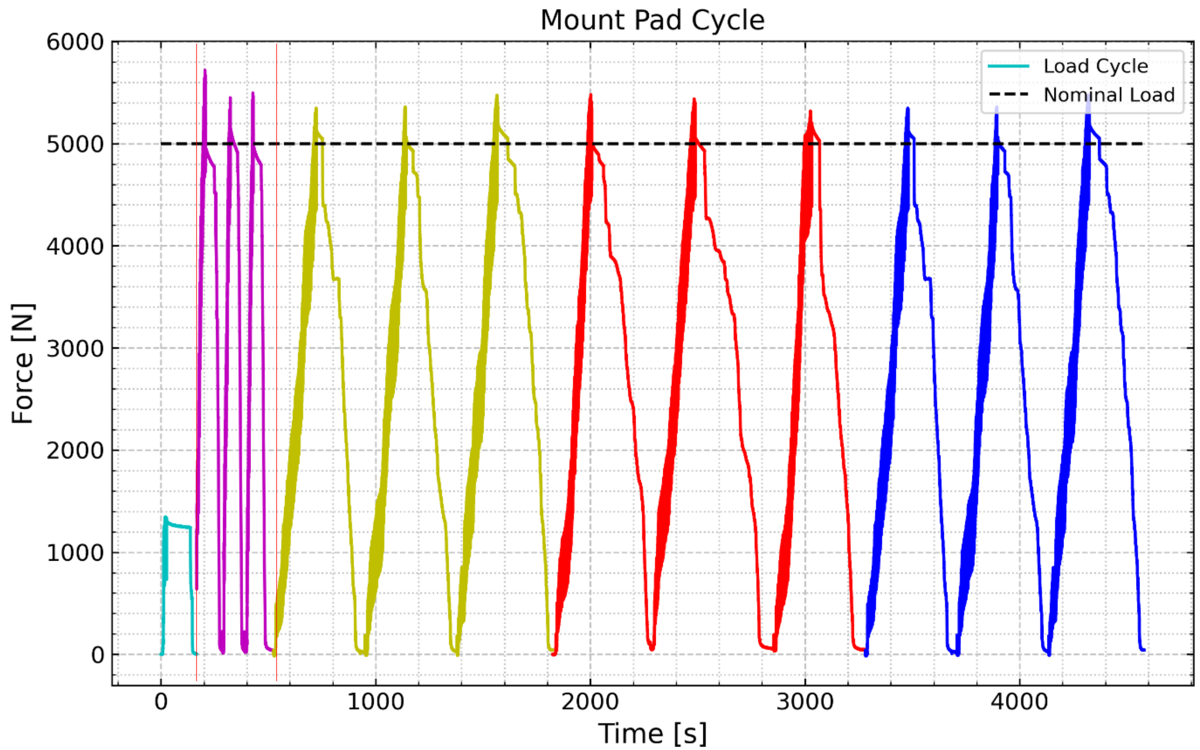
Sensors installed:

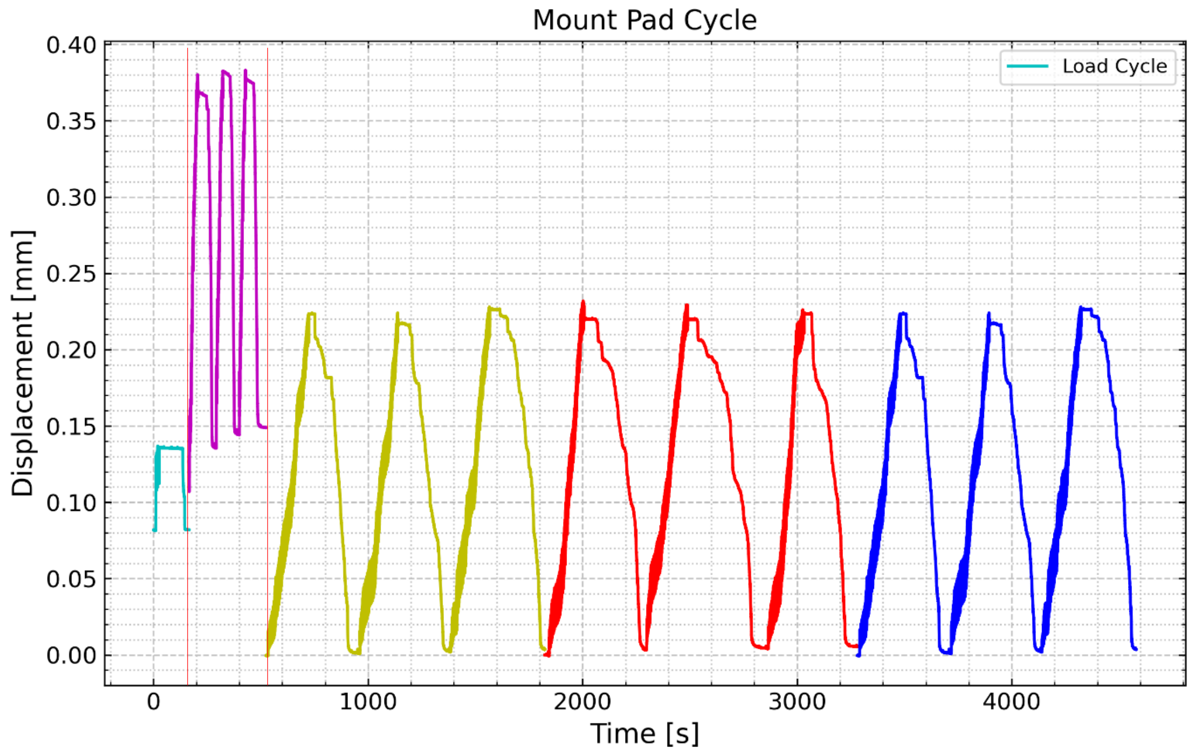
- Dial gauges installed to check against potential displacements of the steel frame
- 3 LVDT to measure the stud displacements in Y (2x) and Z directions
- 1 LVDT to measure the overall motion of the OC
- 1 strain gauges half-bridge on the roller stud
- 1 strain rosette on the mount pad

Differences with the 'designed' set-up

- OC segment is not pinned and bolted to the main frame, only bolted to the main frame
  - Possible motion of the OC segment
  - Easier and faster disassembling of the set-up

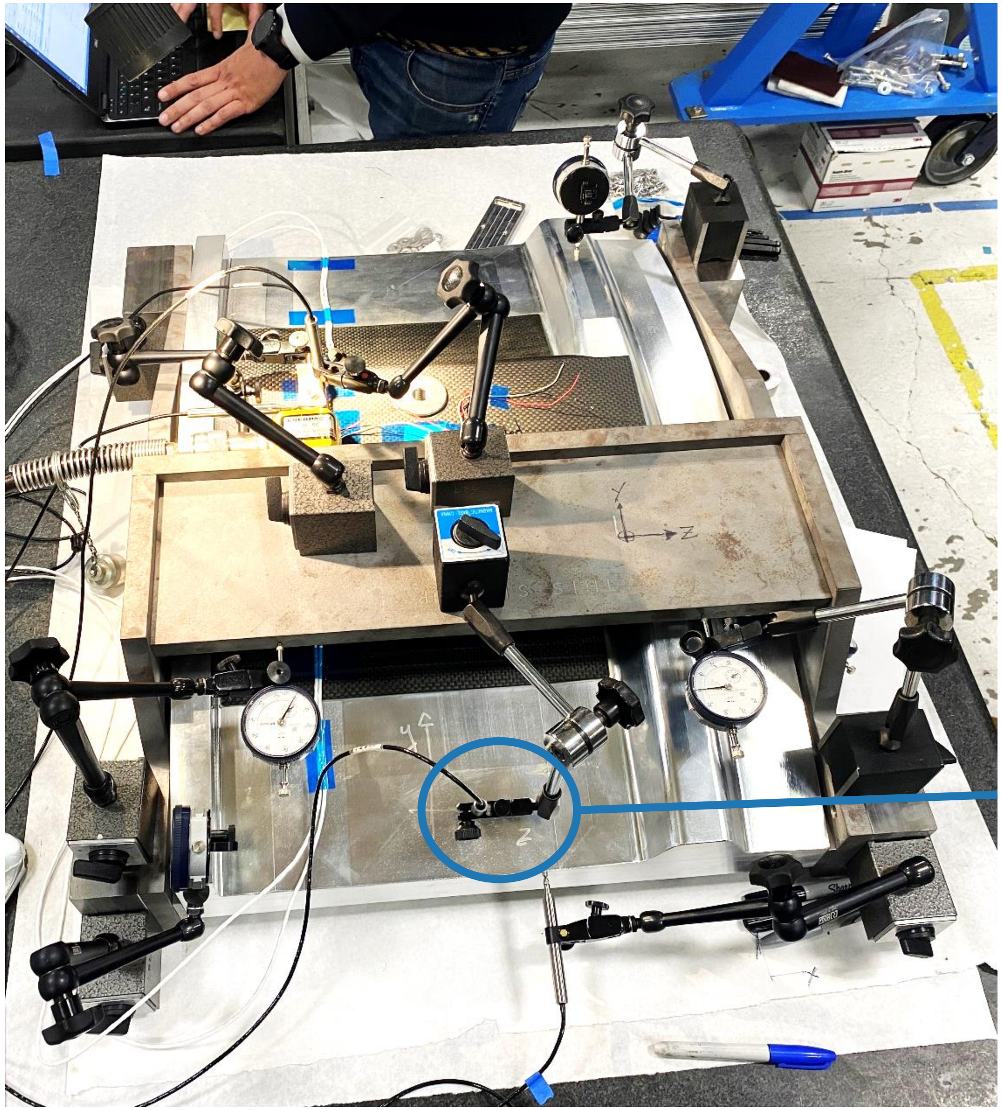
Testing Campaign – Stud Load

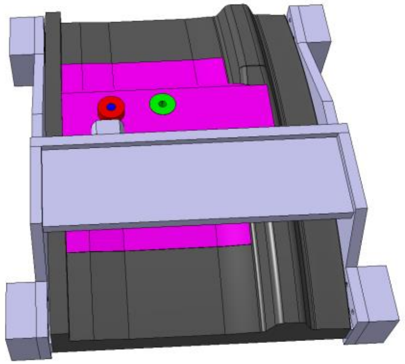




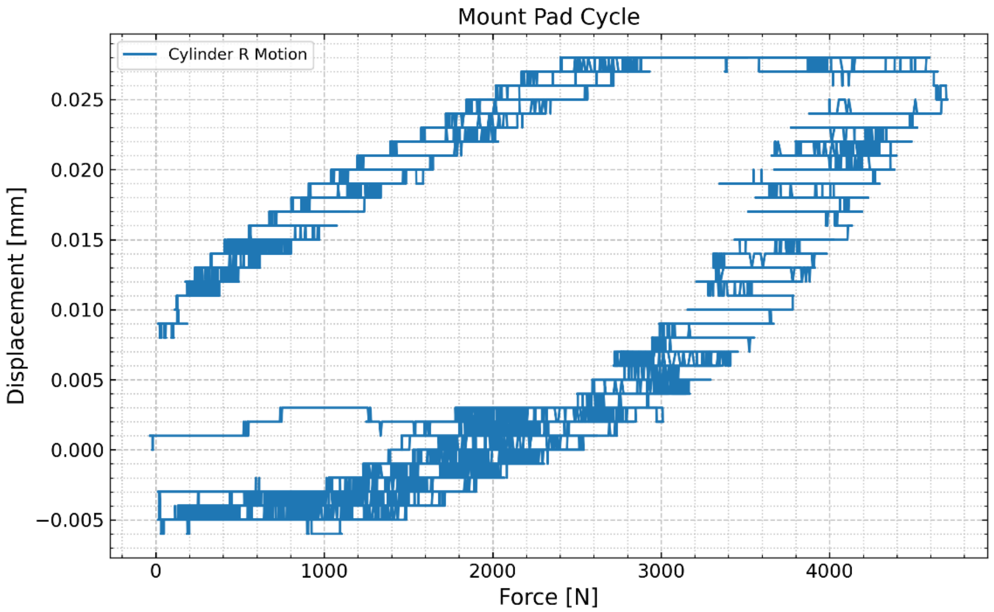
- Phase 1 – Load up to 1000N.
    - LVDT measuring stud displacement not zeroed.
- Phase 2 – Load up to 5000N. Visible motion of the stud during cycling.
    - LVDT measuring stud displacement not zeroed.
- Phase 3 – Cycling up to 5000N.

