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Additive Manufacturing: A Guide to Material Testing and Performance Verification

Date: 13 May 2026

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ENGINEERED SOLUTIONS

Agenda

- Why Additive Manufacturing?
- Laser Powder Bed vs. WAAM
- Industry Codes and Standards and Challenges
- Performance Verification and Validation through case studies
- Material Testing and Capabilities
- Overview of FEA vs Actual Performance of Burst Test Vessel

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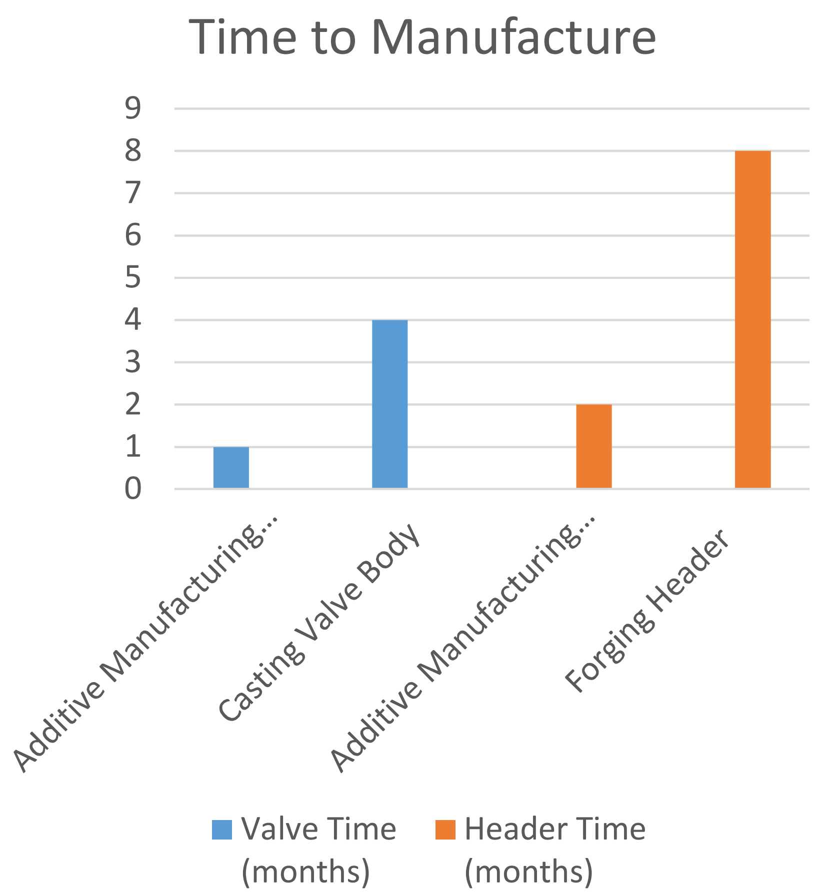
Why Additive Manufacturing

- Design Freedom
- Reduction in Lead Time
- Reduction in downtime
- Material Comparison
- Inventory Control



***Based upon SES and Lincoln Electric joint case studies*

Laser Powder Bed Fusion vs. Direct Energy Deposition (DED) Wire Arc Additive Manufacturing

Laser Powder Bed Fusion (LPBF)

- Precision Manufacturing: Ideal for fine geometries
- Materials: Ni-based, Ti, Al, CoCr, stainless
- Applications: Aerospace, medical implants, micro heat exchangers
- Challenges:
  - Small Components (Microwave)
  - High cost per part due to powder handling and slow build rate.
  - Sometimes requires post processing (heat treatment, machining)

Wire Arc Additive Manufacturing (WAAM)

- Scalability & Deposition Rate
- Materials: Carbon Steels, Ni alloys, Cu, Al, Ti.
- Applications: Pressure components, offshore, repair/refurbishment.
- Challenges:
  - Poorly controlled environment and weld parameters can lead too welded indications
  - May requires machining for net shape and precision.
  - Welding Orientation and part manipulation

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WAAM Snapshot

- GMAW — The Workhorse of WAAM
  - High deposition rates
  - Stable metal transfer modes (pulsed, CMT, controlled spray)
  - Readily available welding consumables
  - Robotic integration
  - Cost-effective and adaptable from existing welding cells
  - High wire utilization efficiency (>95%)

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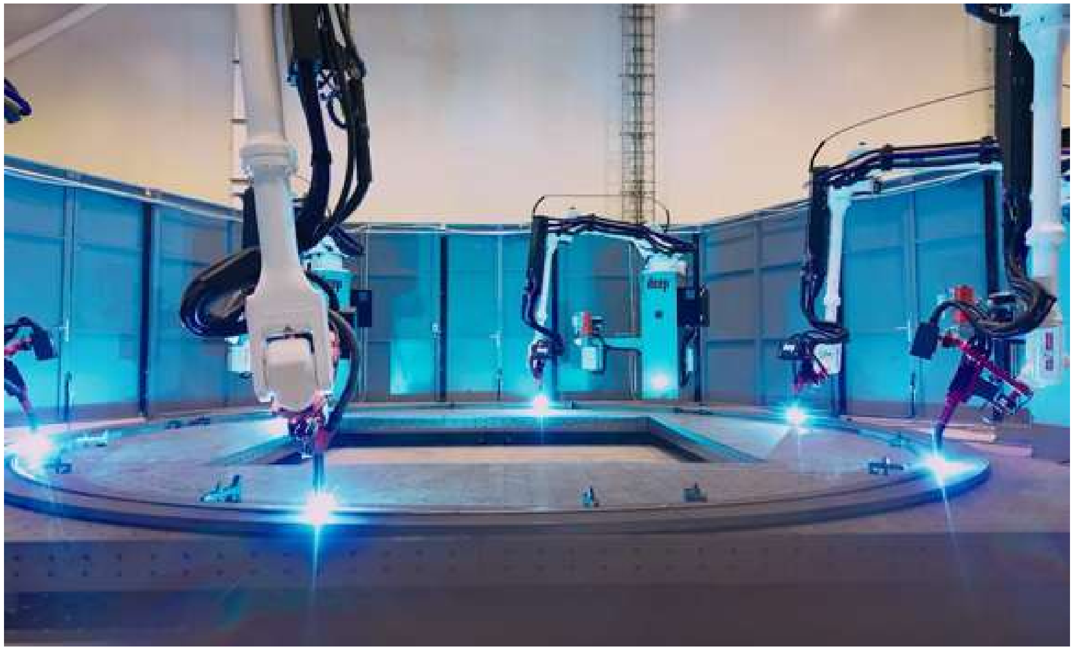
WAAM Snapshot

- Other Welding Processing/Technology
  - Gas Tungsten Arc Welding: Highest precision, low deposition, used for thin-wall or exotic alloys
  - Plasma Arc Welding: Concentrated arc with stable transfer, medium deposition, better bead definition.
  - Submerged Arc Welding: High deposition for large builds, ideal for cladding and heavy-wall sections.
  - Laser Welding: Combines laser and wire feed, fine control and improved surface finish
  - Multi-Robotic Systems



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Industry Codes

Industry Codes

ASME IX QW 600

Boiler and Pressure Vessel

NAVSEA S9074-A4-GIB-010

Requirements for Metal Directed Energy Deposition (DED)

API 20S

Qualification of Metal Additive Manufacturing Processes

NAVSEA S9074-A2-GIB-010

Requirements for Metal Powder Bed Fusion

AWS D20.1

Specification for Fabrication of Metal Components

DNV-ST-B203

Additive Manufacturing of Metallic Parts

<u>Design Codes</u>
ASTM 52910
ASME Y14.46

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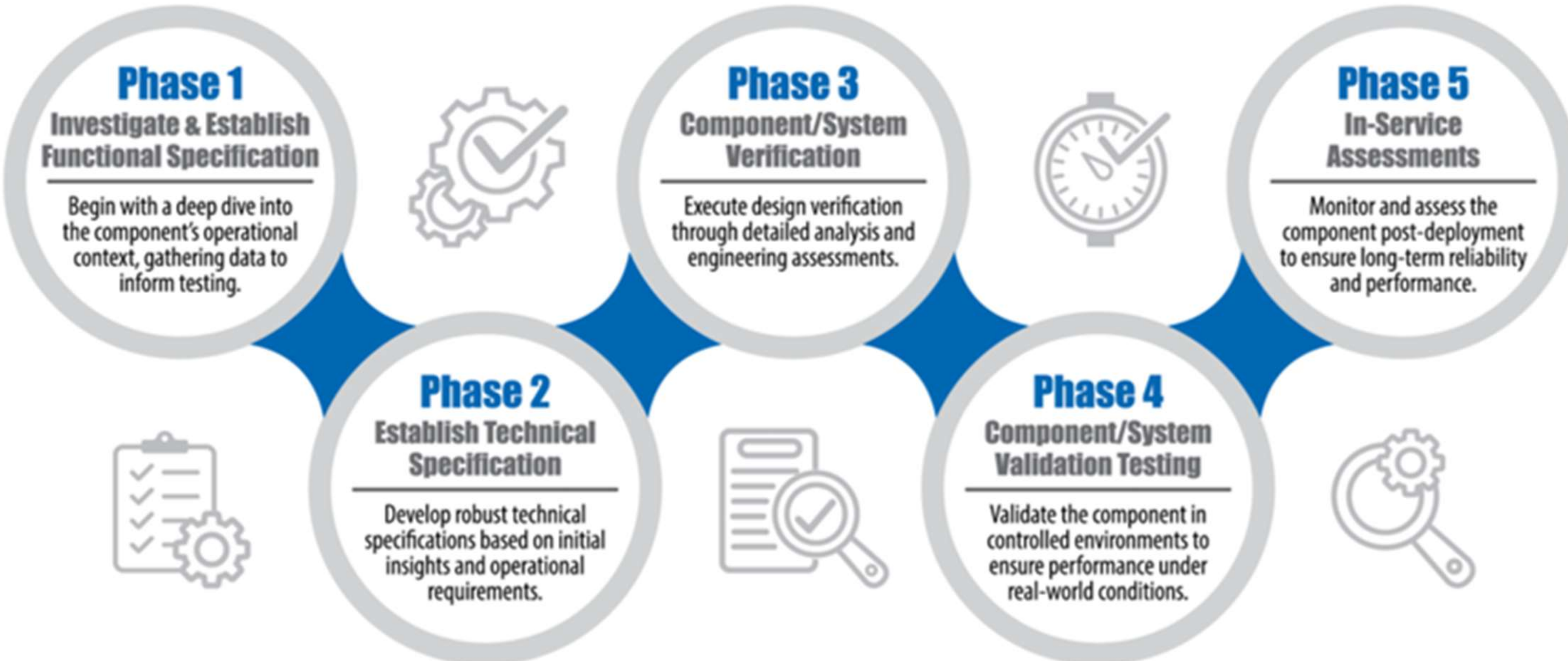
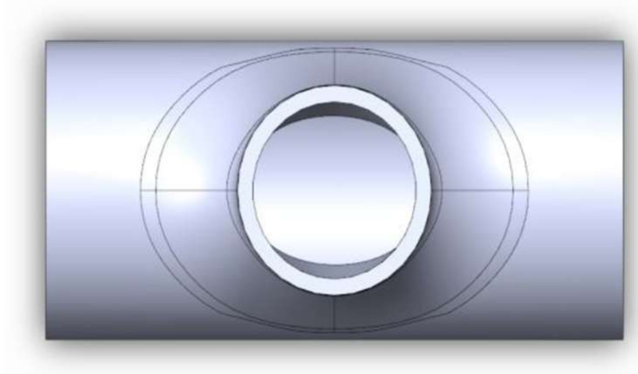
Road Map to Qualification



Subsea Tee: Design Basics

- Header Pipe Size: 20” nominal x XXXX wall thickness
- Branch Pipe Size: 14” nominal x XXXX wall thickness
- WAAM Material: Low Alloy Carbon Steel
- Tee Design Loads in Consideration
  - 20” Bending
  - 14” Bending
  - 20” Tension
  - Design Pressure

Isometric View



Top View

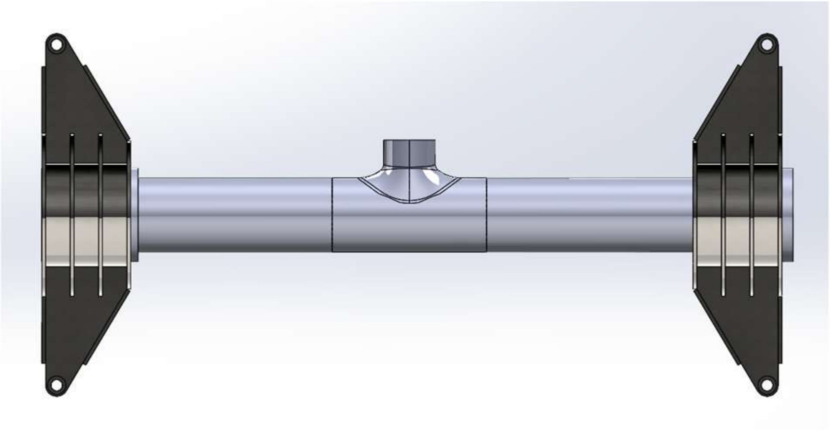
The Tee design per ASME Section VIII, Division 2 (Design by Analysis).