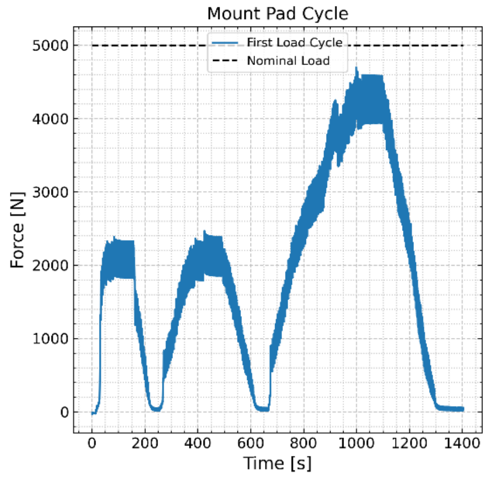
Results (Stud Load) – Cylinder Motion



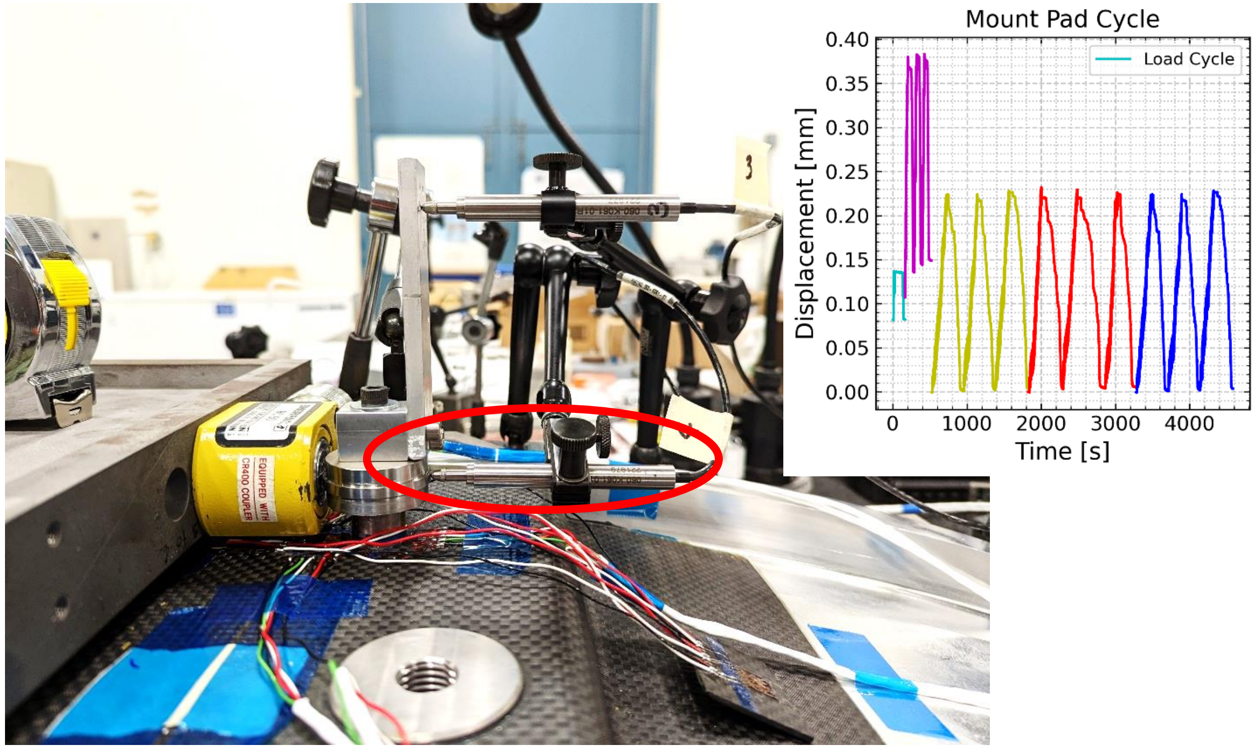


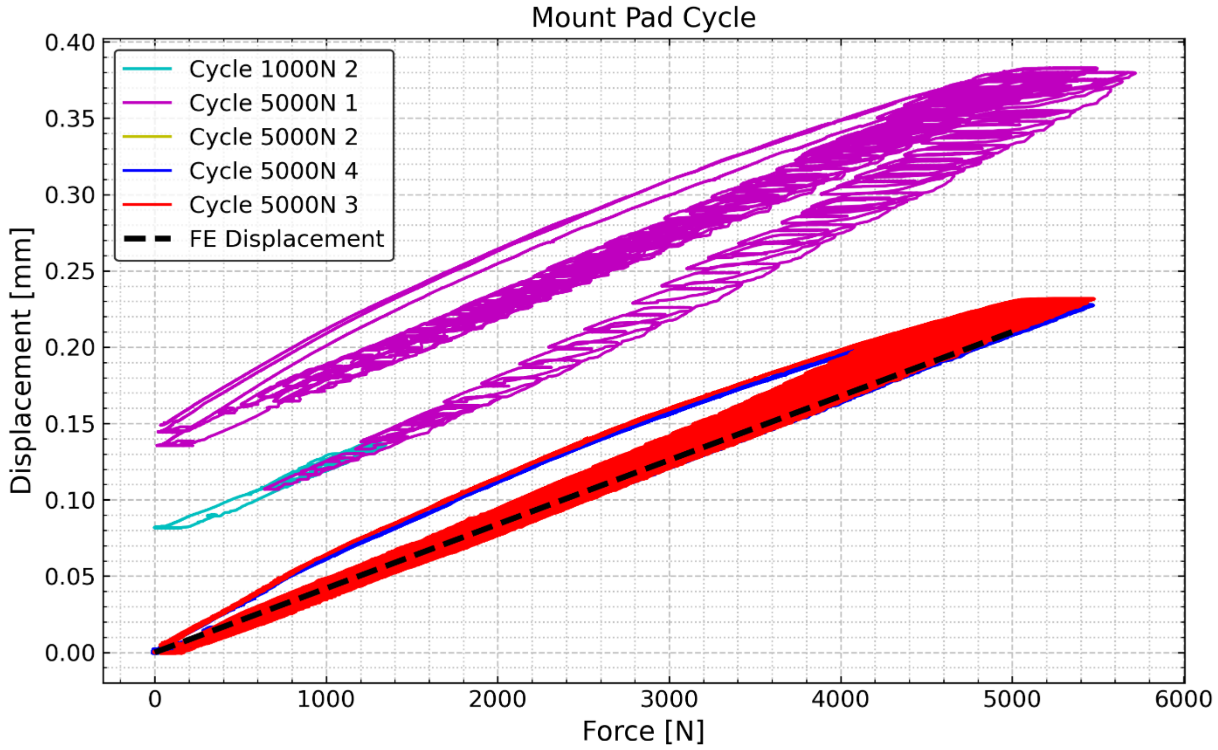
- Small motion of 0.015mm on the LVDT located radially on the cylinder
  - The displacement remains after the unloading.
  - -> slipping in cylinder fixture.
- Measurement done for one cycle only.





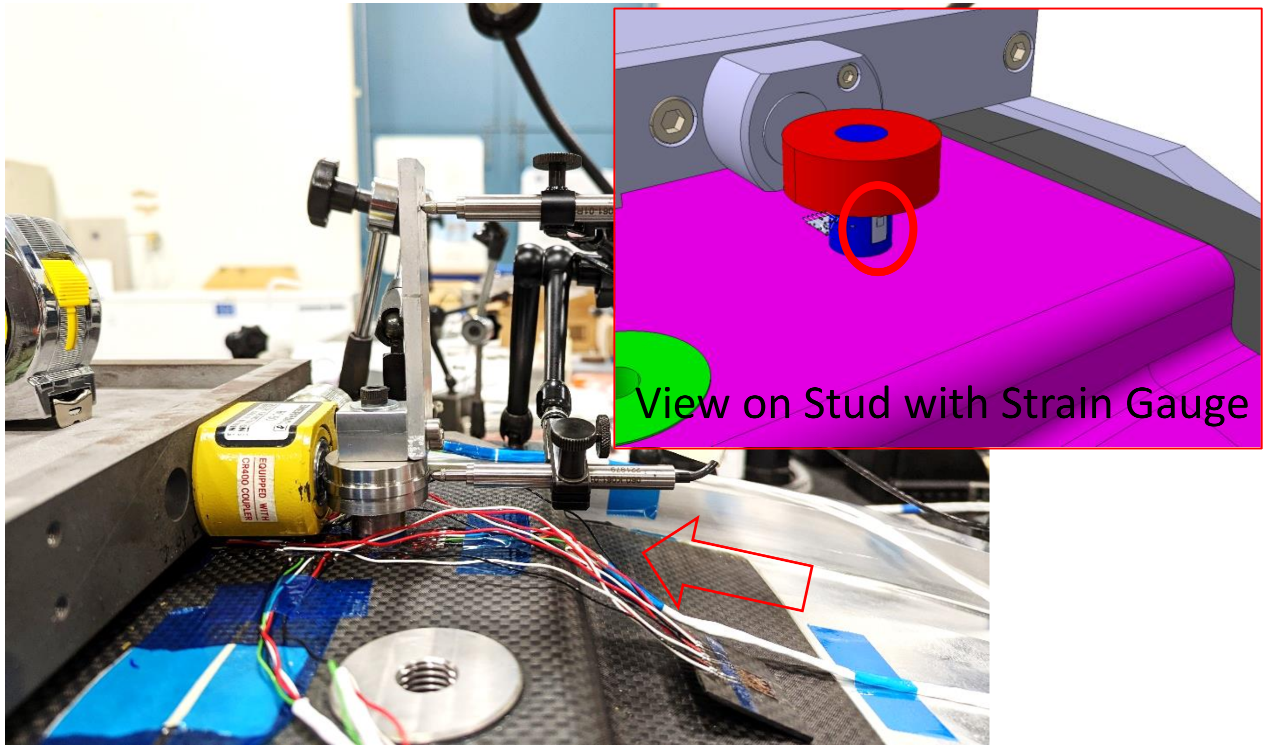
Results (Stud Load) – Stud Displacement

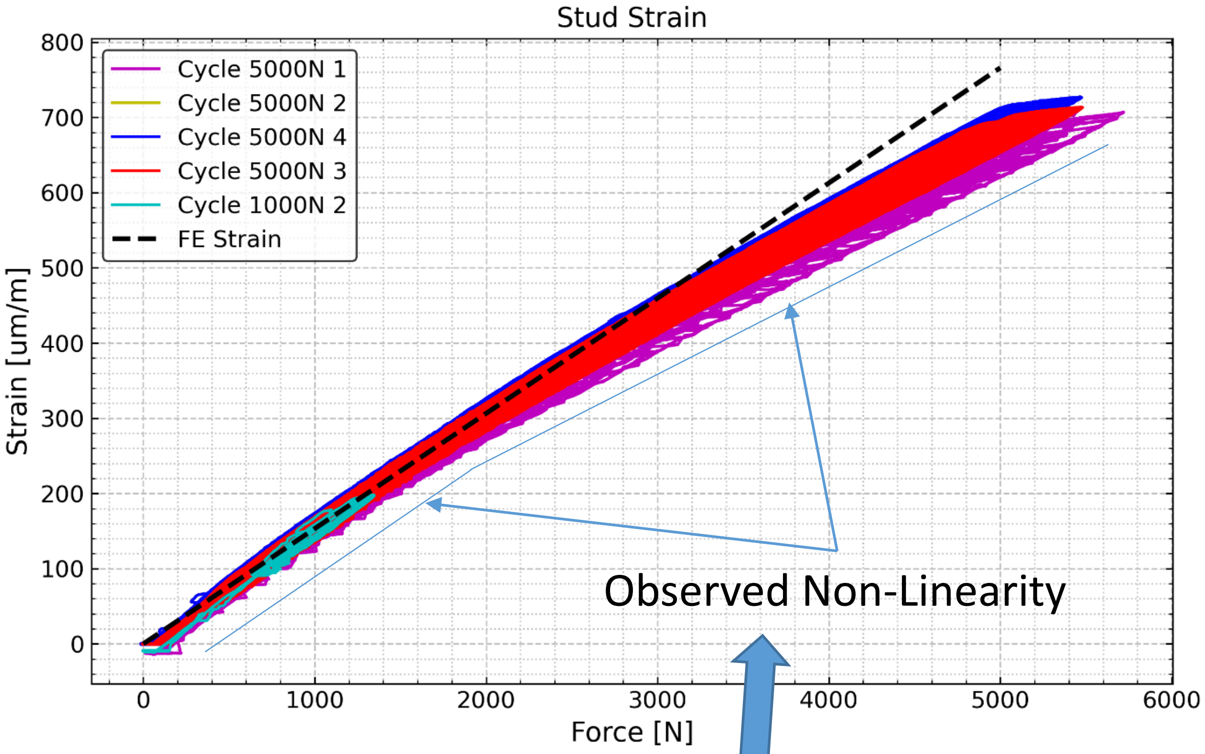


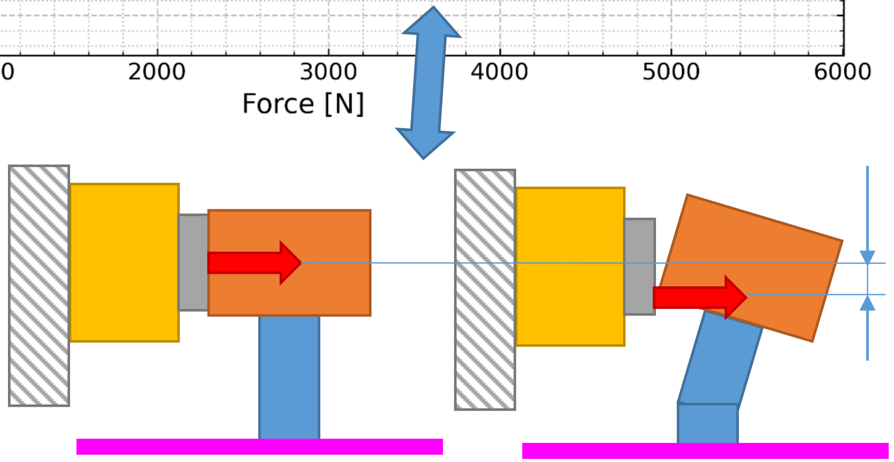


- Total displacement in the test set-up correspond to the displacement predicted by FE analysis – error up to 9%.
- Small hysteresis in the system caused by the pressure regulation.

Results (Stud Load) – Stud Strain

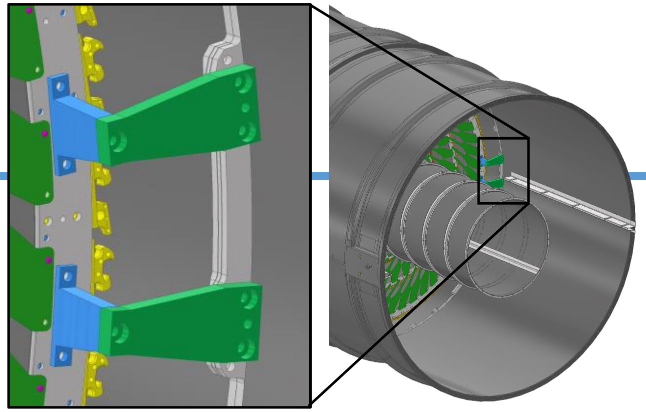


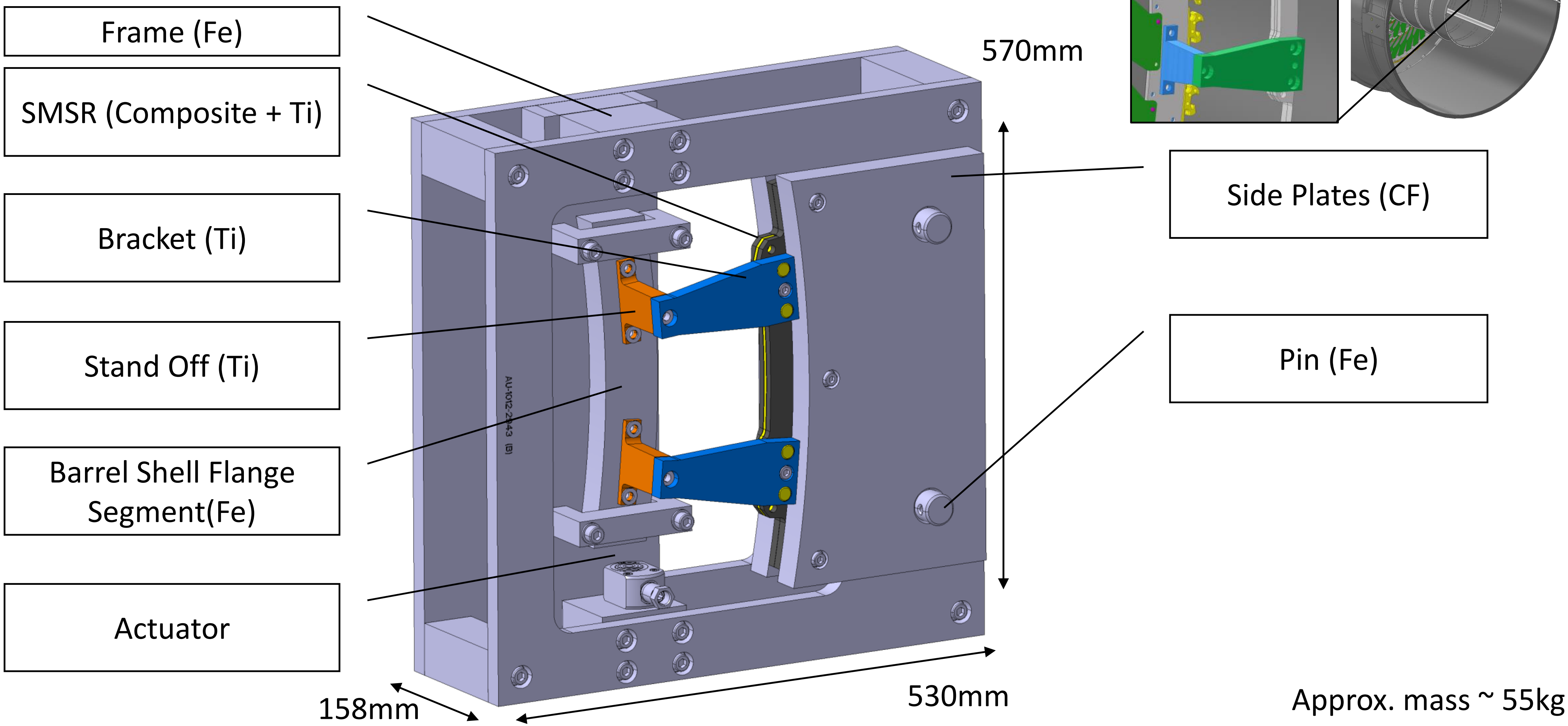




- Strain gauges half-bridge (bending) on the roller stud.
- Measured strain follow the slope of the FE strain up to ~1.7kN (error up to 5%).
- Possible source of the observed non-linearity could be change in the position of the force applied on the stud caused by the stud deflection.