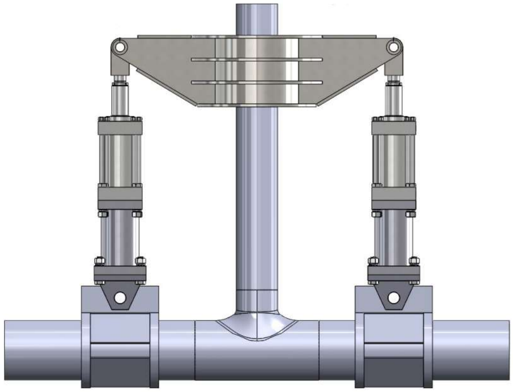
Tee Design , Analysis and Testing

The Tee design per ASME Section VIII, Division 2 (Design by Analysis).

Stress Engineering, as part of the qualification program:

- Supplemental engineering
  - Fracture Mechanics (FM) analysis
  - Engineering Critical Assessments (ECA)
  - Local Thin Areas (LTA) evaluations
- Testing
  - Load
  - Pressure
  - Burst
- Test Monitoring
  - Data Acquisition System
  - DIC
  - AE



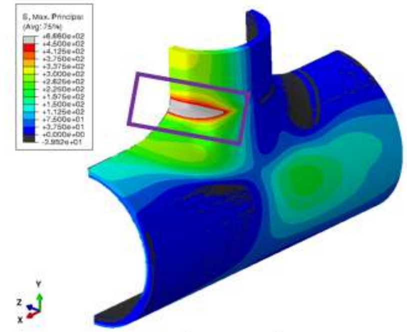


14” Bending Setup in test Fixture with hydraulic cylinders shown

FEA & ECA Analysis

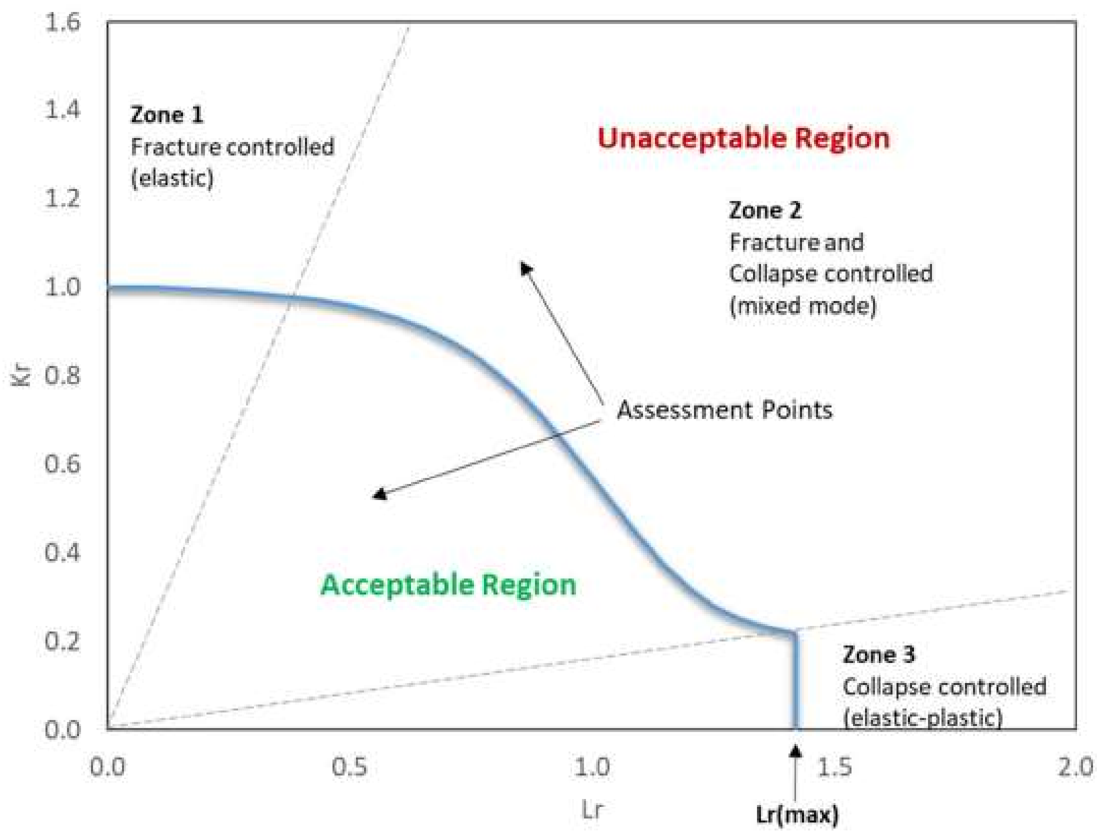
- FEA and ECA Result Summary

- Results show that inspection indication sizes fall within the acceptable range in the main header, under pressure and header tension cases
- The 20” tension case represents the least severe loading
- The results of this evaluation suggested that the TEE should survive testing loads without a fracture dominated failure, based on the size of indications that have been detected



Branch Bend

Example of DIC target location identified in report



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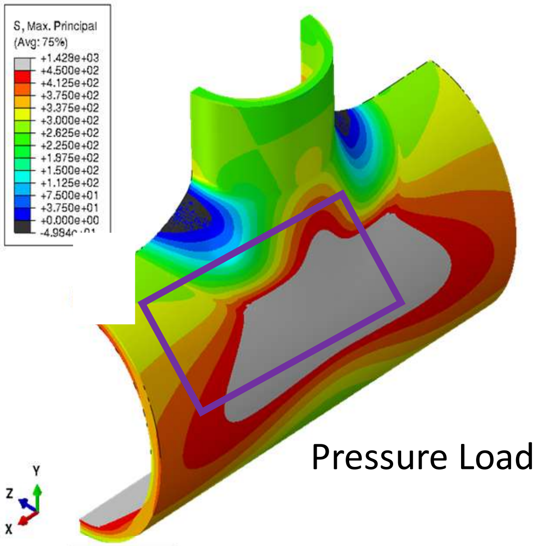
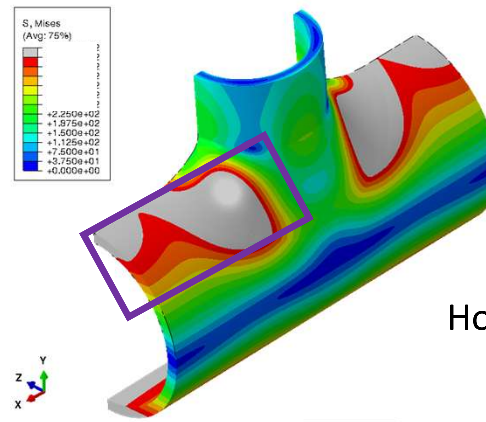
Locations of Interest for DIC

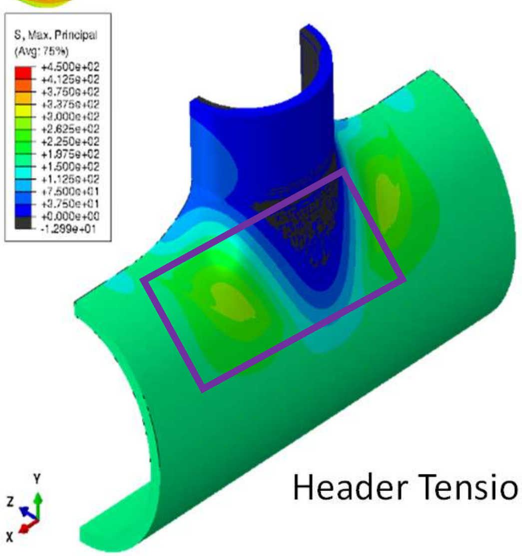
High stress locations on the OD of the sample are identified in each load case for digital image correlation