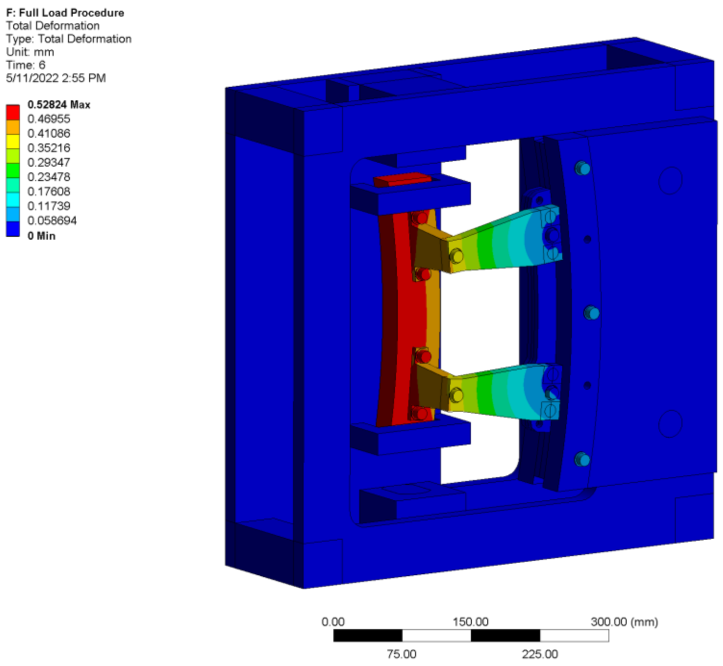
Bracket Test Setup

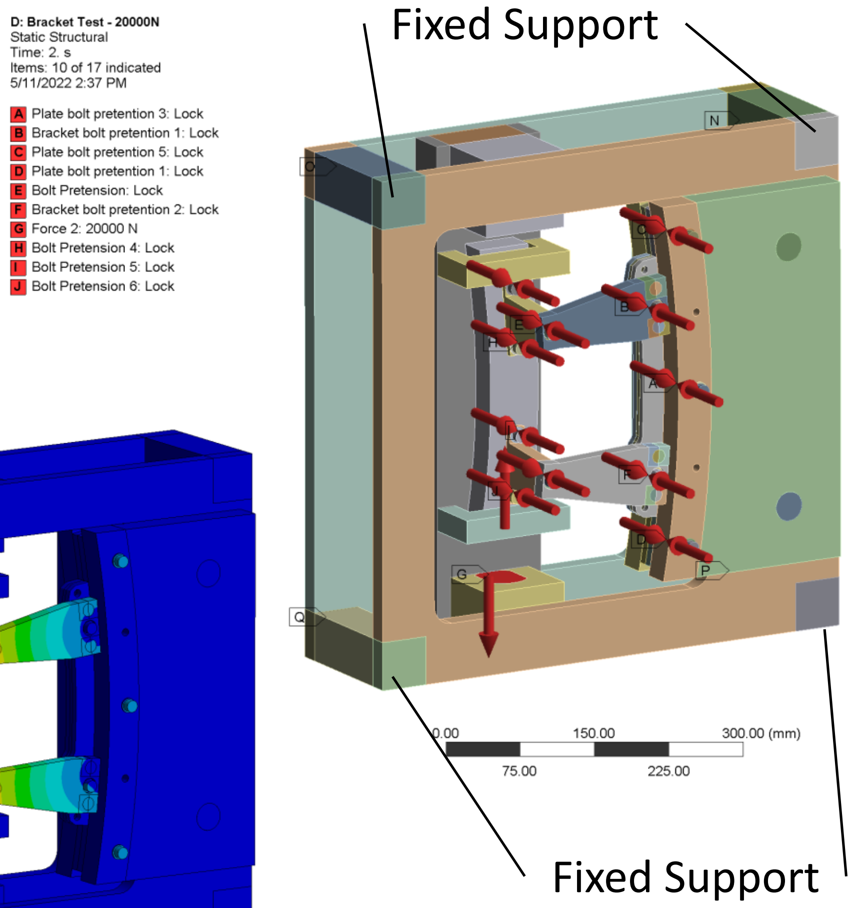




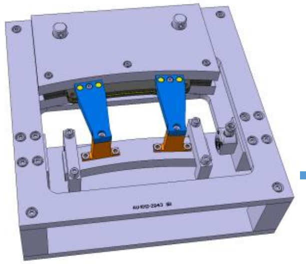
FE Model Description

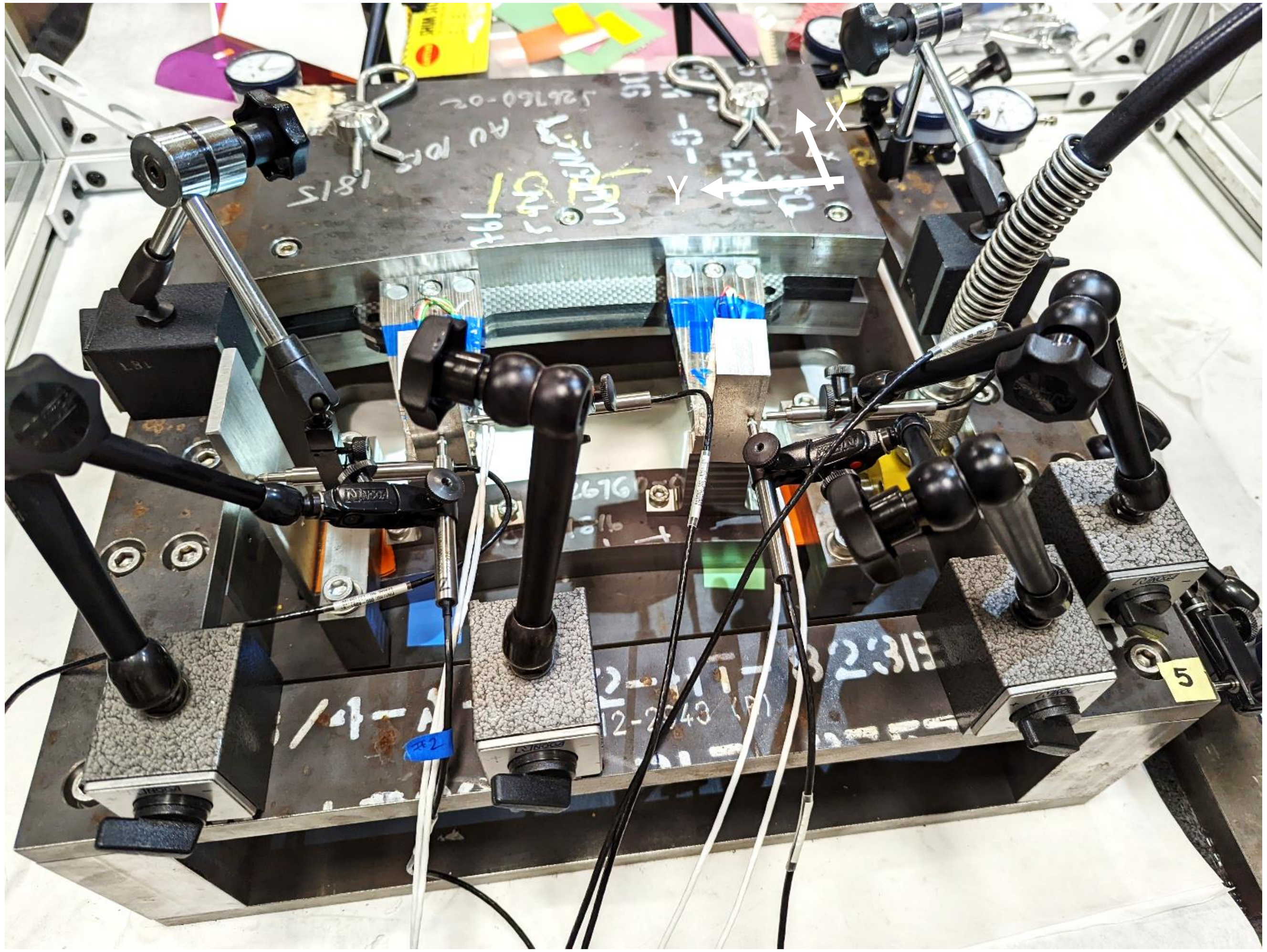
- Mesh
  - Everything modeled with solid elements
  - Carbon fiber components modeled with ACP
- Boundary conditions:
  - Fixed Supports on the Support Frame
  - Rest of the assembly connected with frictional contacts, FF=0.1
- Load steps:
  1. Bolt pretension
  2. Load to nominal load (5kN)
  3. Cycling around nominal load
  4. Load to failure (20kN)





Bracket Test Set-Up





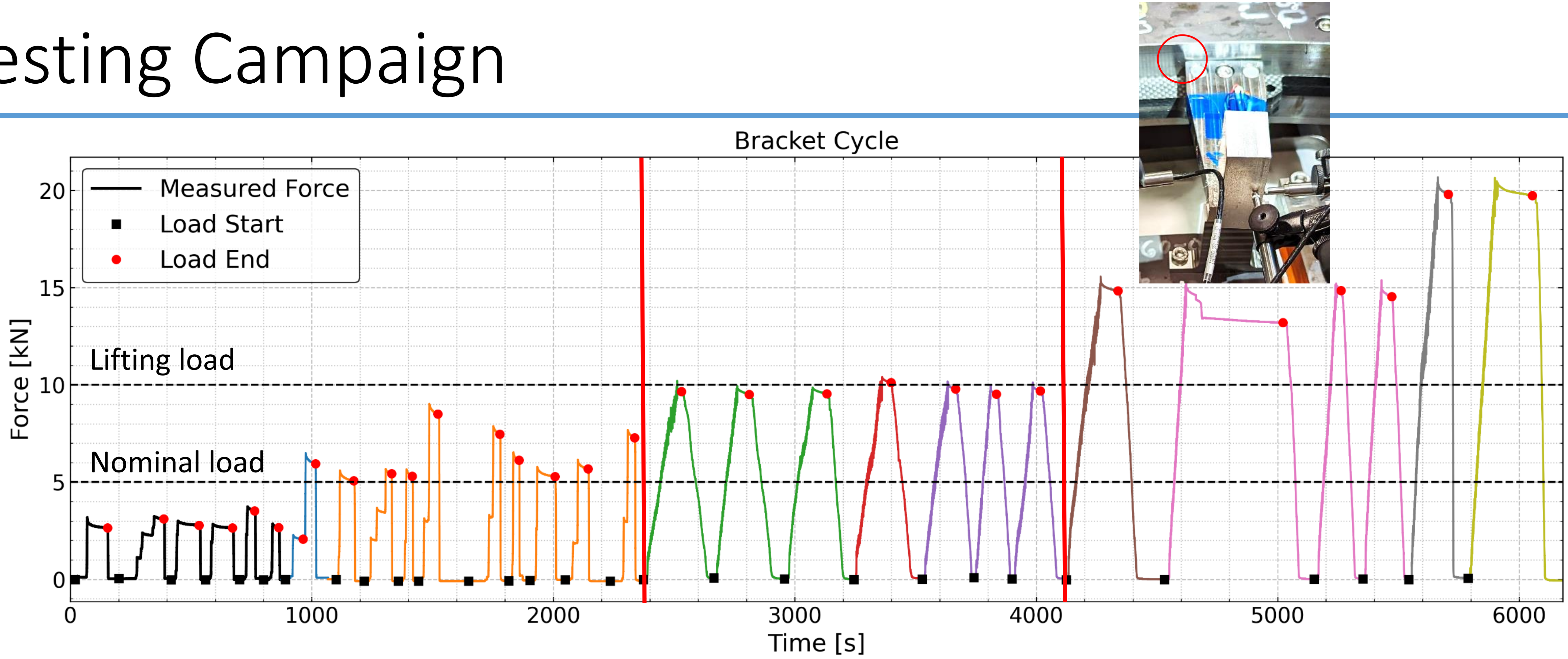
Sensors installed:

- Dial gauges installed to check against potential displacements of the steel frame
- 4 LVDT to measure the bracket displacements in X and Y directions
- 1 LVDT to measure the overall motion of the SB flange
- 2 strain gauges half-bridges on the brackets