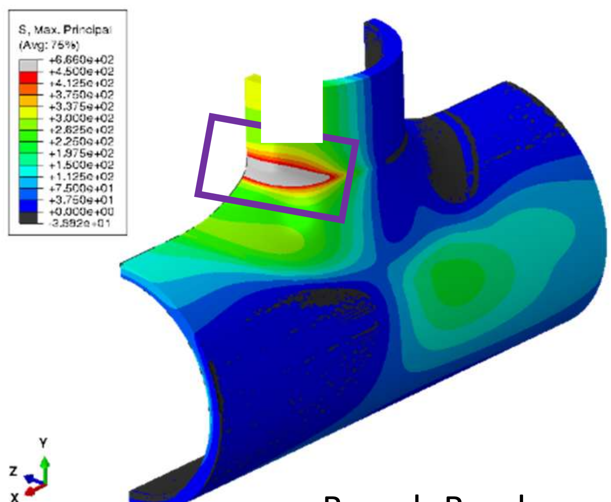
Pressure Loading



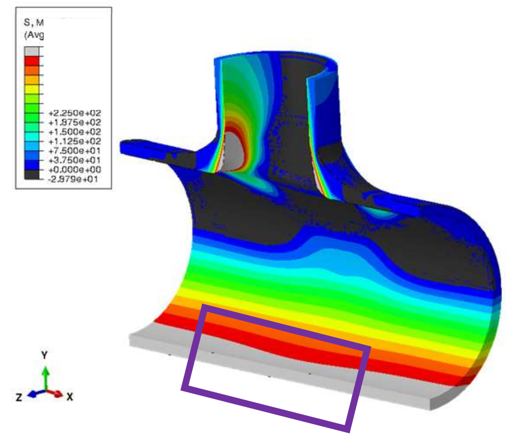
Hog Bend Loading



Header Tension



Branch Bend



Sag Bend Loading

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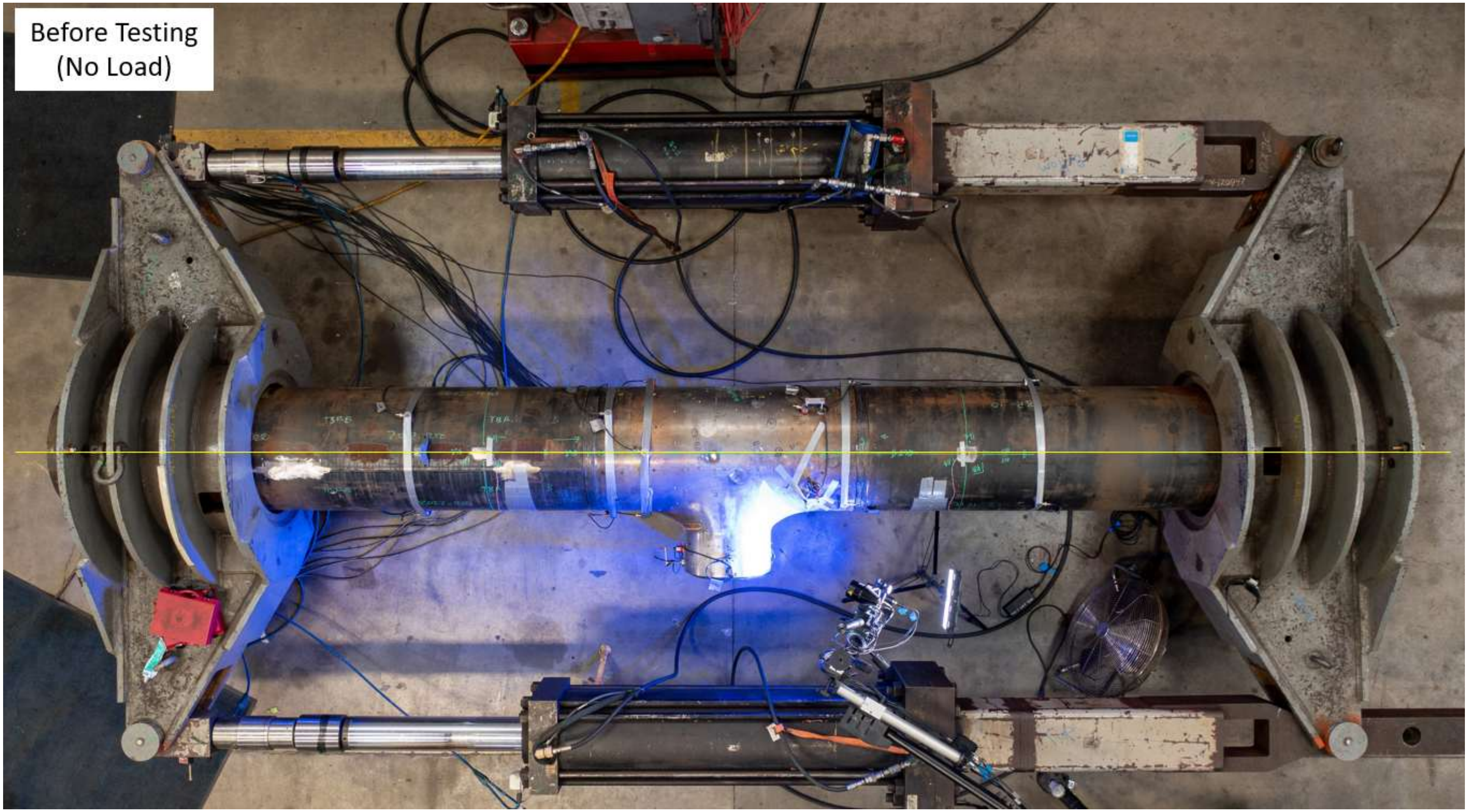
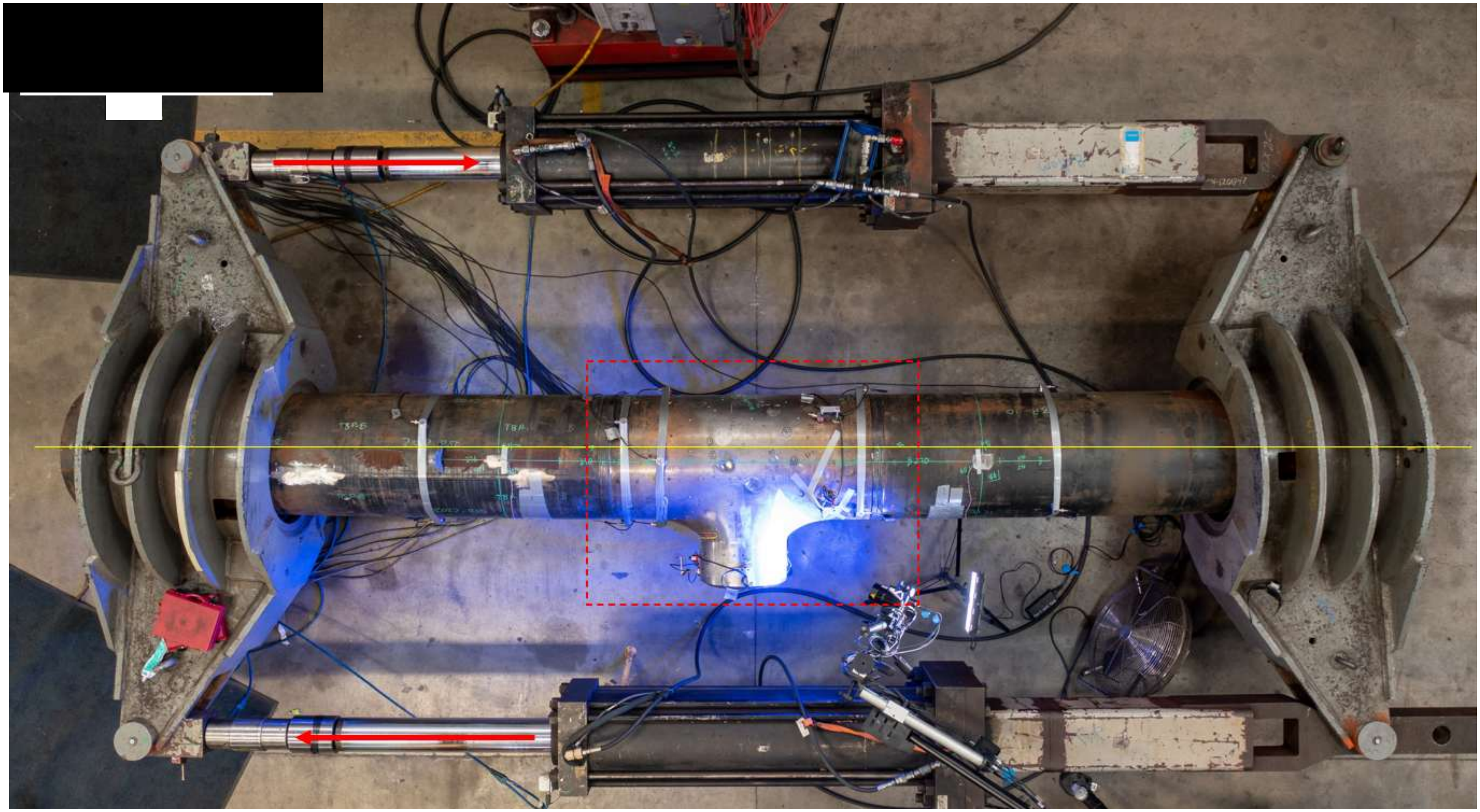
Bend Testing Pictures



Bend Testing Pictures



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Bend Testing Pictures

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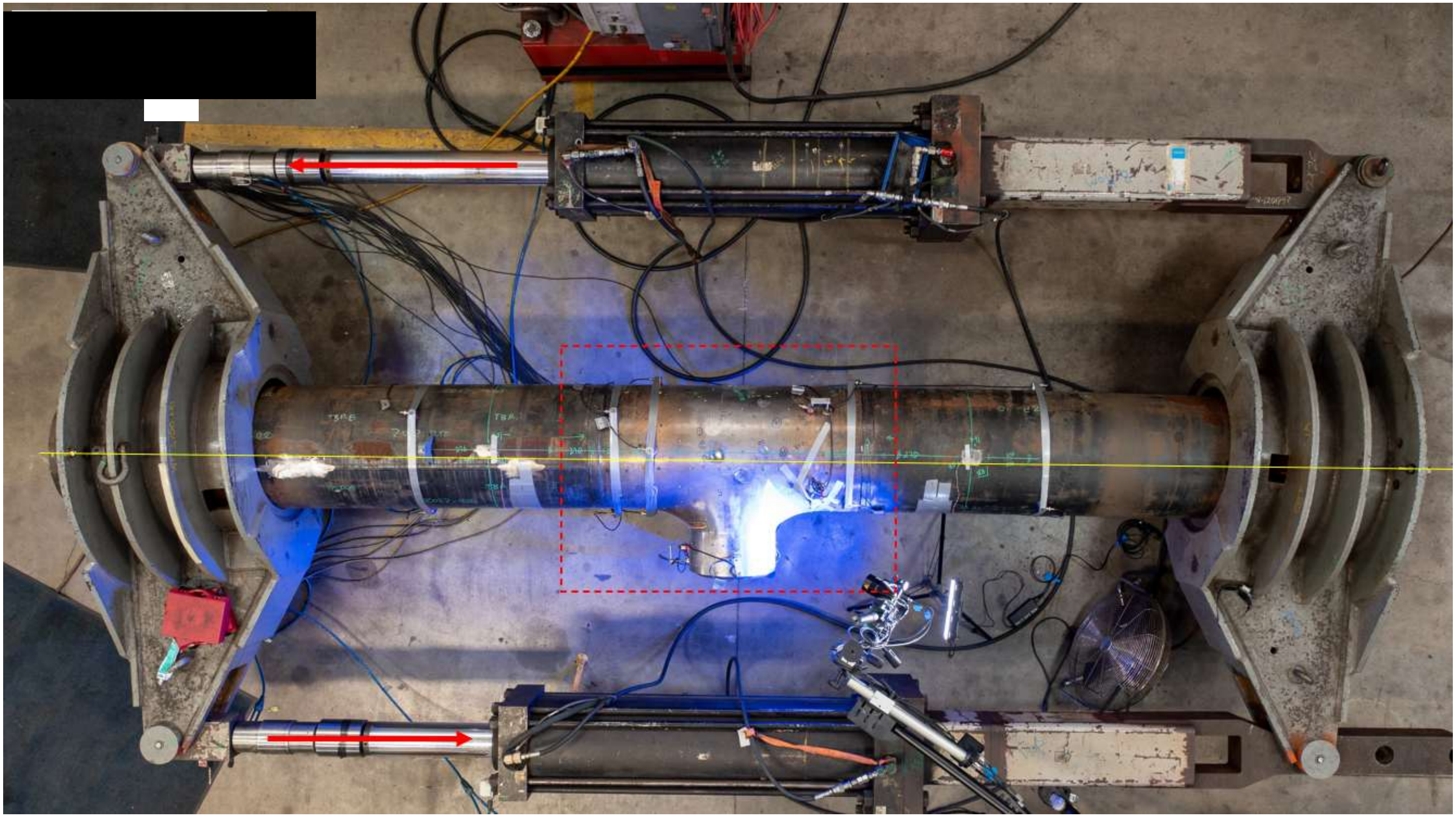

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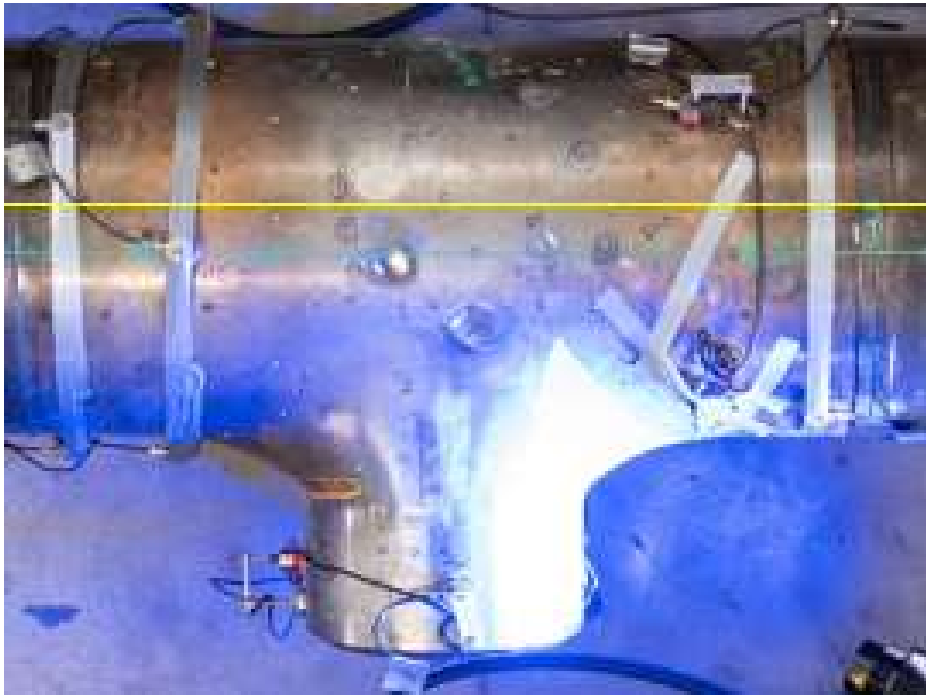
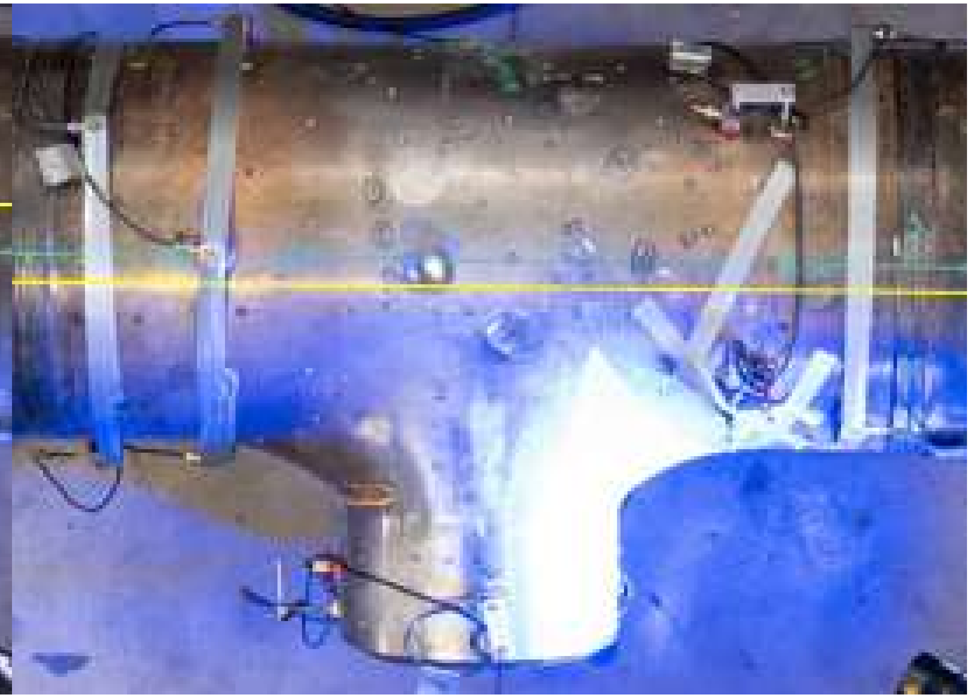
Bend Testing Pictures