Differences with the 'designed' set-up

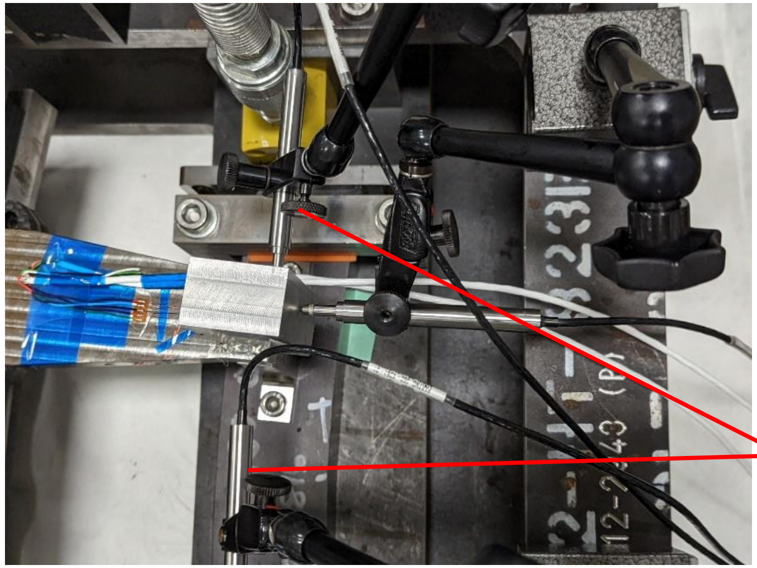
- OC flanges in steel
  - Impact on deformation is very low and this reduces significantly the cost of the experiment
- Bolts design and material (stainless steel)
  - Yield limit ~1/4 of Titanium grade 5
  - Applied pre-stress is much lower, which could impact stiffness of the measurements
  - Could also impact failure
  - Even if not 'real', is 'conservative'

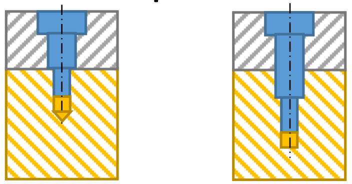
Testing Campaign



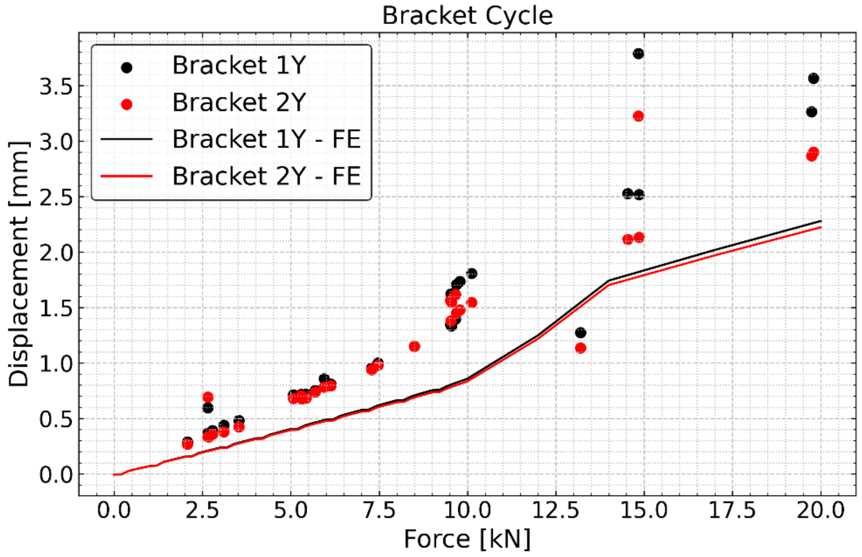
- Phase 1 – difficulties in controlling the pressure – did not manage to get to the planned load most of the times
  - New pressure sensor was installed to improve the acquisition frequency (first one was going trough a very old digital conditioner)
  - New control procedure devised
- Phase 2 – reached Ultimate Load State (Lifting load). Ramps up and down much better controlled now.
- Phase 3 – Bracket corners machined. Reached 20 kN. Yield around 12.5 kN.

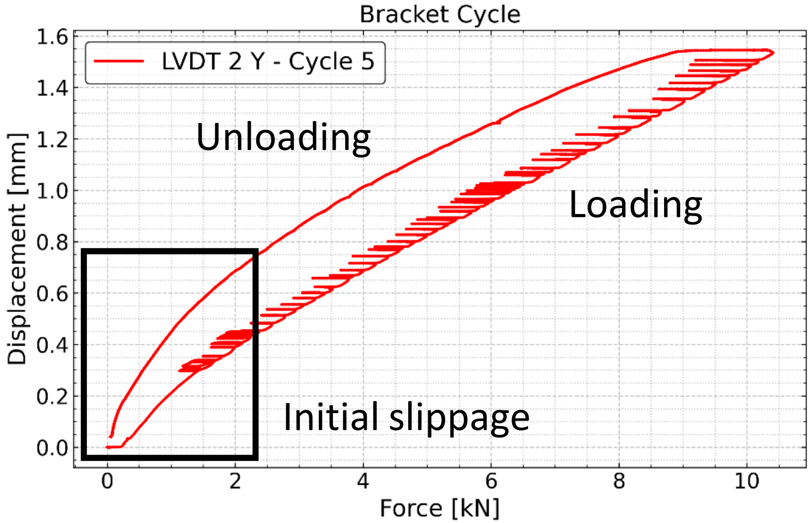
Results – Vertical Displacements

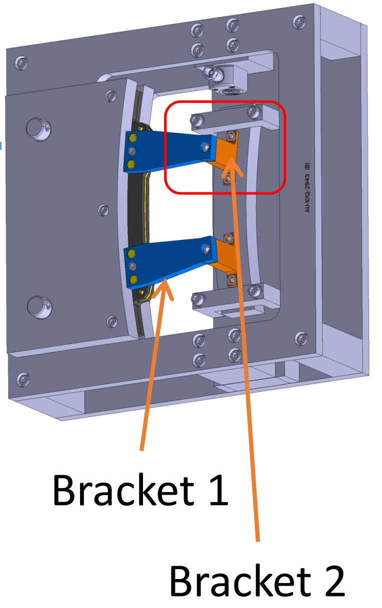




Difference in the stud design



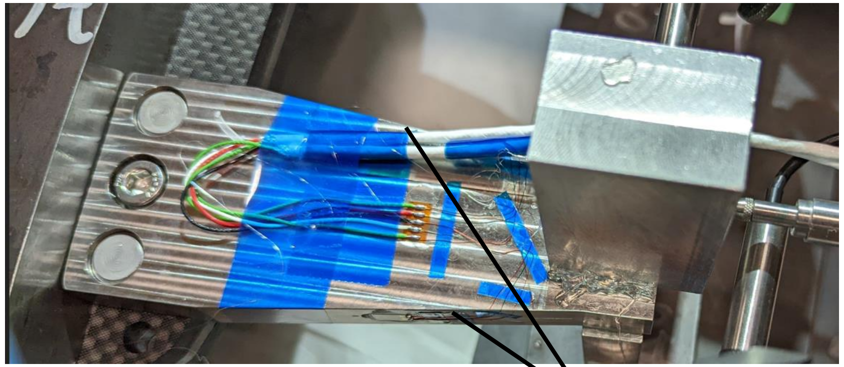


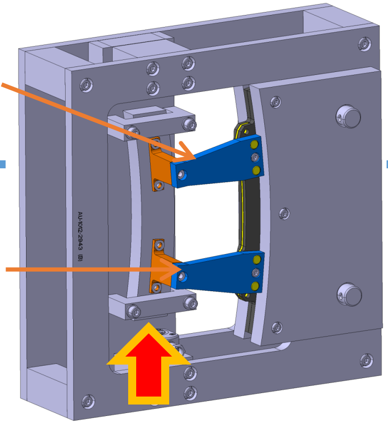


LVDT – Vertical Displacements:

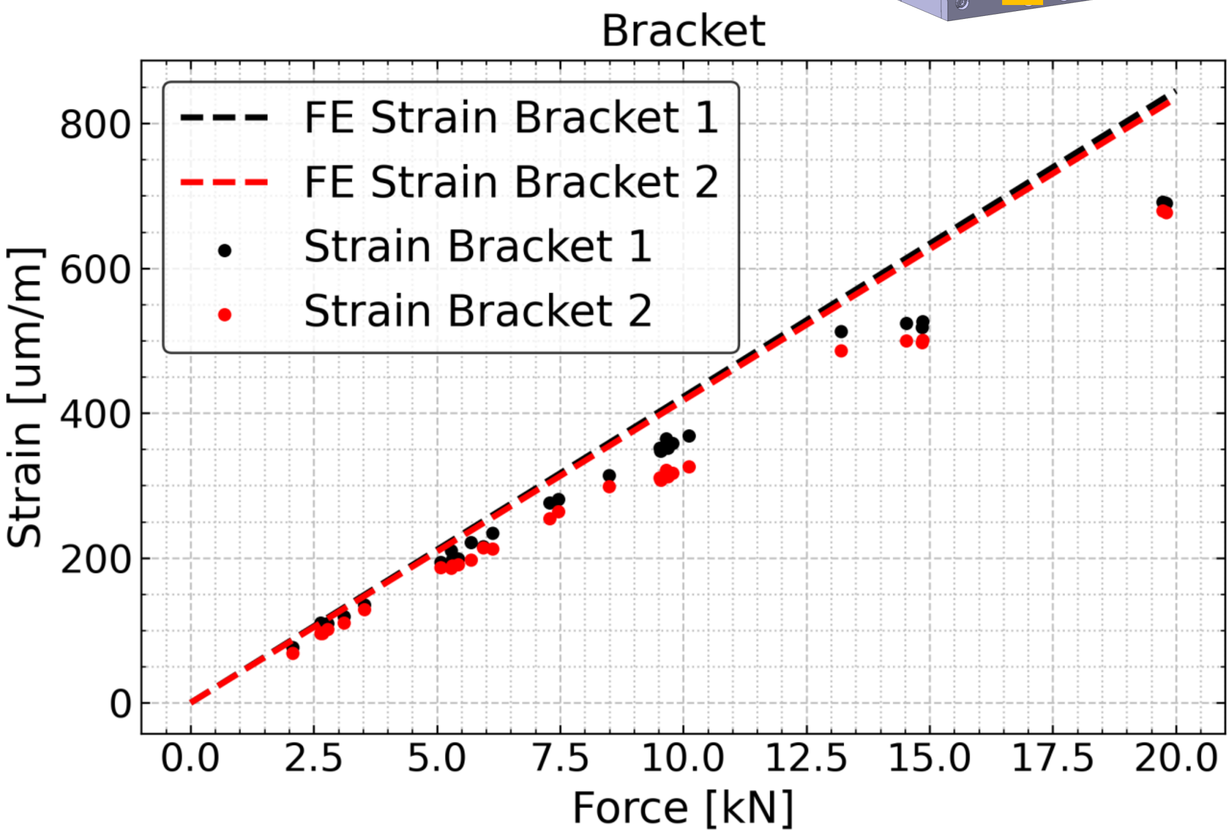
- FE model seem to match the overall non-linear shape
- The initial slope is slightly higher than expected
  - This is not the slope needed for stability
  - There is some slippage at the beginning that is pre-stress and friction dependent, and bolts are not pre-stressed at the 'design/FE' level
- The measurements deviate around 7.5 kN
  - Possible plasticization in the studs

Results – Strain Gauges





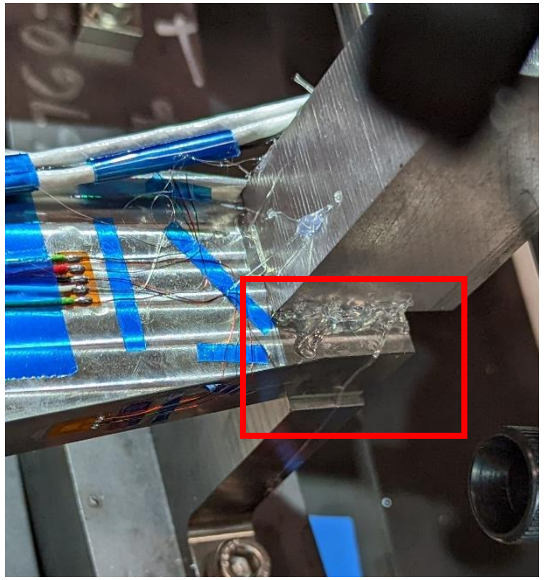
Strain gauges
Half bridge

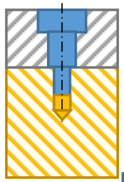


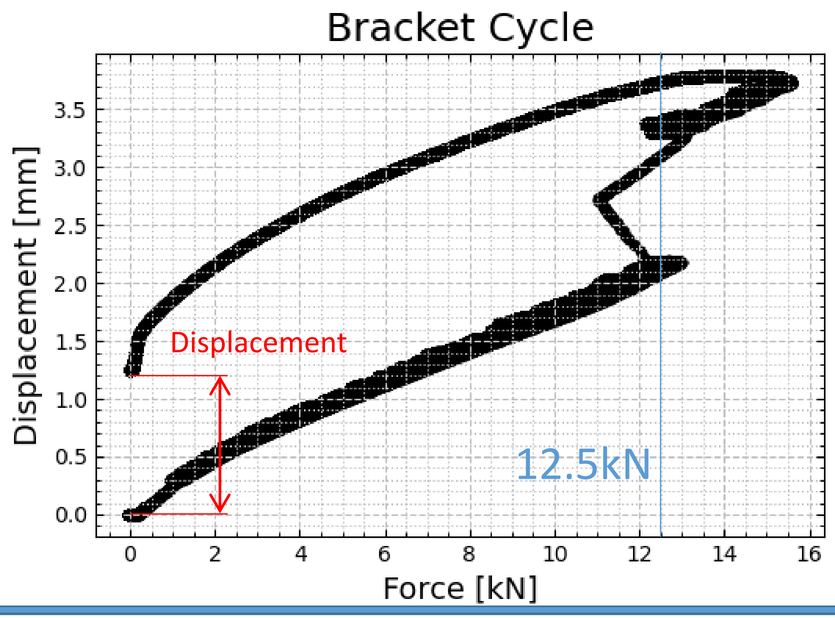
Strain gauges:

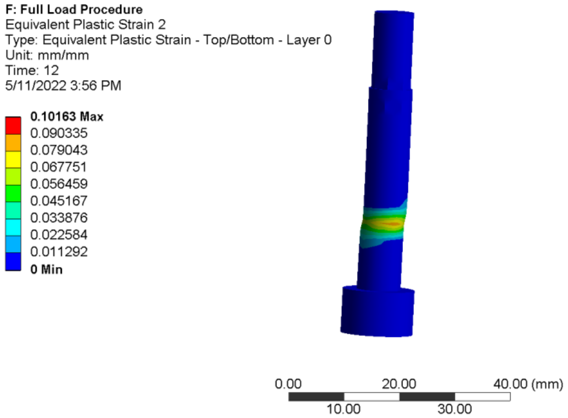
- Signals are linear with load
- Half bridge removes thermal effects
- Compared with measured strain, the FEA strain is by 20% higher.