Max Hog Bending



Max Sag Bending

For Both Pictures

- Green Line is Painted on Part
- Yellow Line is aligned with outer Center Point of Wings

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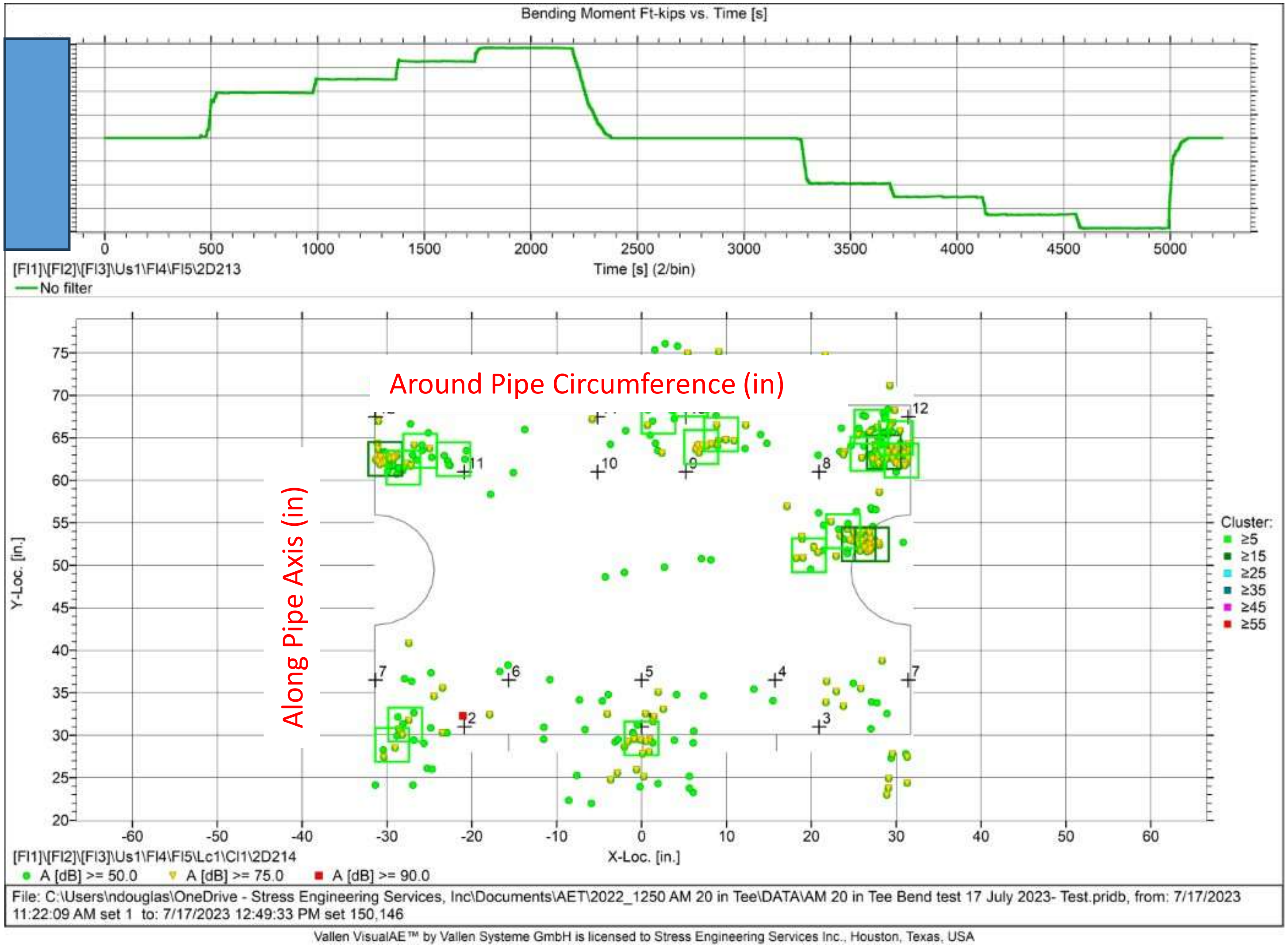
AE Tee Bending Observations



Cumulative Bending Cycle #1

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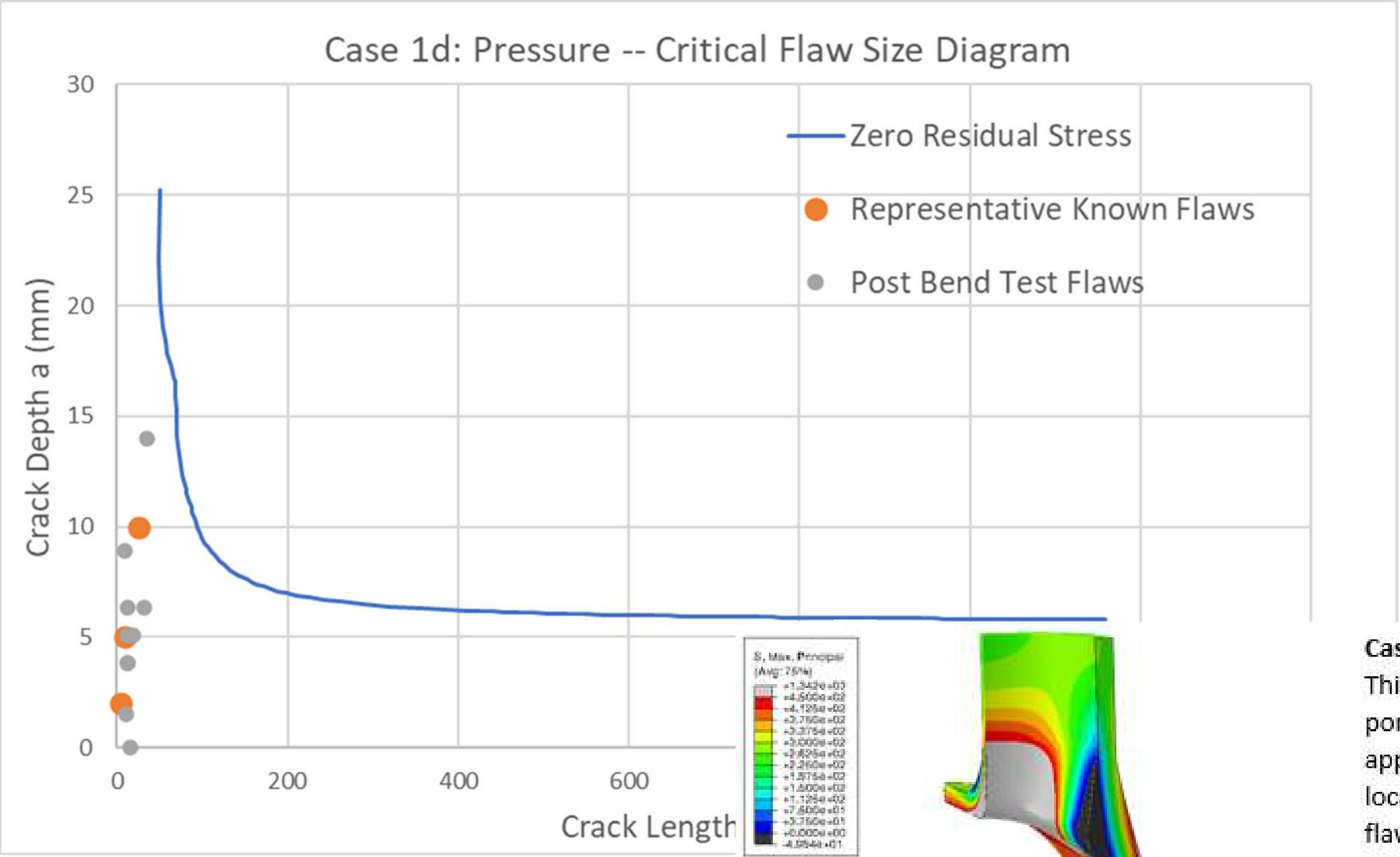
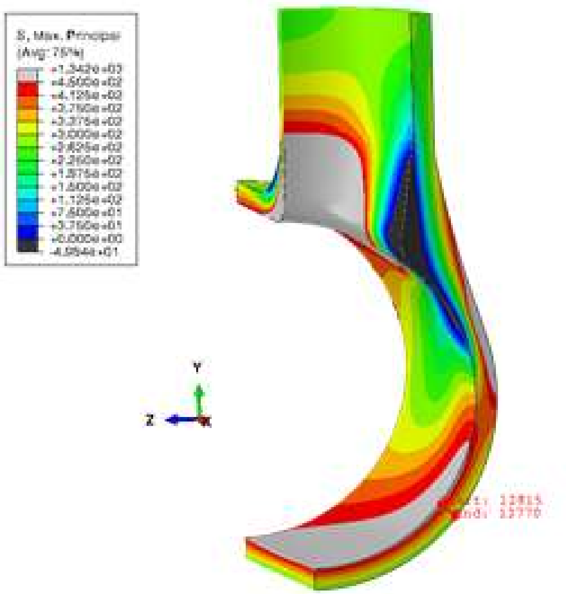
Revisiting the ECA due to New NDE Indications





Case 1d – Pressure
This pressure case on the lower portion of the Tee appears most appropriate based on the location of the post bend test flaws. The chart shows all flaws are smaller than the critical flaw sizes. Note: This ECA was done for axial flaws since hoop stress is generally higher. **These results are conservative for the detected circumferential flaws.**

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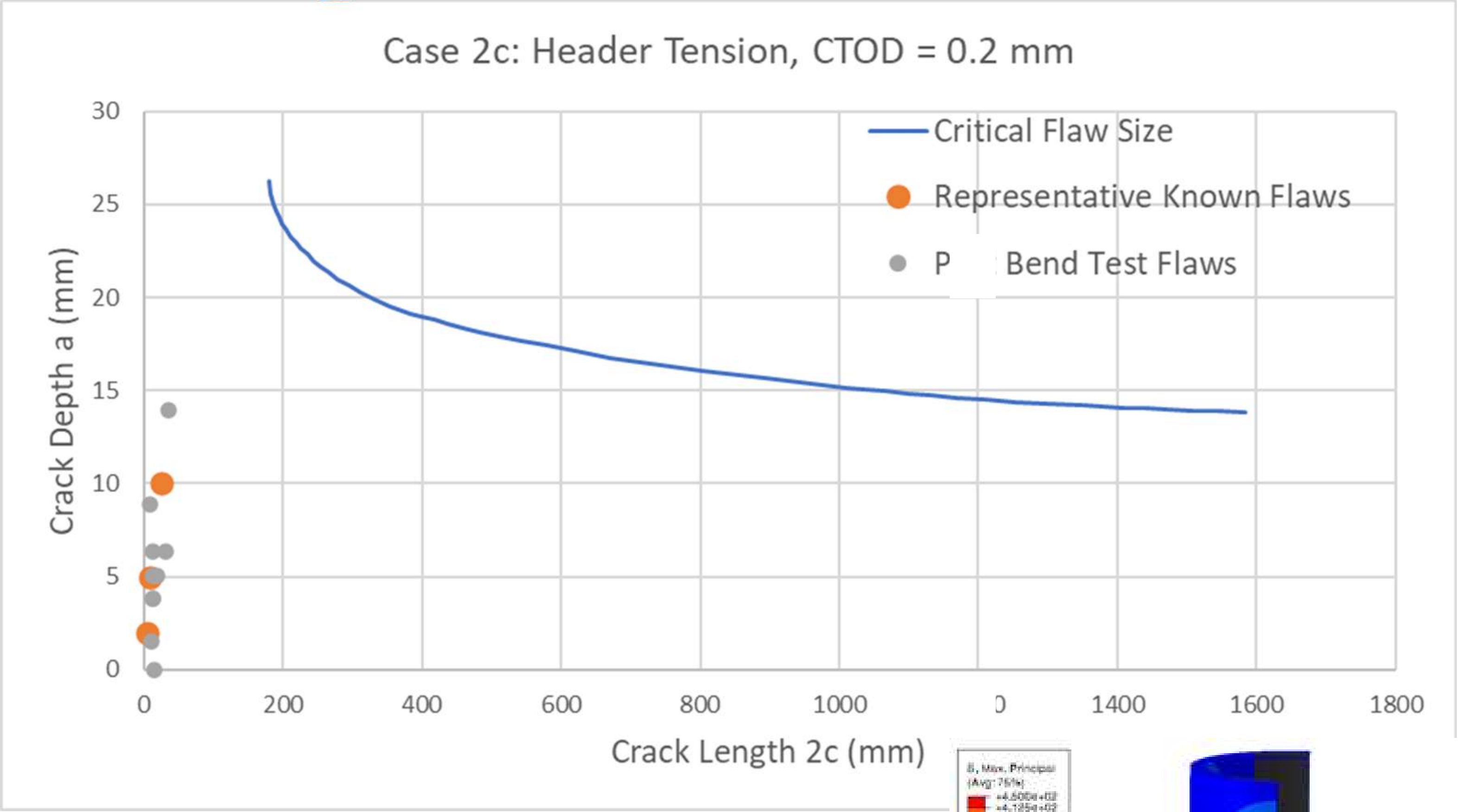
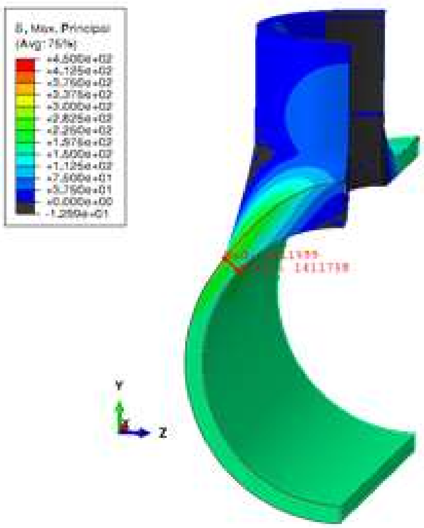
Revisiting the ECA due to New NDE Indications





Case 2c – Tension
For the tension case there is even more room between the critical flaw size curve and the post bend test flaws

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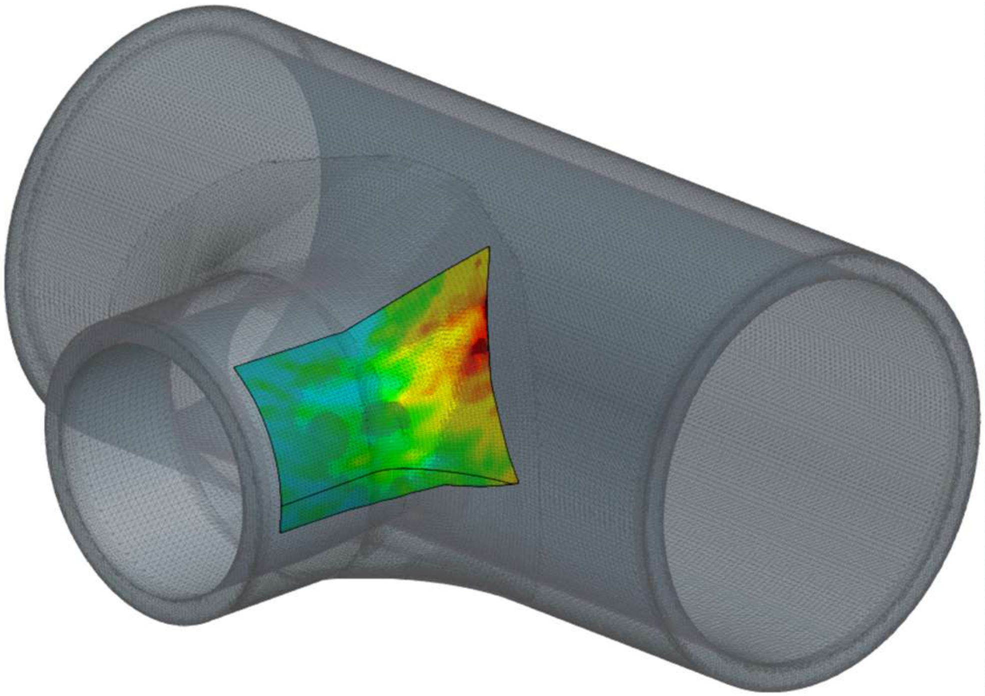
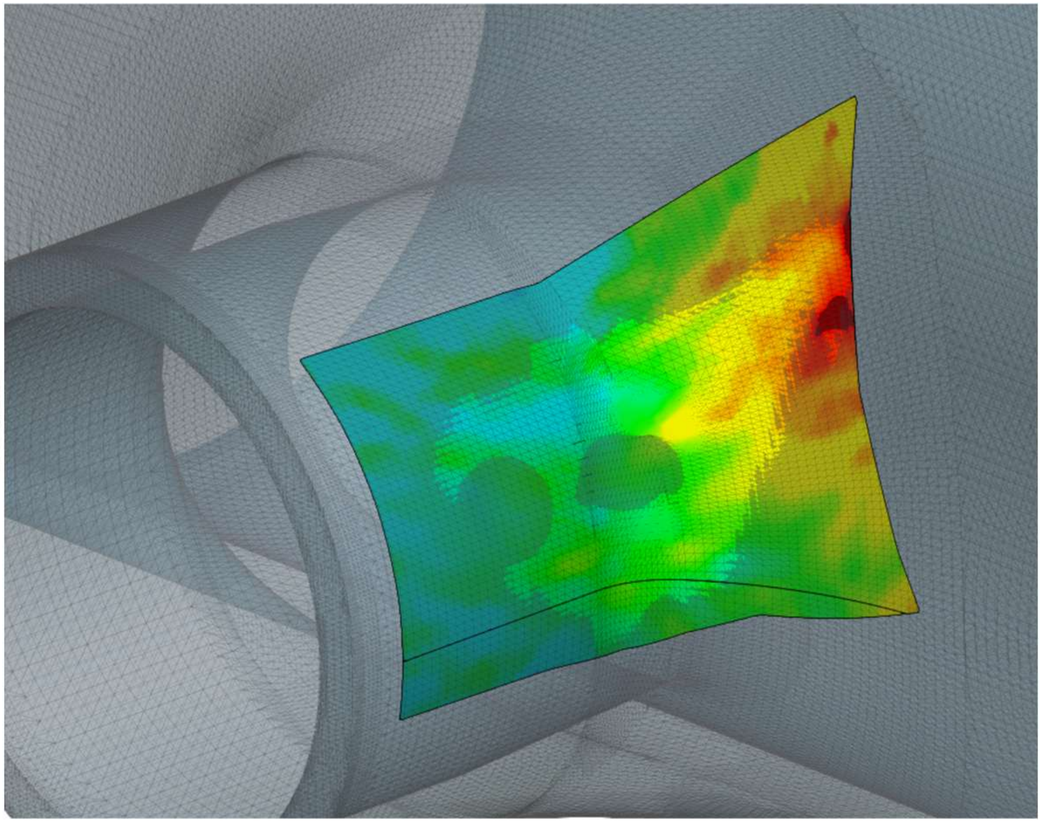
DIC Field of View Visualization





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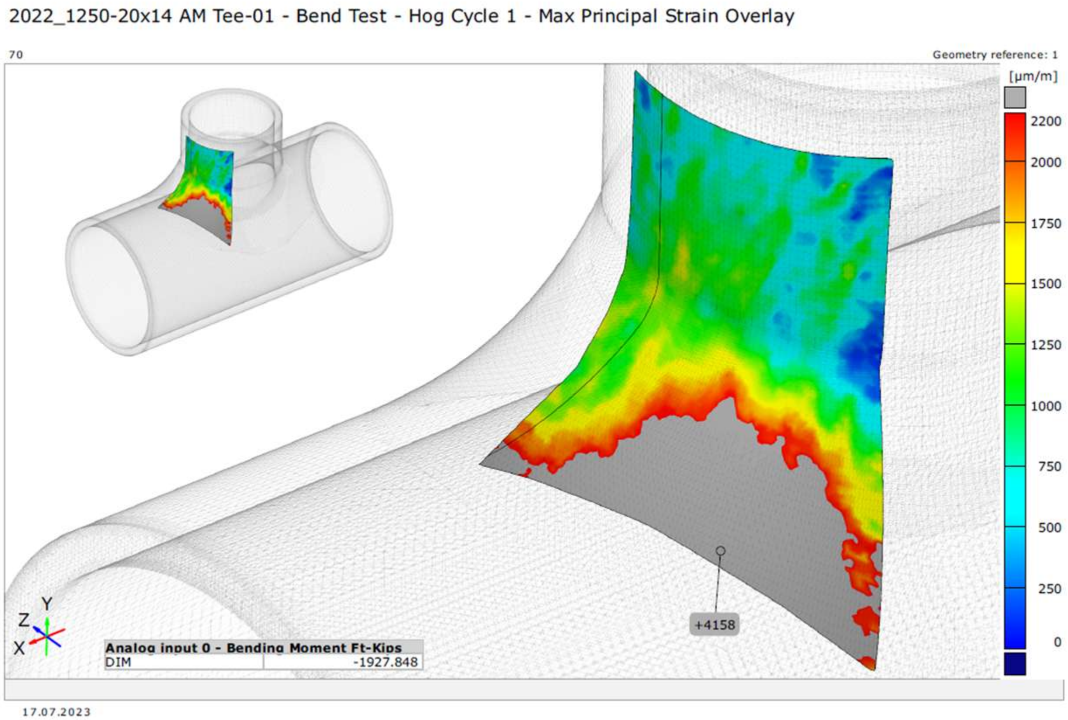
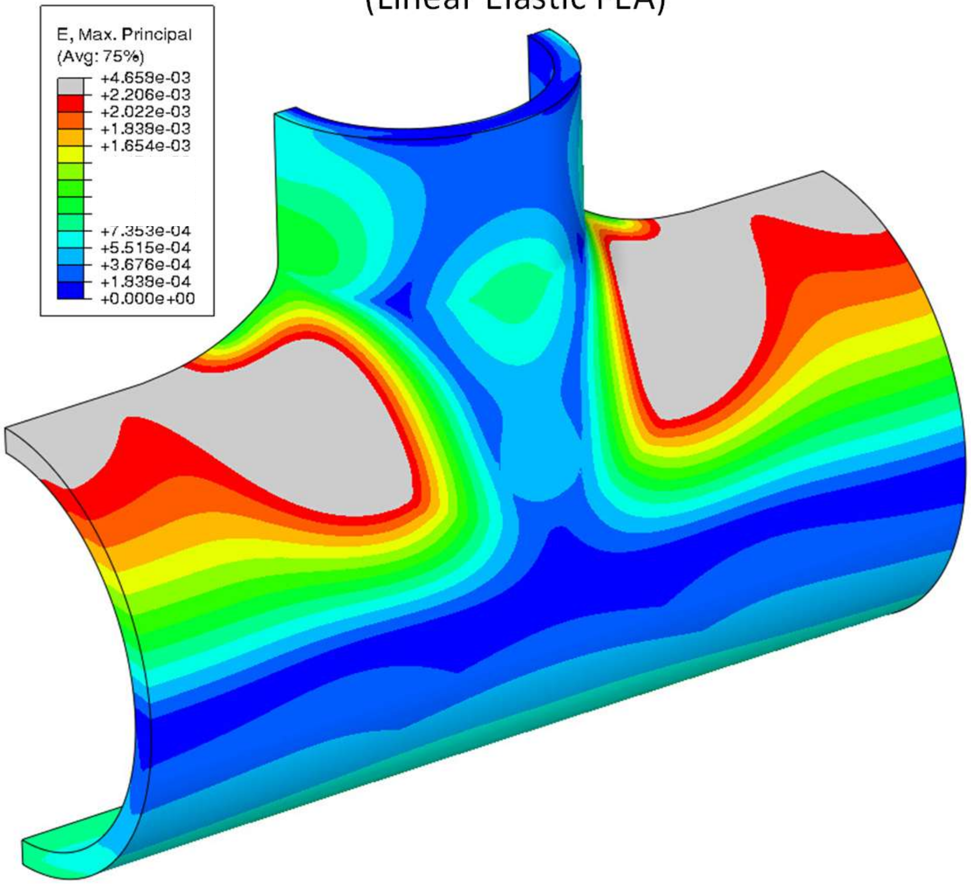
20” Bending Max Principal Strain, DIC vs FEA

Measured Strain
(DIC)



Calculated Maximum Principal Strain
(Linear Elastic FEA)



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Tension Testing Overview

- The Tee and pipe extensions were cut short and had pressure caps welded onto them.
  - 20” Load frame caps have integral attachments to allow for load frame interaction.
  - 1 single tension test
  - Continuously monitored with Strain Gages, DIC, and AE.

Tee in 6 Million Pound Load Frame – Isometric View

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Burst Testing Summary -Continued

- Burst of the Tee/Pipe weldment occurred in the Pipe welded to the Tee and not in the Tee itself. Failure in the DSAW Pipe was located away from the Long Seam Weld.
- A 3D scan of the Tee shows that in some areas, it is up to ~1/2” difference in dimensions from prior to burst testing.

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Refinery Success Story

- In early 2022, a facility turnaround needed replacements for several components in hydrogen furnace service. These components were critical path to restart the facility.