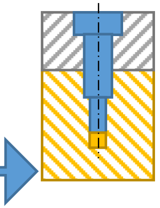
Results – Failure Load











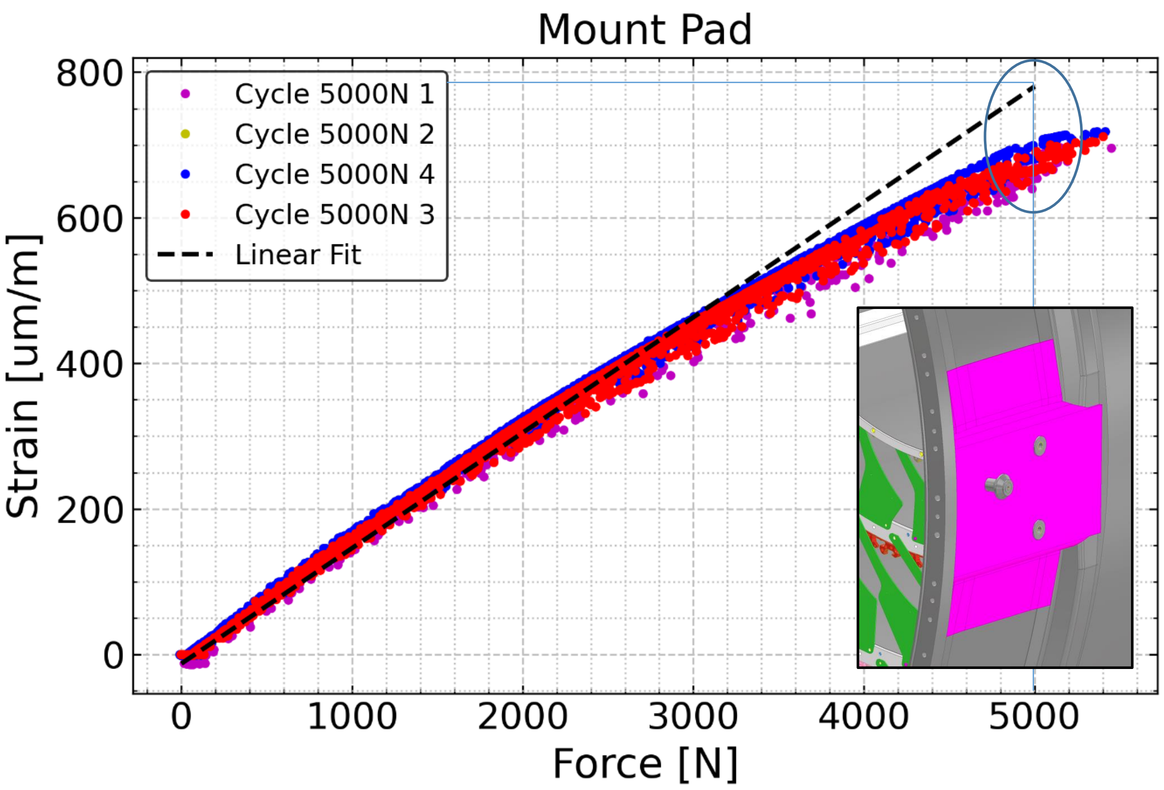
Measurement

- The system 'yielded' above 12.5 kN, but reached 20 kN (safety factor ~4)
- The failed component is the stud connecting the bracket to the bracket extension
  - Significant plastic deformation, but still carrying the load
  - Bushing was fine, as all the other components
  - This component is not in the correct material and geometry!
    - Titanium grade V yield is ~4 times higher
    - Design geometry has a larger cross-section

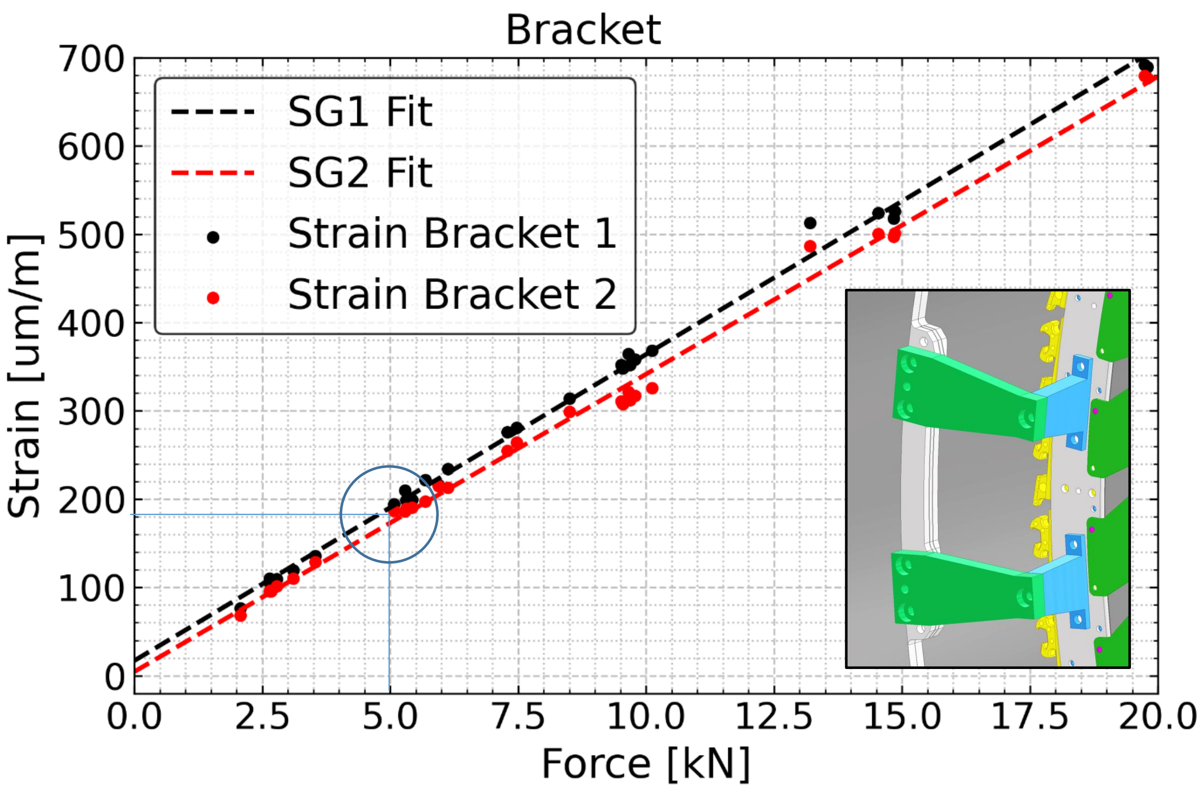
FEA

- Updated analysis performed with correct bolt material
- With conservative material properties model predicts significant plastic strain starting from 12 kN
  - Bolt eqv. stress ~200 MPa, but Titanium grade V has a yield strength of ~880 MPa
  - Still not 'failing' as the bolt hardens

Structural Health Monitoring



- Good sensitivity to applied load: ~150 (µm/m)/kN
- We expect around 750 µm/m at the nominal load



- Good sensitivity to applied load: ~34 (µm/m)/kN
- We expect around 200 µm/m at the nominal load

- Expected noise in the order of 5 µm/m (was ~1 µm/m during measurements)

Conclusion

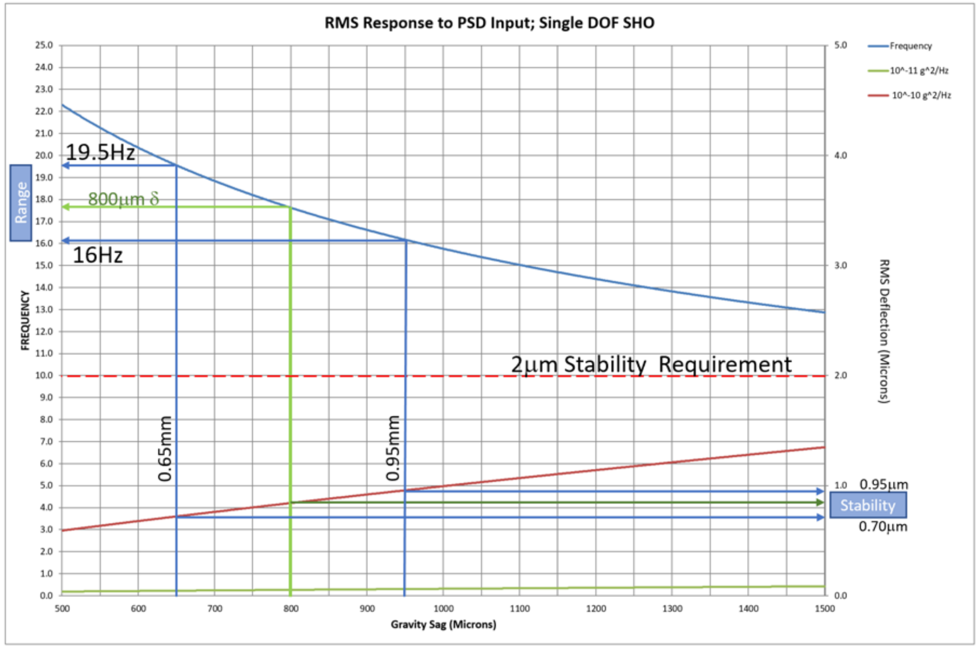
- Tests were designed for critical ITk OC structure interfaces

- Mount Pad test set-up
  - Stiffness as expected – by 9% higher than predicted by FEA
  - Strain as expected
    - by 10% lower than predicted by FEA compared to non-linear behavior observed in measurement
    - less than 5% lower than predicted by FEA compared to linear fit obtained from measured data
  - Slippage in the fixture
  - Second load case and Failure load ongoing

- Bracket test set-up
  - Failure load ~12.5 kN ~1.5 ultimate (with stainless steel bolts)
  - Deflection higher than expected – probably bolt geometry.
  - Titanium bolts are being procured, the experiment will be repeated soon

- Structure Health Monitoring
  - Nominal load of 5kN for both interfaces
  - Mount Pad sensitivity: ~150 (µm/m)/kN
  - Bracket sensitivity: ~34 (µm/m)/kN

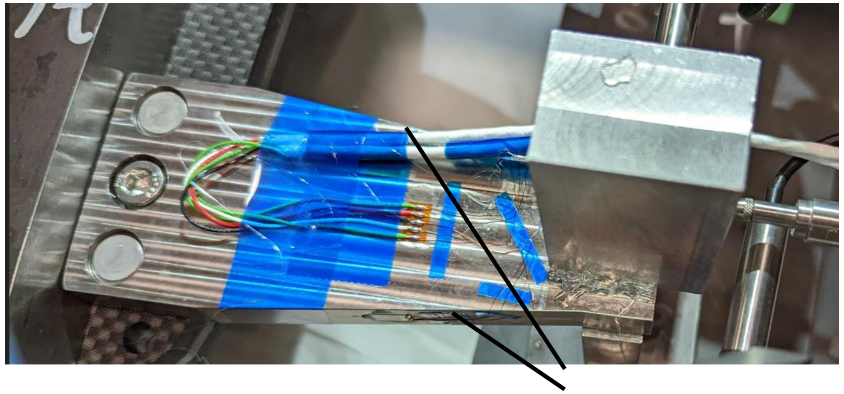
Backup Slides



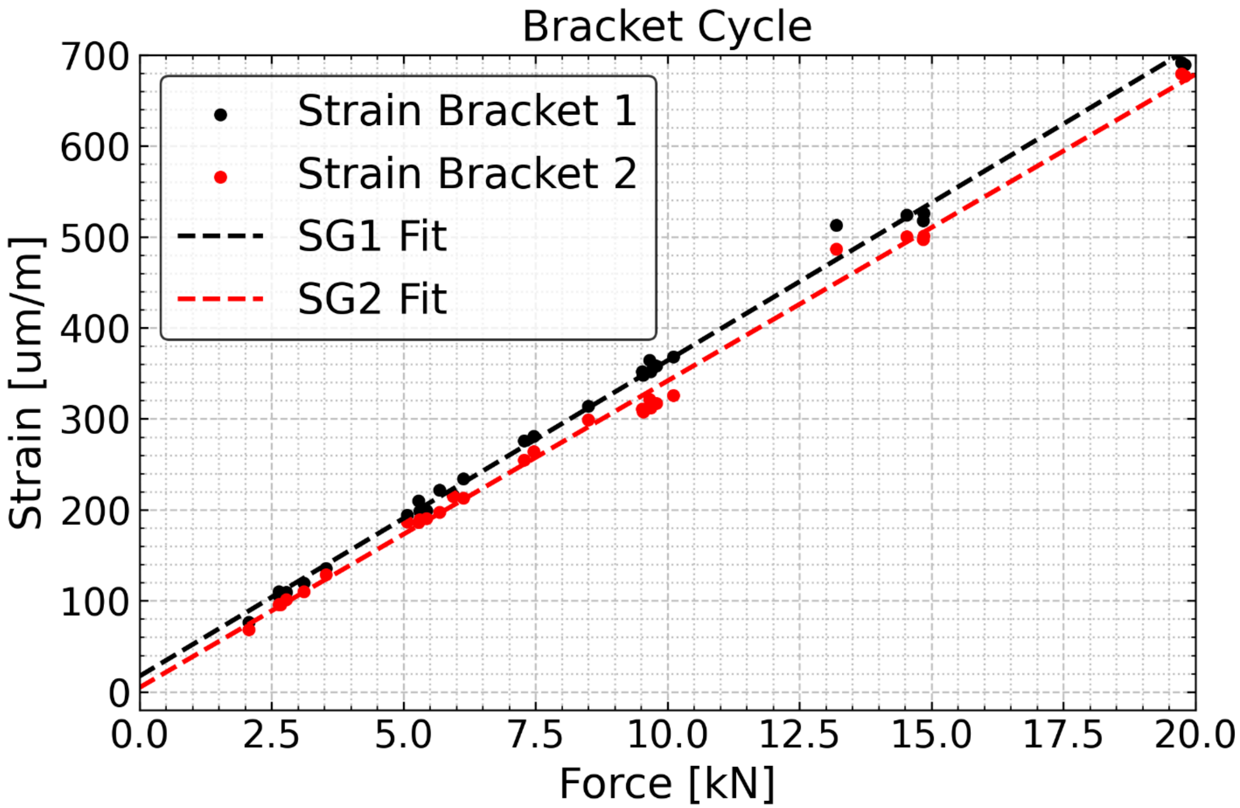
Requirement				
Type	*R (um)*	*Phi (um)*	*Z (um)*	*Other*
Positioning	Assembly Tolerance			
Short Term Stability	20	2	20	
Medium Term Stability	50	5	50	
RMS Stability	20	2	20	
Gravity sag				2 mm
IRF				<0.5