- Application was for a furnace header. Previous installation were two different Ni Alloys

- Existing components were damaged and unusable. Replacement using traditional methods estimated ~3 months.

- 3D printing was used to deliver replacements in just under 4 weeks, **avoiding a significant shutdown.**

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Refinery Success Story- Process

LINCOLN ELECTRIC

- Laser Scanning for reverse engineering by Customer
- WAAM Print (Manufactures) Header
- Shares Files

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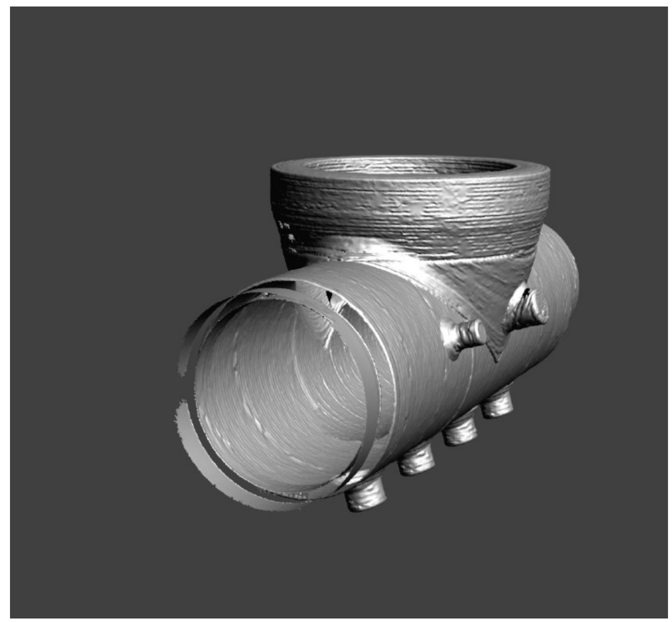
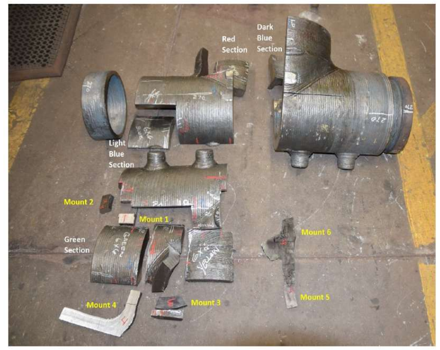
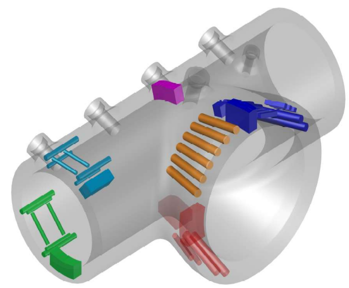
- Using LECO files
- Develops Prototype Qualification
- Inspection & Testing



Refinery Success Story:
Product Verification, Validation, Delivery





Creep Test Specimen

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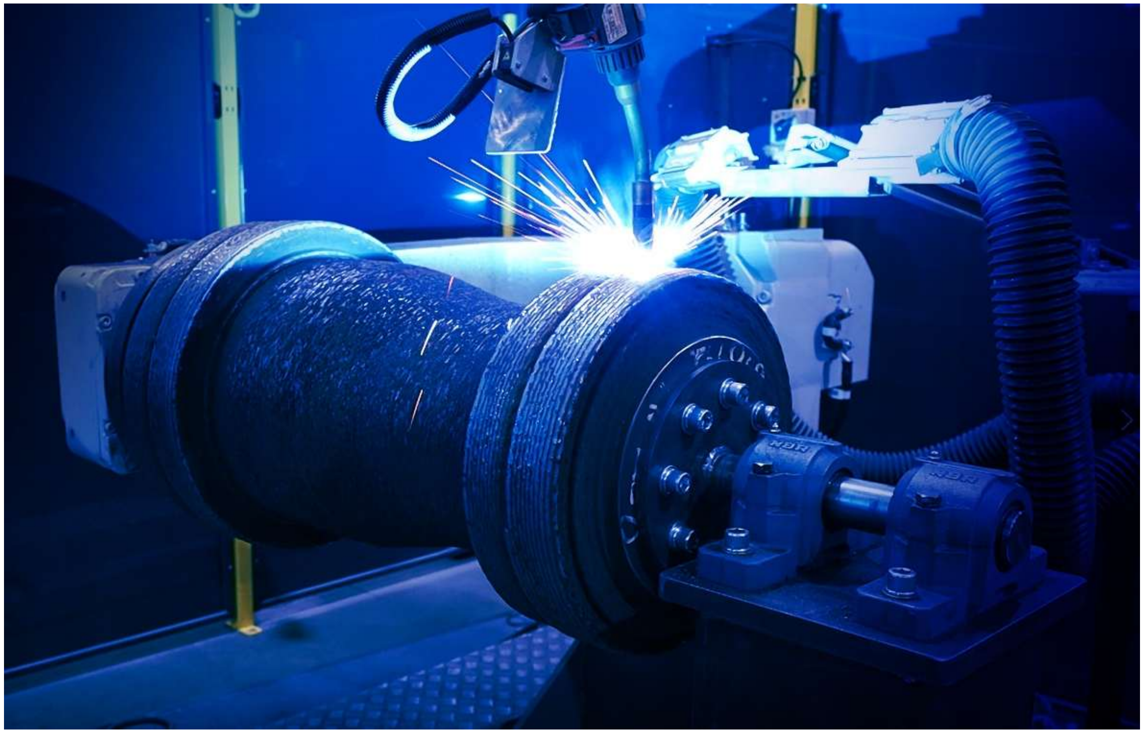
Pipe Spool Manufacturing

AML3D



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Other Applications

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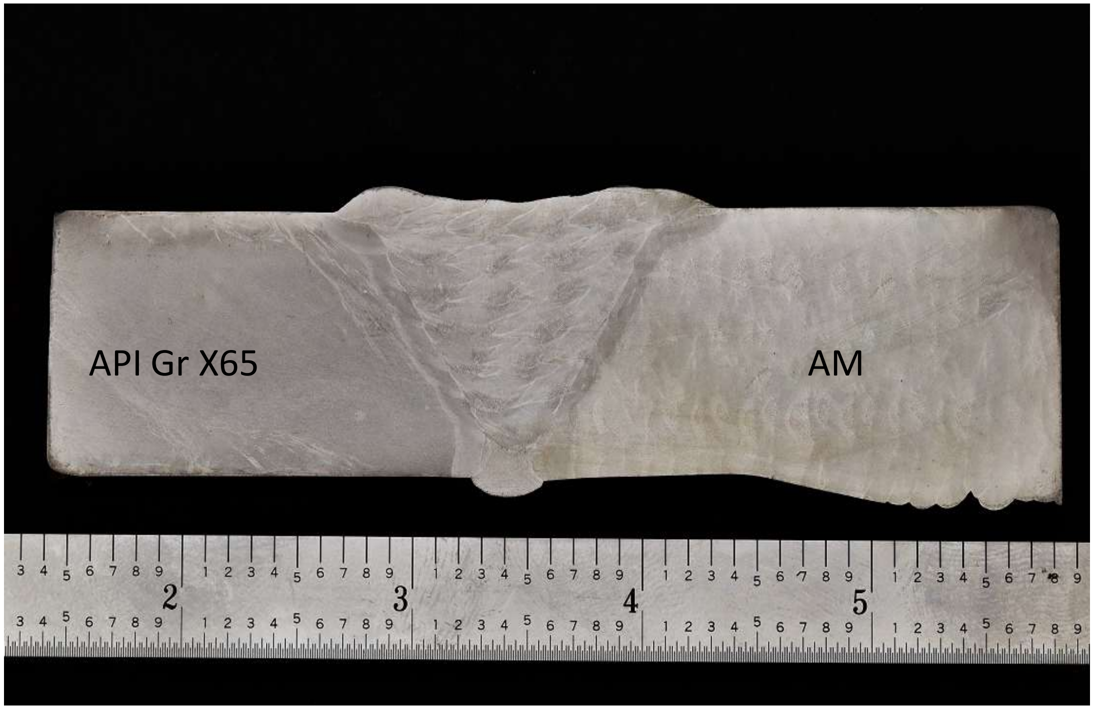
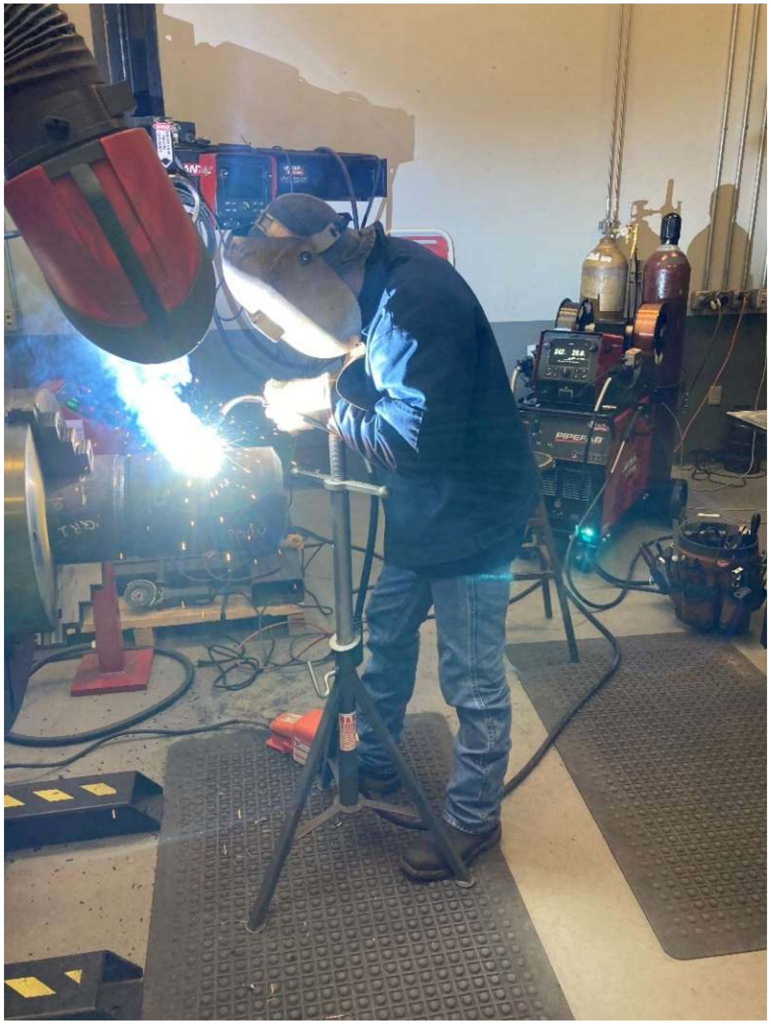
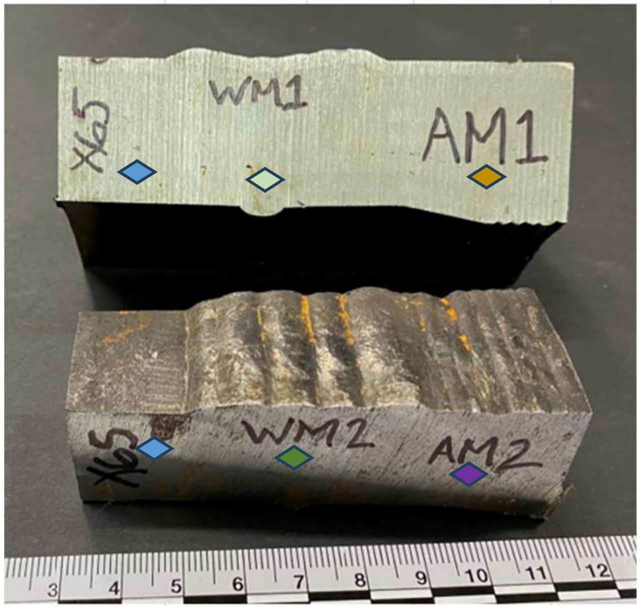
Girth Welding

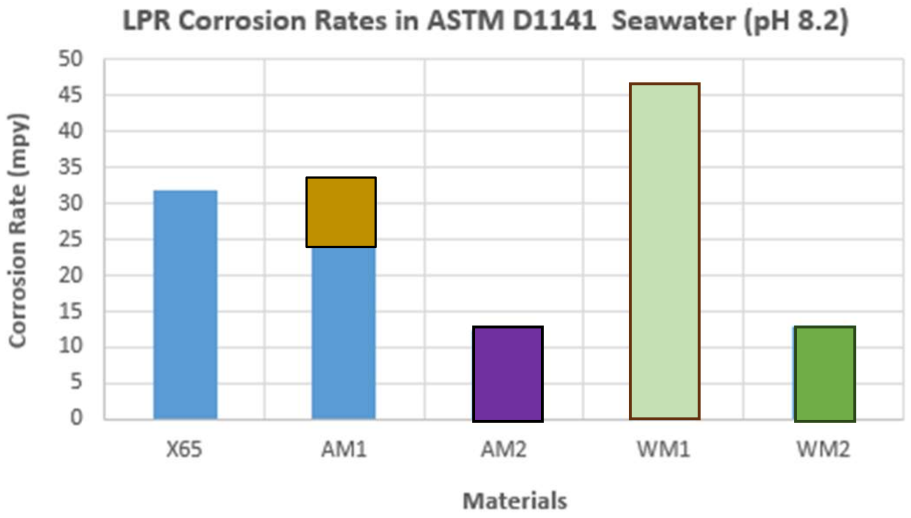
ASME IX Qualification
- GMAW Root
- FCAW