- Requirements from: *ATU-SYS-ES-0027 - Alignment and positioning requirements (…)*
- RMS **stability** requirement (most stringent):
  - Azimuthal: 2 µm
  - Other directions: 20 µm
- Designs with a **vertical sag** lower than **1 mm** provide a margin factor of ~2

Results – Strain Gauges



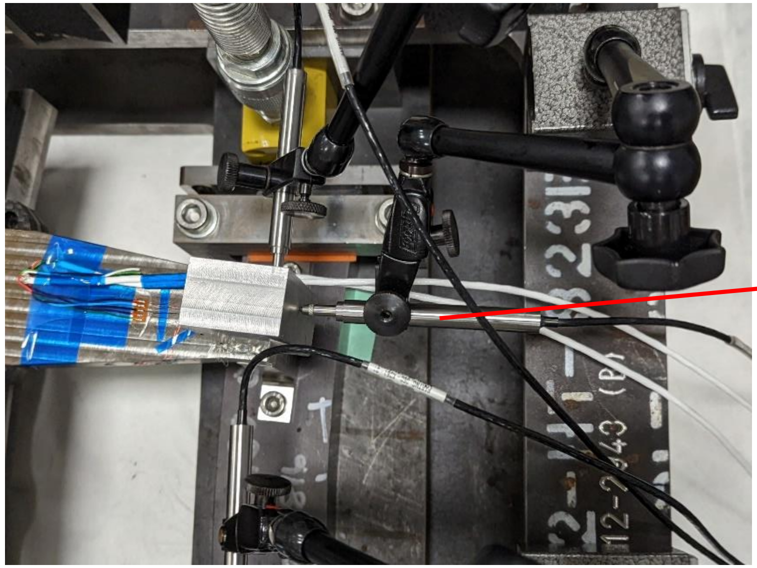
Strain gauges
Half bridge



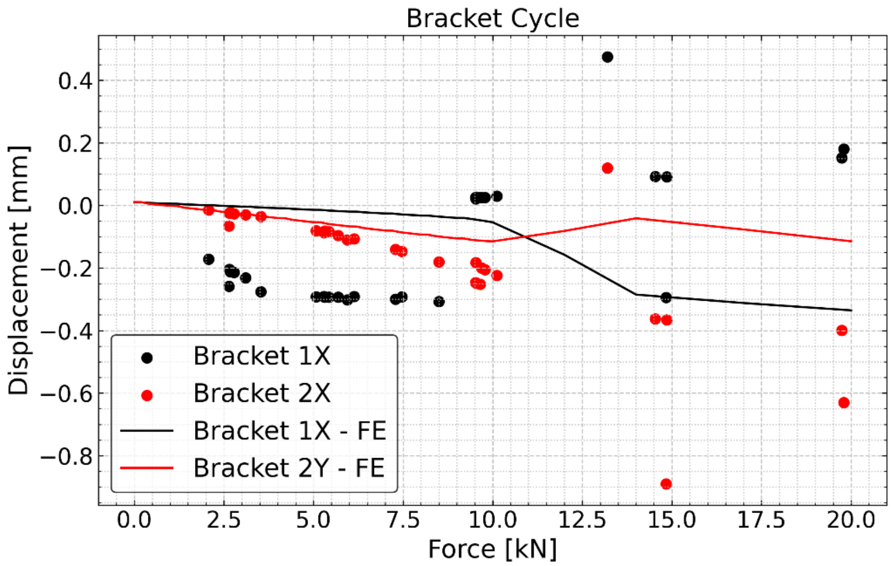
Strain gauges:

- Signals are linear with load
- Half bridge removes thermal effects
- Good sensitivity to applied load: ~34 (μm/m)/kN
  - FE prediction was 32 (μm/m)/kN
  - Expected noise in the order of 5 um/m (was ~1 μm/m during measurements)
  - We expect around 200 um/m at the nominal load
- Promising SHM tool

Results – Horizontal Displacements

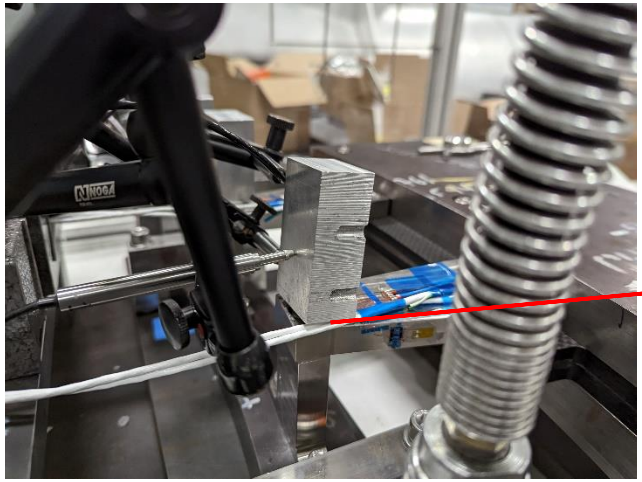


LVDT Horizontal



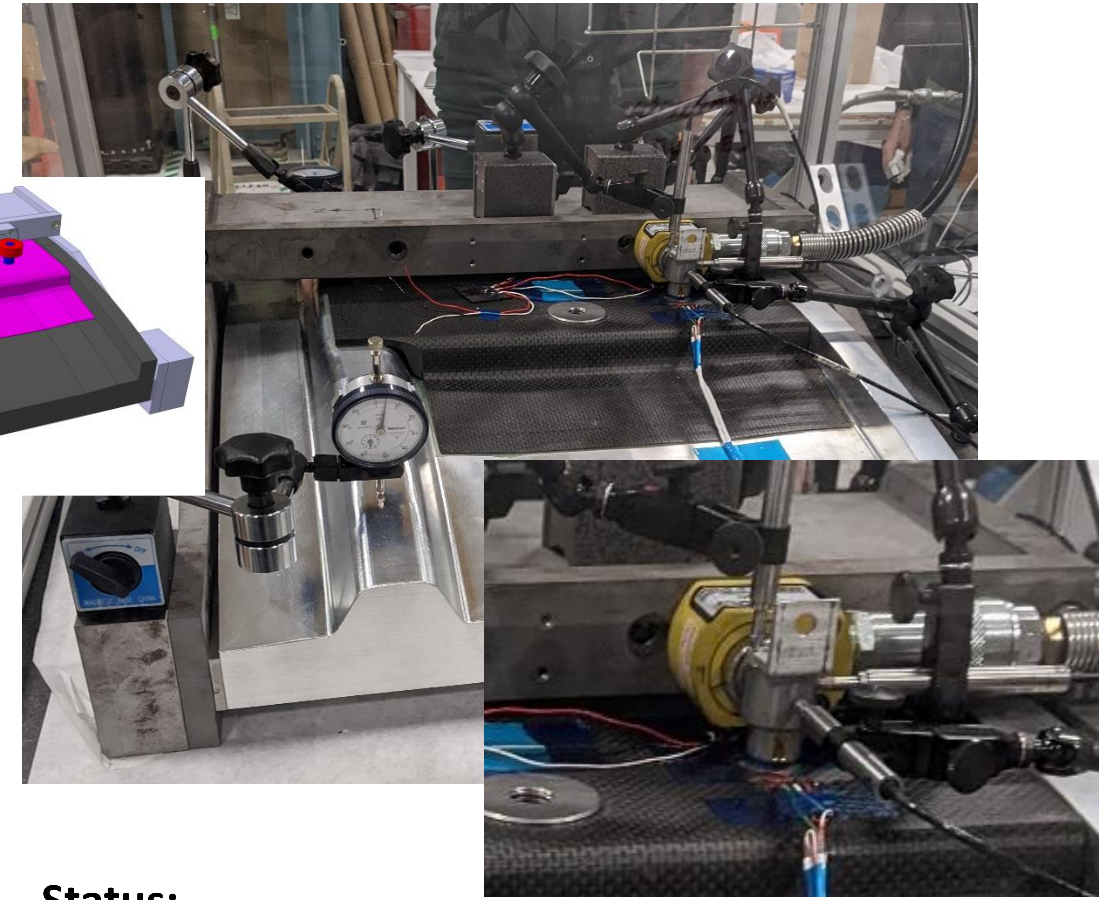
LVDT – Horizontal Displacements:

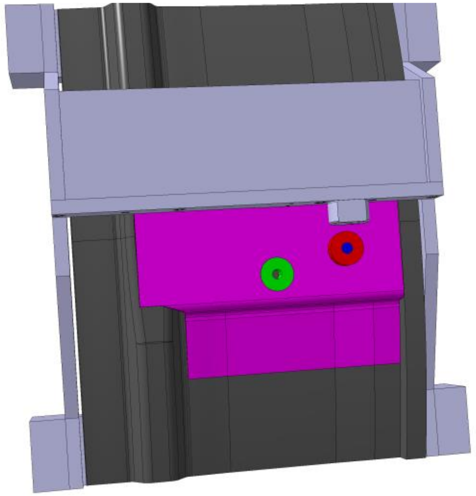
- Something strange in bracket 1 signal
  - Saturates at around 10 kN (in fact we moved it)
  - Then seems to provide random numbers
- Bracket 2 matched up to ~nominal load
- Not clear what happens after – more time needed to correctly post-process the data
  - Some measuring blocks unglued during testing
  - Need to check the history with test engineer

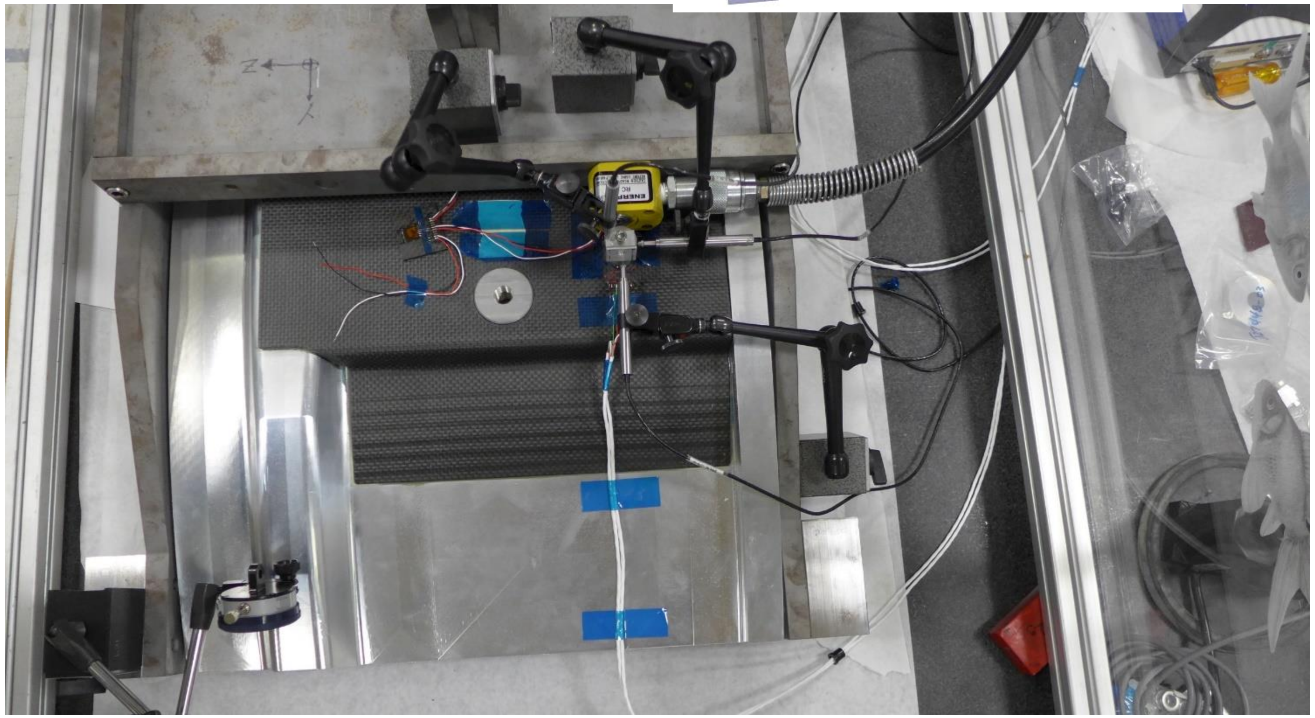


Debonding

Mount Pad Test Set-Up



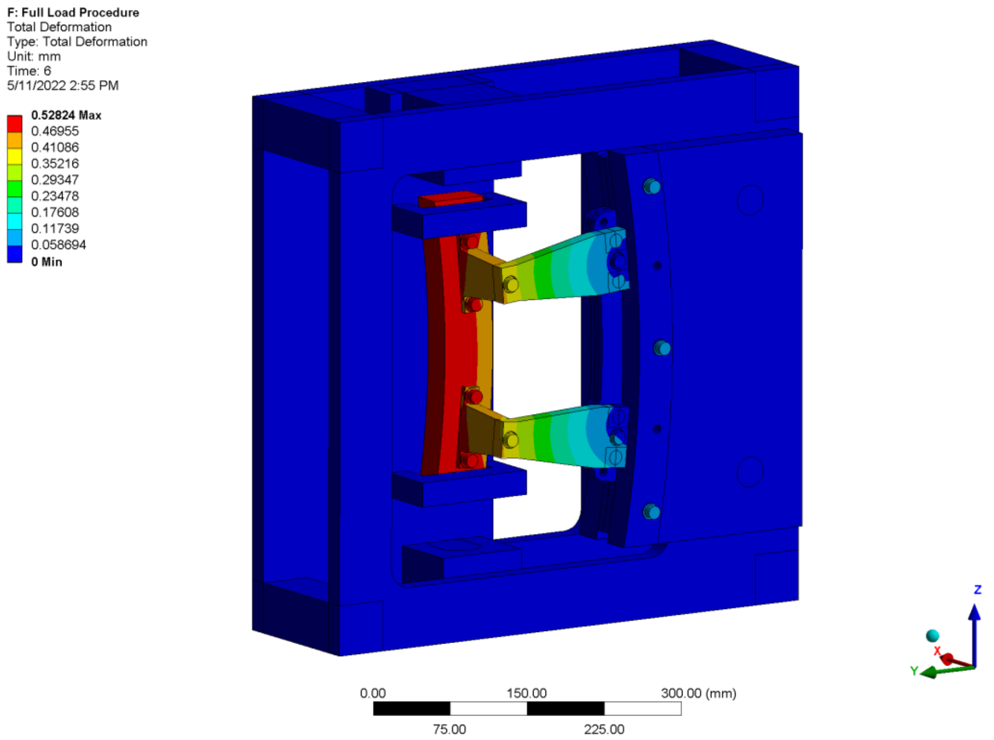


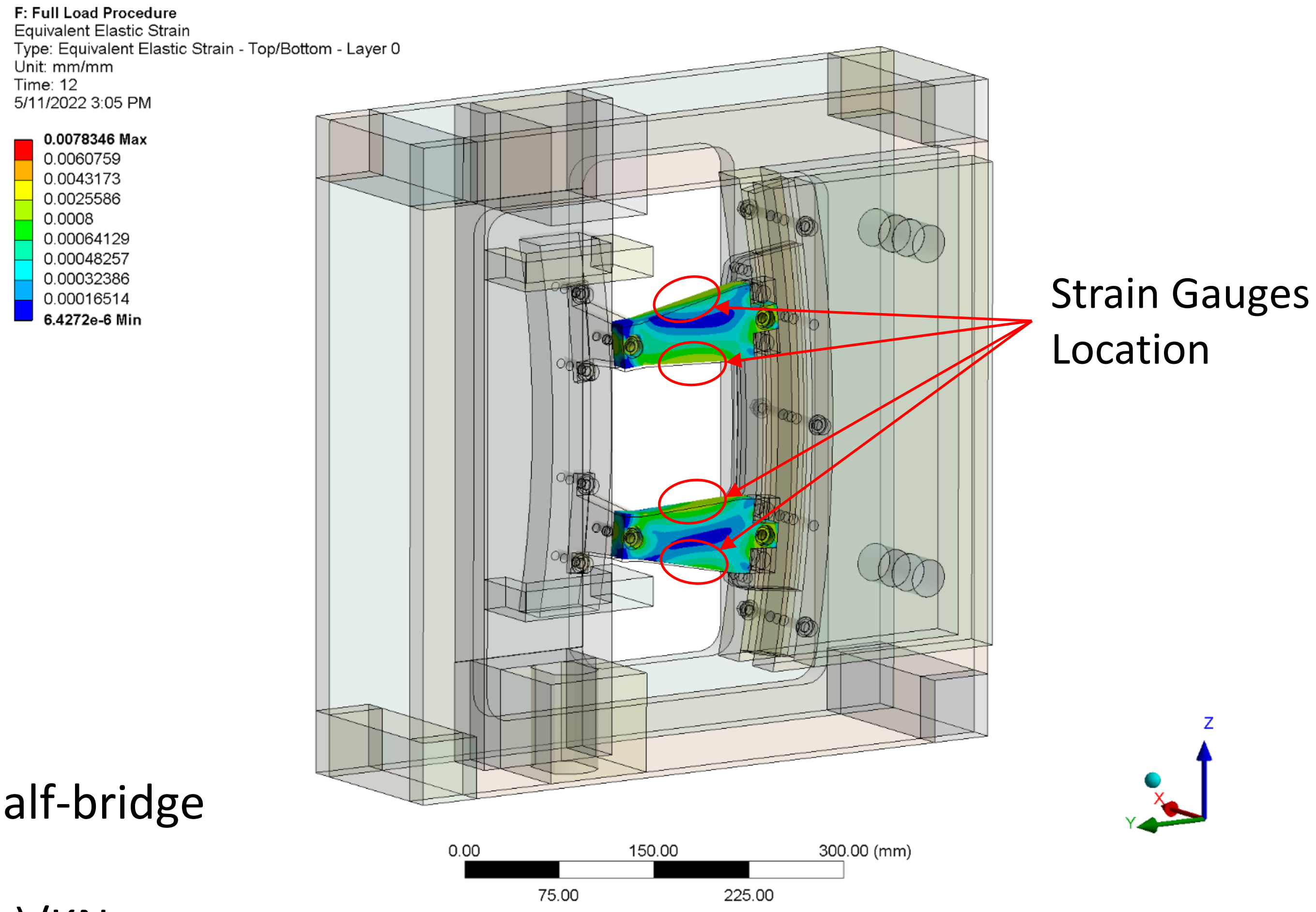


Status:

- Set-up is complete
- First load cycle performed
- Preliminary post-processing in progress, after sanity checks are passed we will apply the nominal load

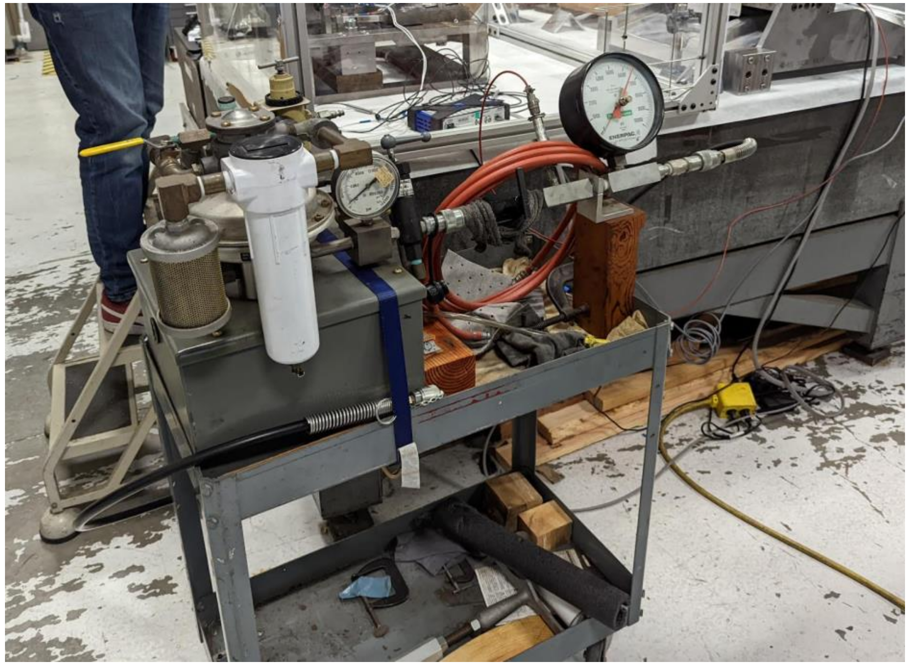
FE Analysis - Results

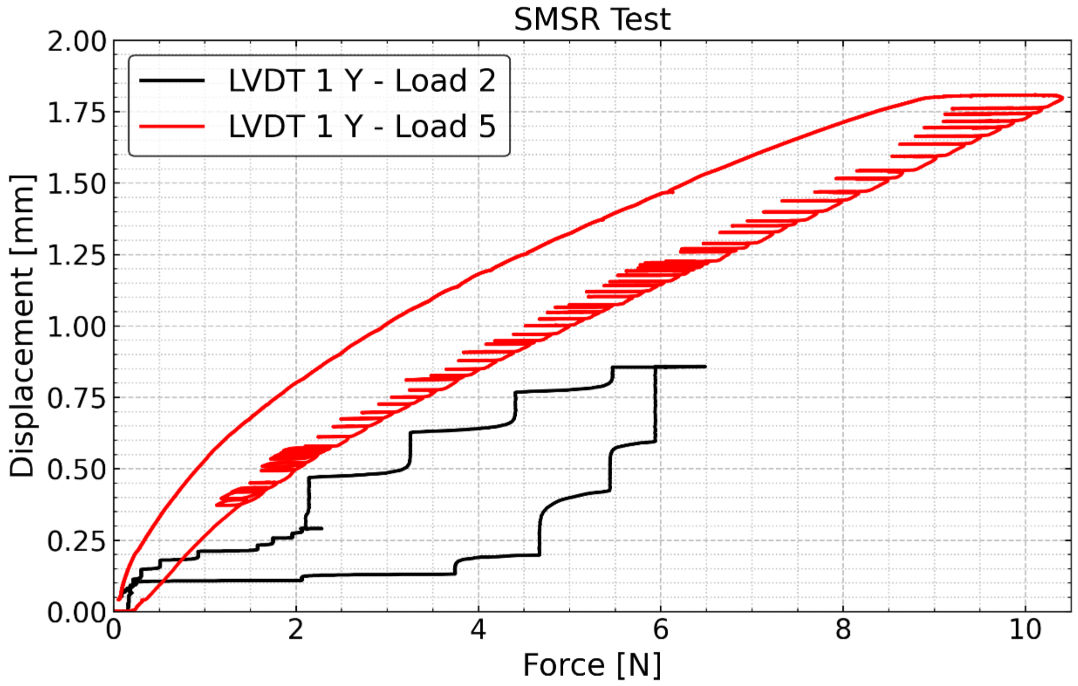




- SHM sensor strategy
  - Bending measurement on the brackets (half-bridge configuration)
  - Sensitivity: 16 (μm/m)/KN x 2 = 32 (μm/m)/KN

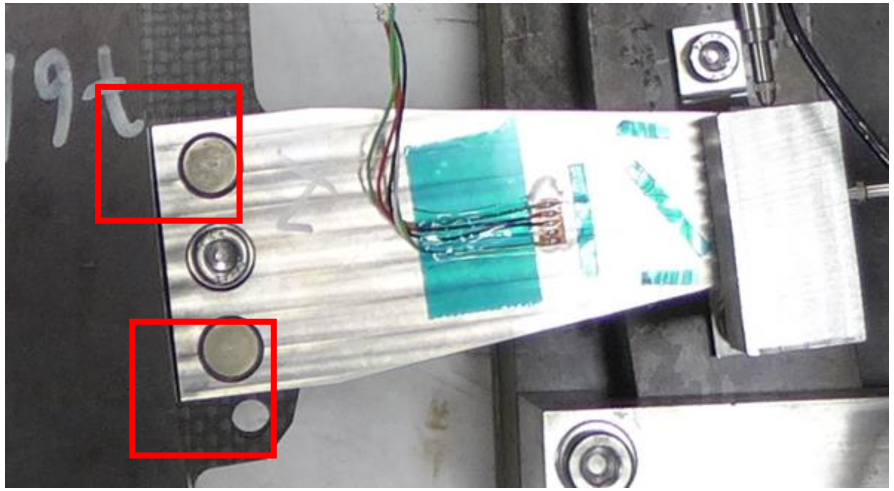
Testing Campaign – Improvement 1

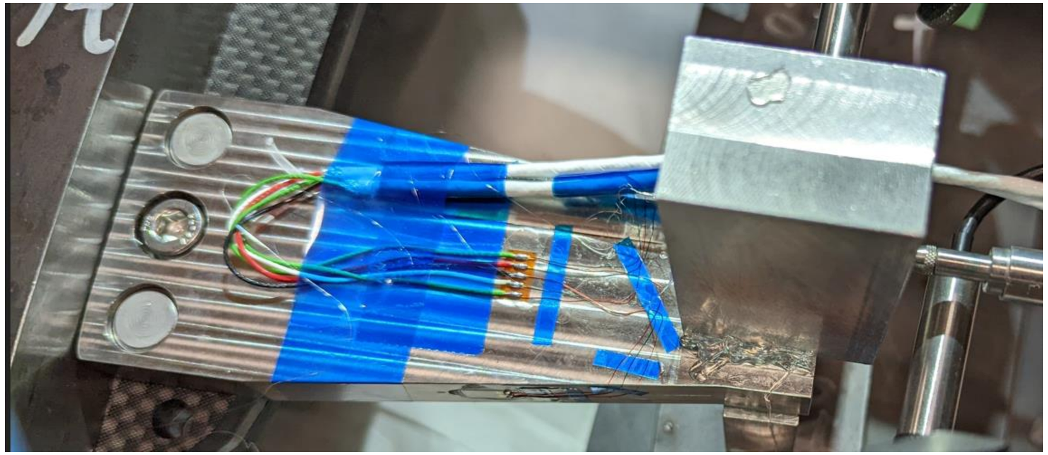




- Pressure 'control' machine borrowed from superconducting magnets group
  - Usually, they just target a pressure level, and do not care about slowly increasing the load (maybe they should)
  - Pressure levels required are much higher (~10 times)
  - New procedure allows to improve ramp up and down, and to get to the desired load with good precision
  - There is still some 'lag' between the pressure and displacement readings, to be investigated