Carbon and Low Alloy Steel AM Corrosion Testing





Material	Corrosion Rate (mpy)
X65	31.85
AM1	33.21
AM2	12.3
WM1	46.42
WM2	12.85

Additive Manufactured Base Material
- **AM 1** Carbon steel "matching" strength = API 5L Gr X65
- **AM 2** Low Alloy steel "over matching strength" > API 5L Gr X65

Construction Girth Weld Material
- **WM 1** Carbon steel "matching" strength = API 5L Gr X65
- **WM 2** Low Alloy steel "over matching strength" > API 5L Gr X65

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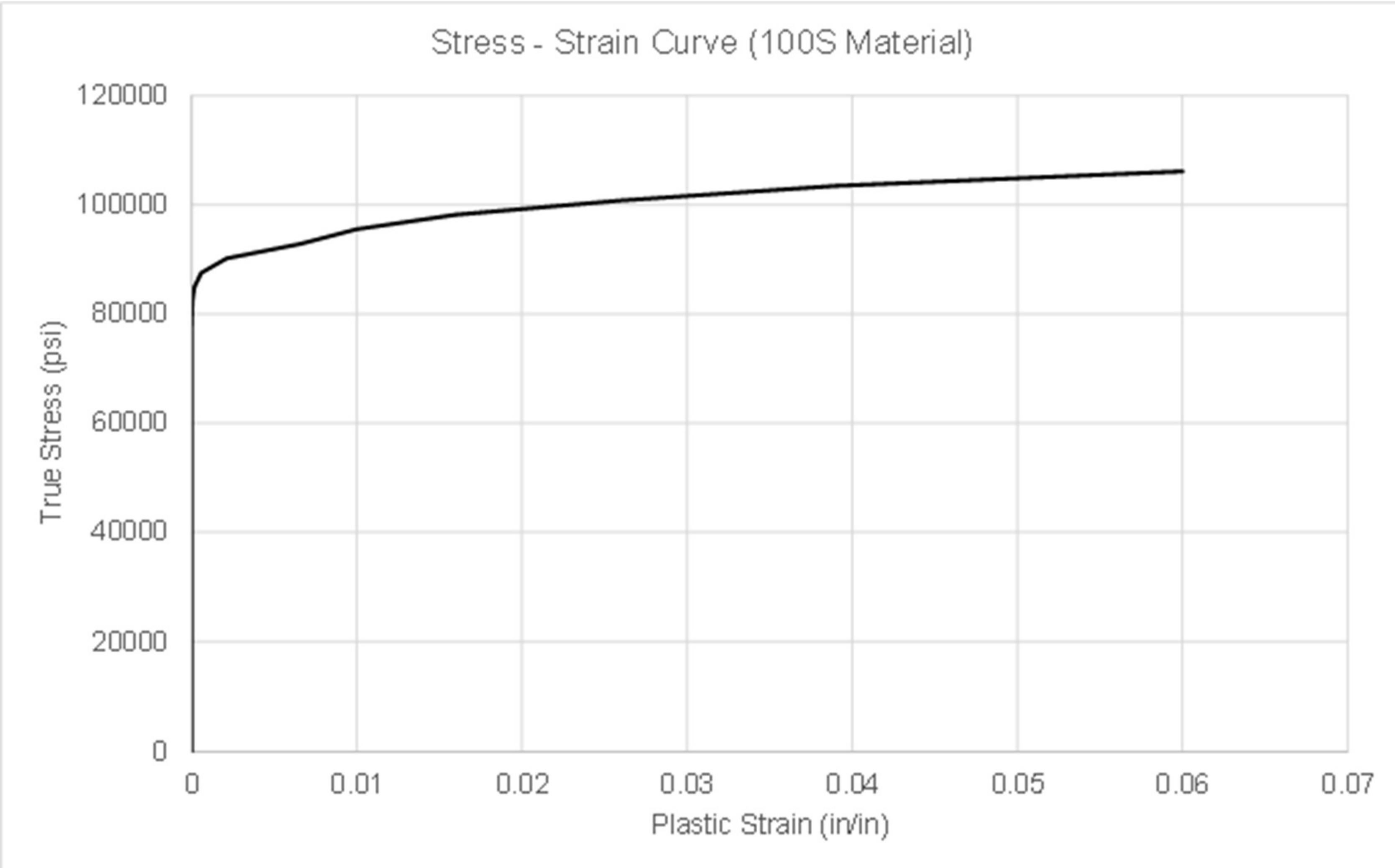
Burst Test Vessel – FEA Material Properties



(Elastic Plastic Material Curve Used in the FE Analysis)

Minimum Specified Material Properties
- Yield Strength = 90 ksi
- Ultimate Tensile Strength = 100 ksi
- Stress-strain using MPC material model from Boiler and Pressure Vessel Code.

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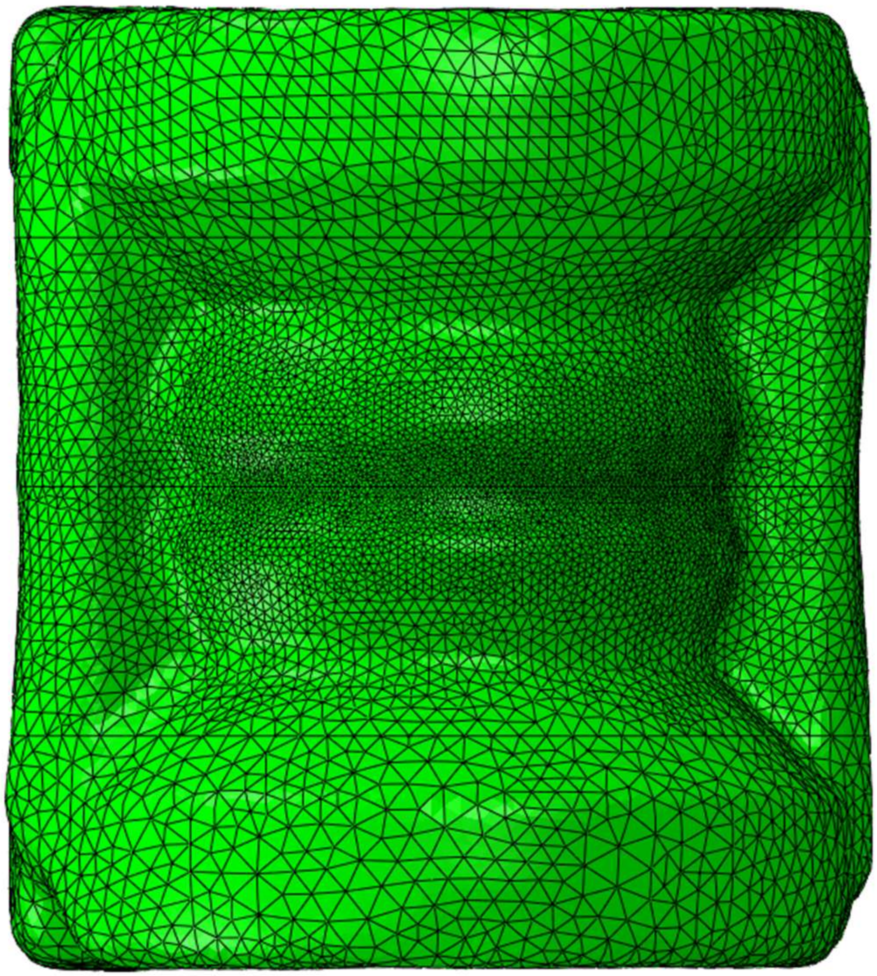
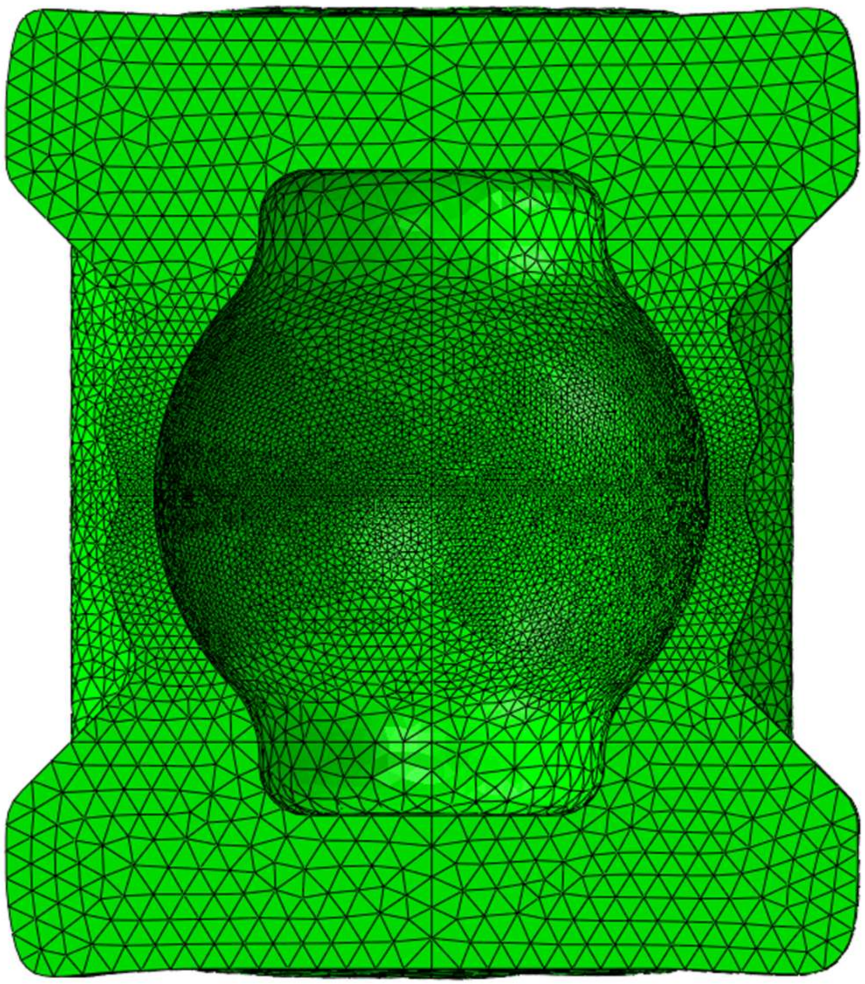
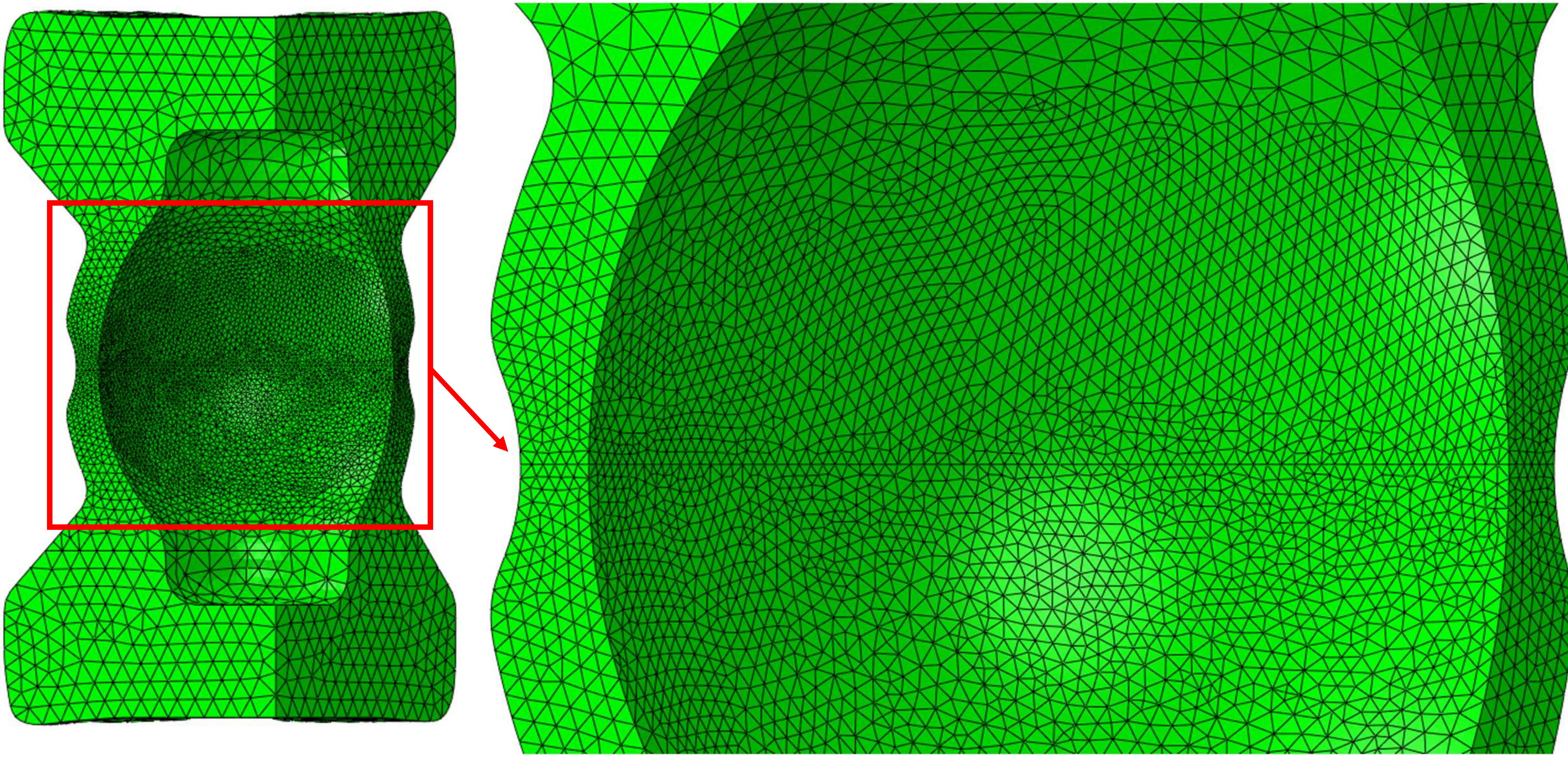
Burst Test Vessel – FEA Mesh