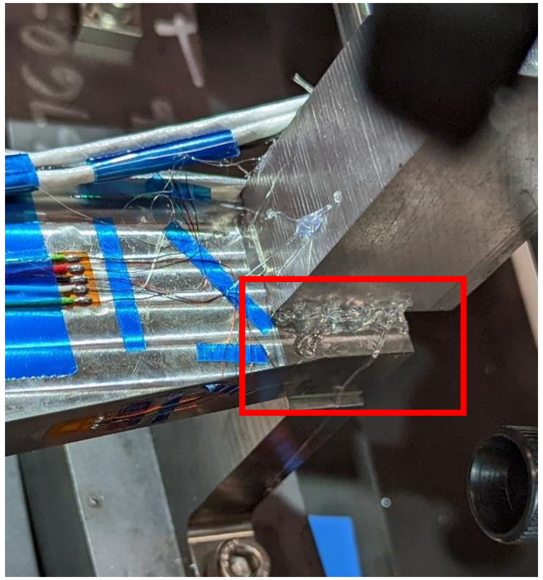
Testing Campaign – Improvement 2

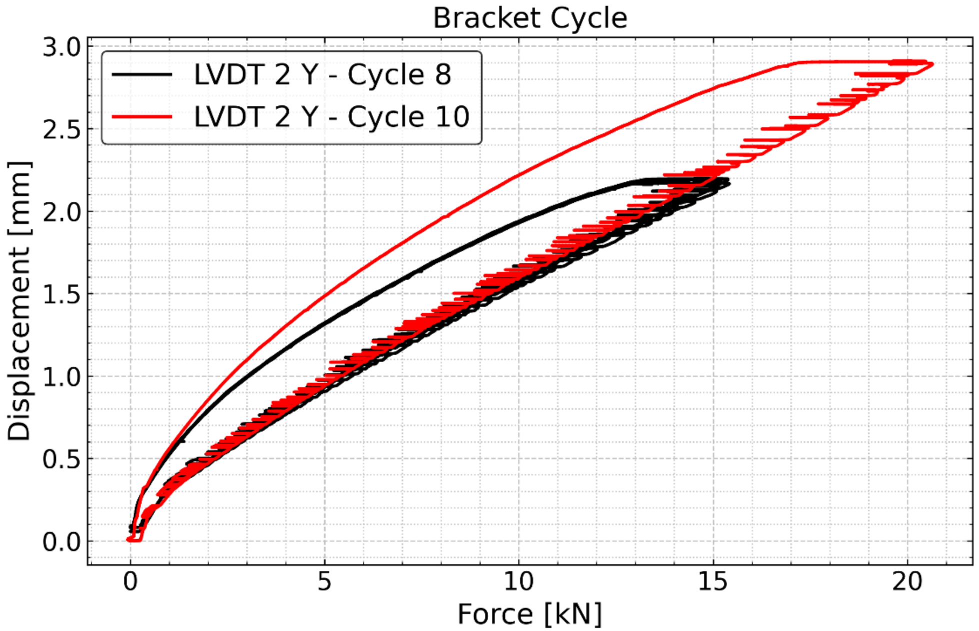




- Corners re-machined – getting into contact with the flange during loading

Results – Failure Load

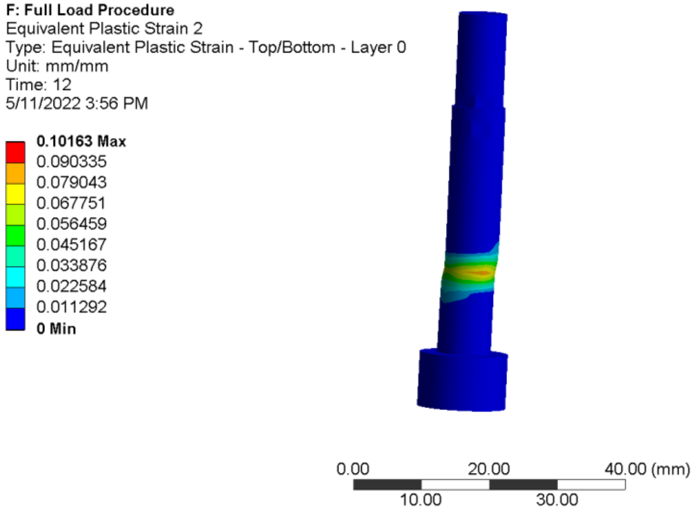


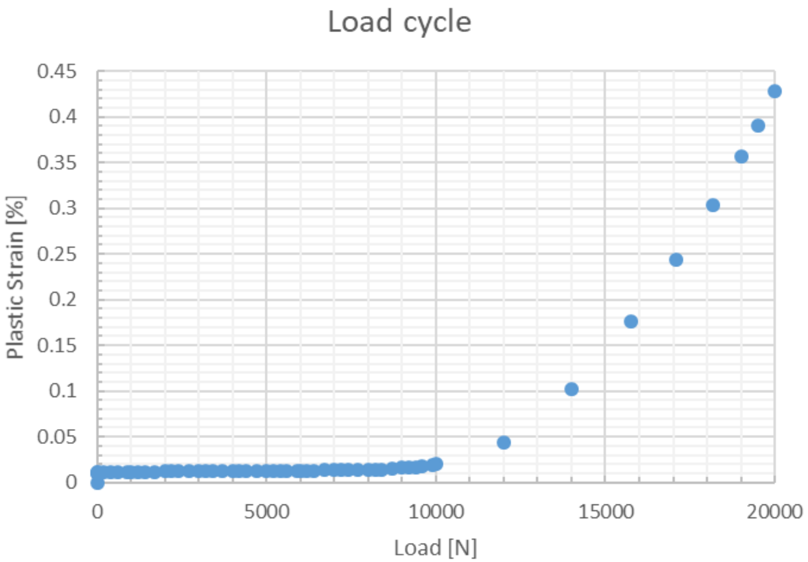


Failure load

- The system 'failed' above 15 kN, but reached 20 kN (safety factor ~4)
- Not easy to see on the measurements – checks in progress
- The failed component is the stud connecting the bracket to the bracket extension
  - Significant plastic deformation, but still carrying the load
  - Bushing was fine, as all the other components
  - This component is not in the correct material!
    - Titanium grade V yield is ~4 times higher

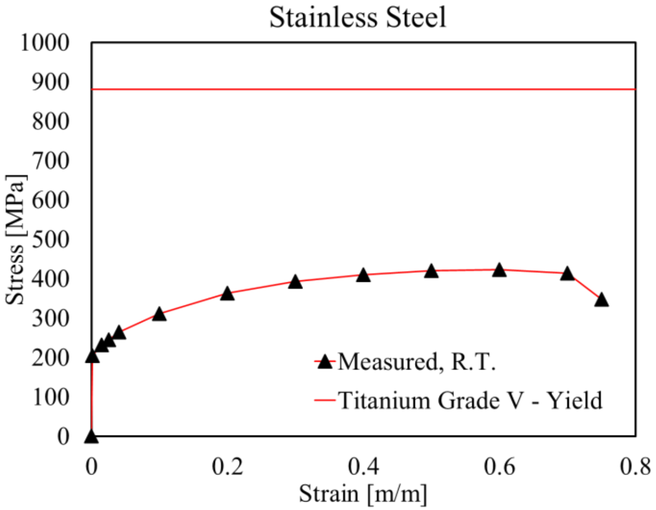
Results – Failure Load - FE



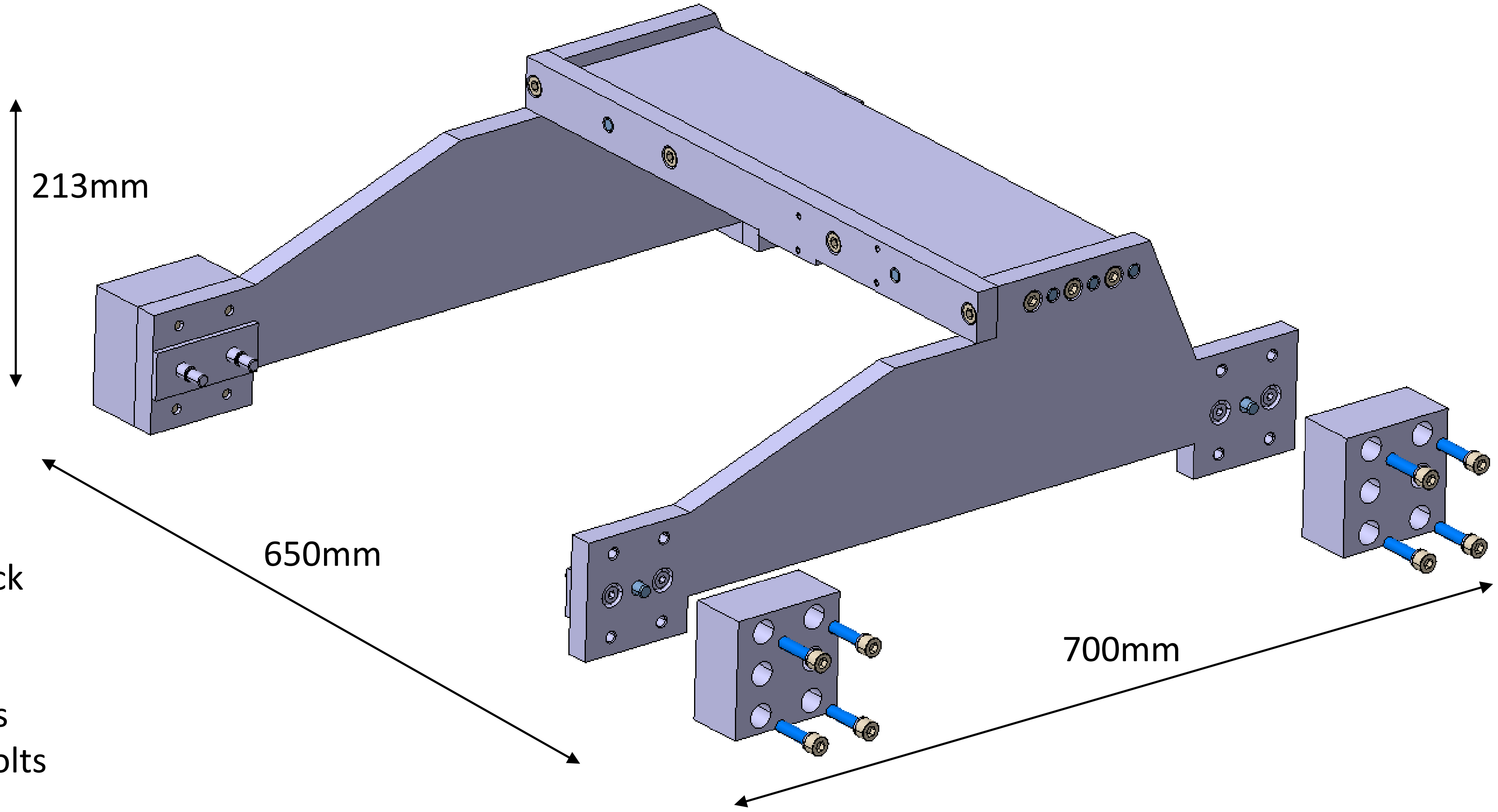


Failure load

- Updated analysis performed with correct bolt material
- Something strange in the geometry
  - Model one seem more optimal
- With conservative material properties model predicts significant plastic strain starting from 12 kN
  - Bolt eqv. stress ~200 MPa, but Titanium grade V has a yield strength of ~880 MPa
  - Still not 'failing' as the bolt hardens

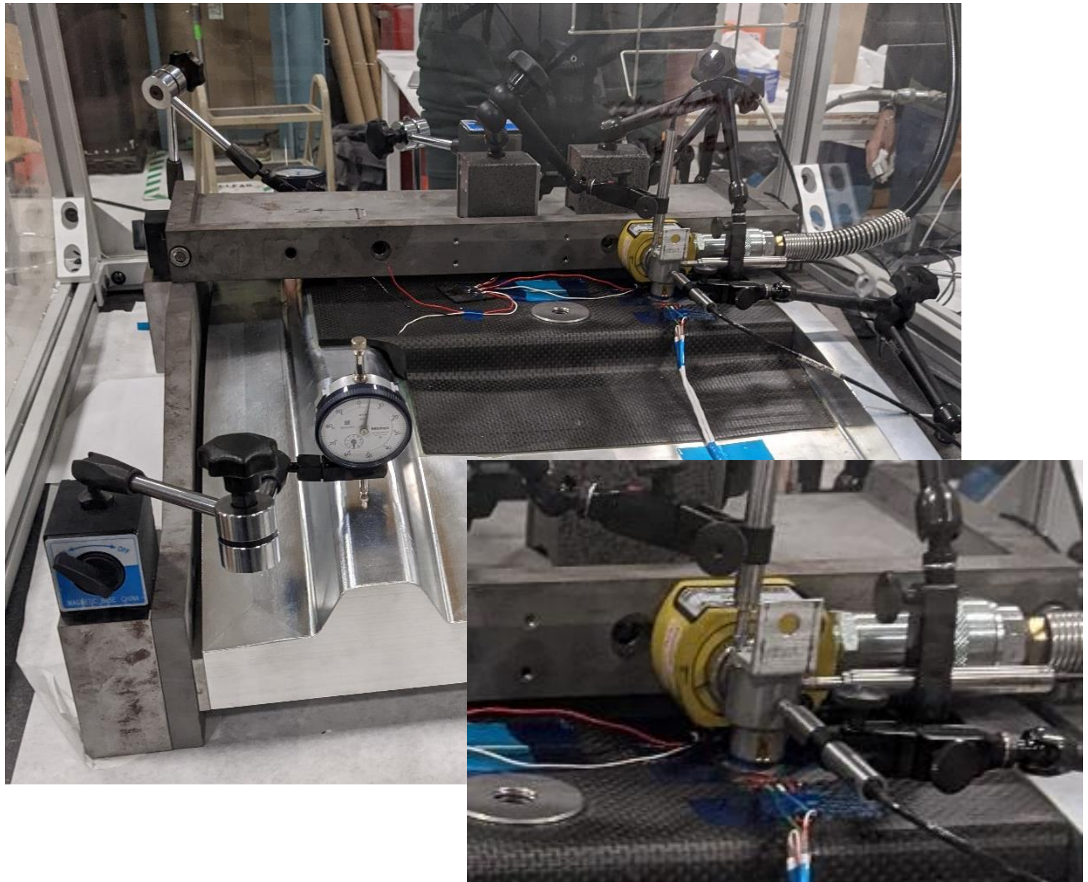


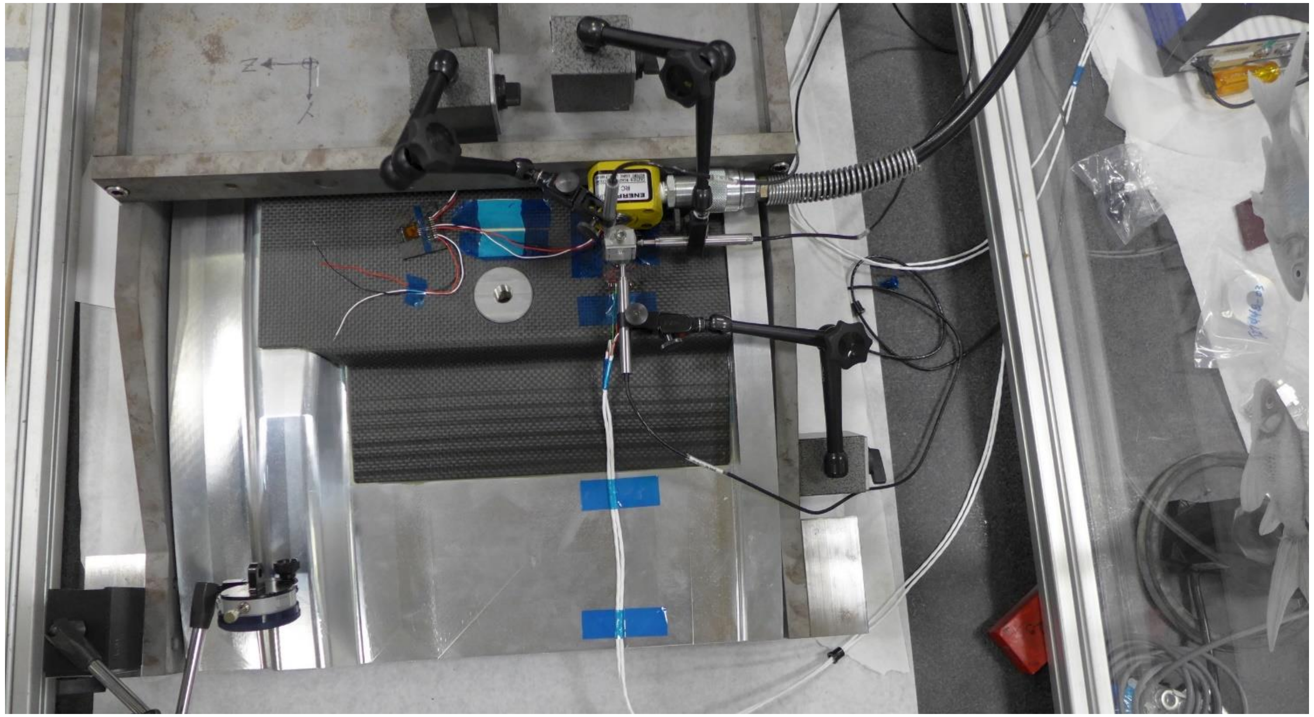
Mount Pad Frame



- Plates of 0.75inch thick
- Approx. mass = 58kg
- Fastners:
    - M10 Socket bolts
    - M10 Shoulder Bolts
    - D10 Pins

Mount Pad Assembly





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