Burst Test Vessel – FEA Mesh



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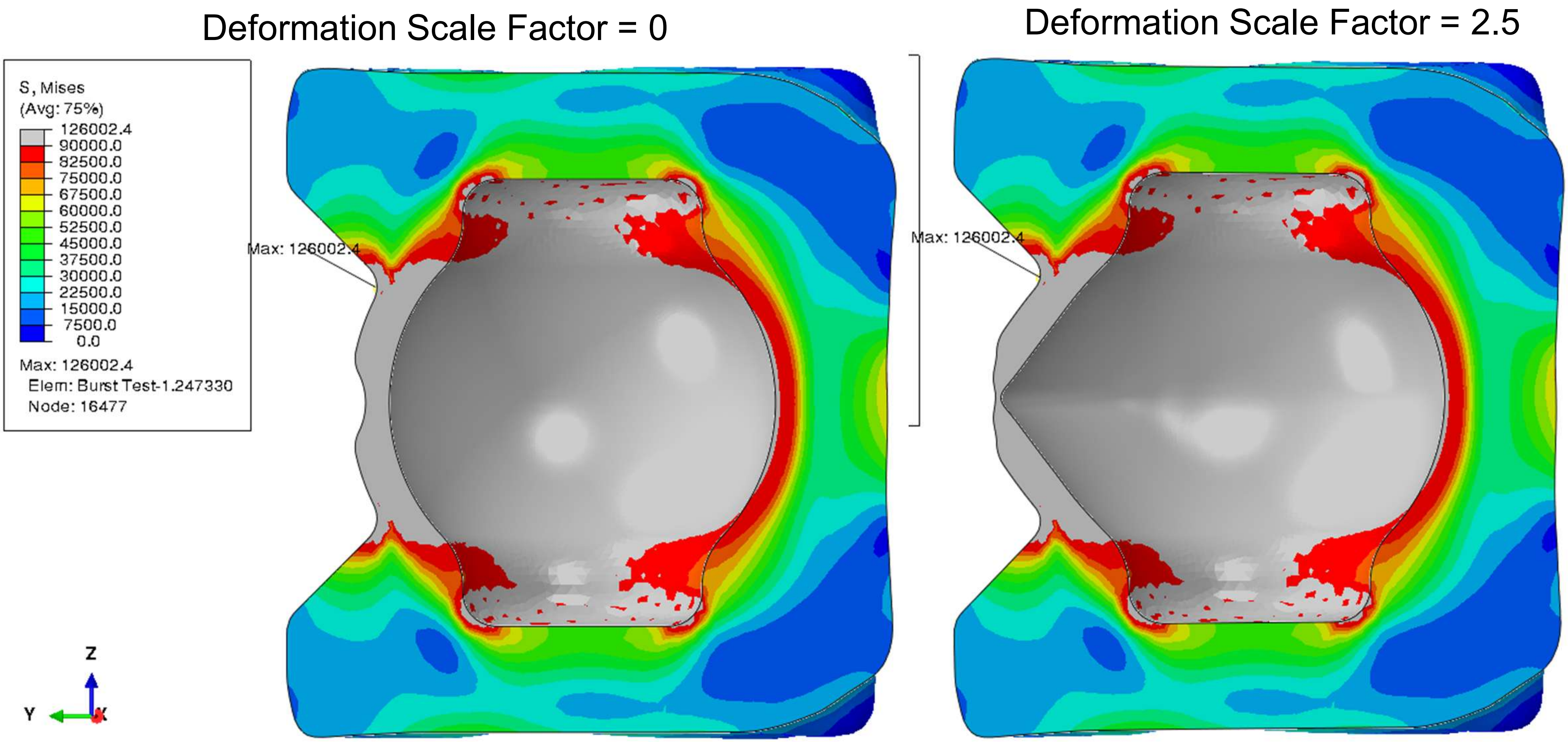
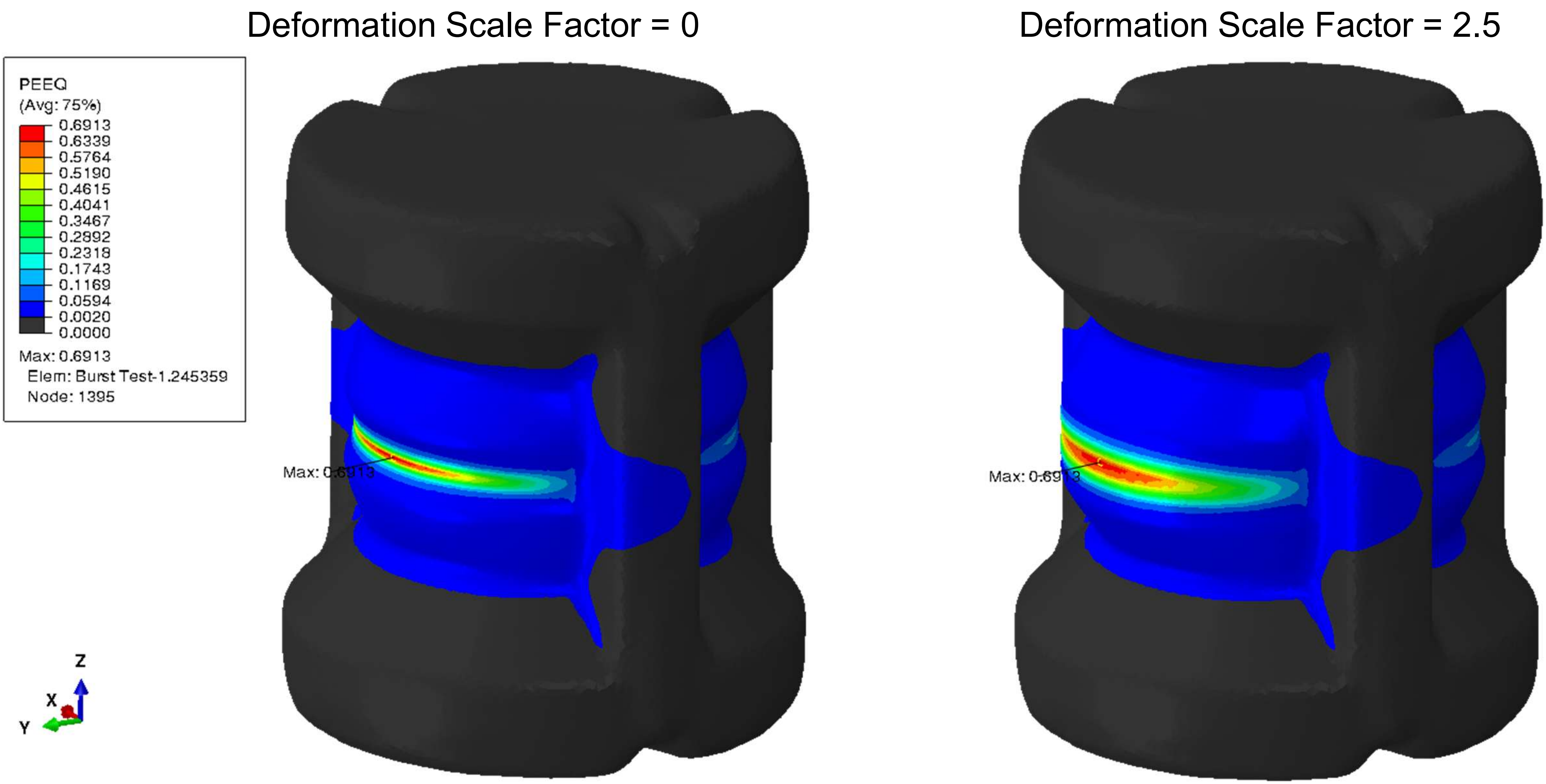
Burst Test Vessel – FEA Stresses



Stress Exceeding Yield are Shown in Grey

Burst Test Vessel – FEA Strains



Plastic Strains less than 0.2% shown in Black.

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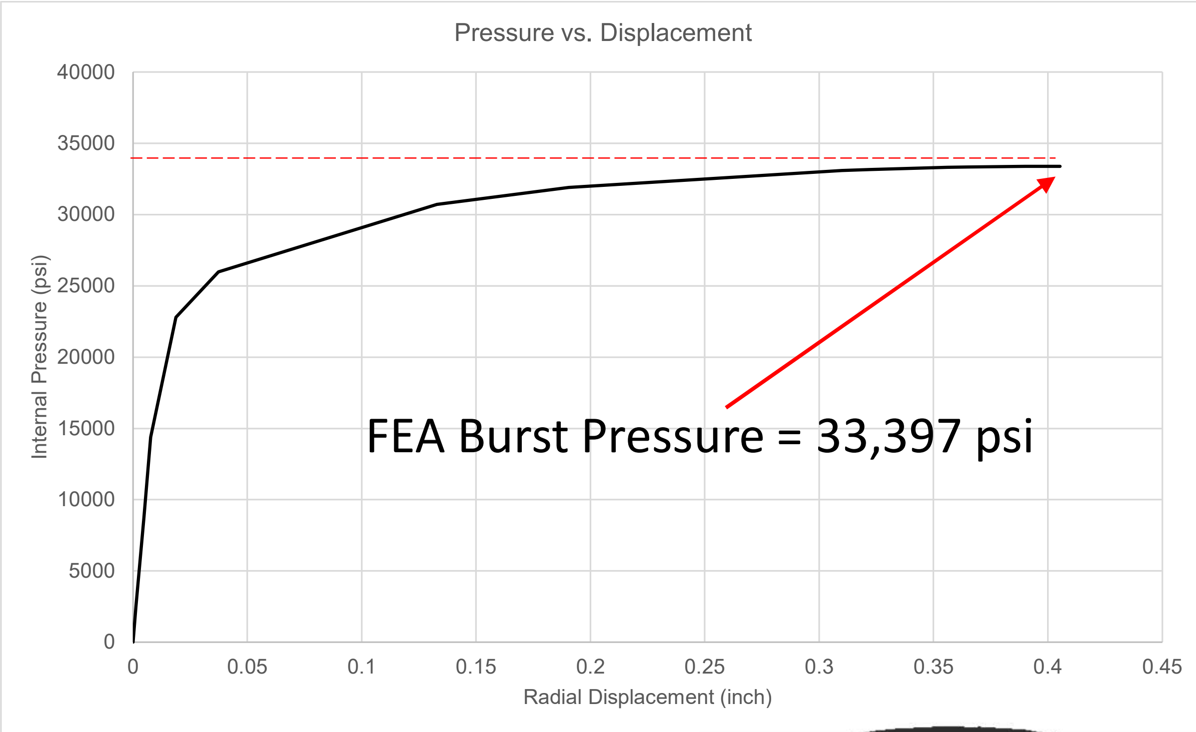
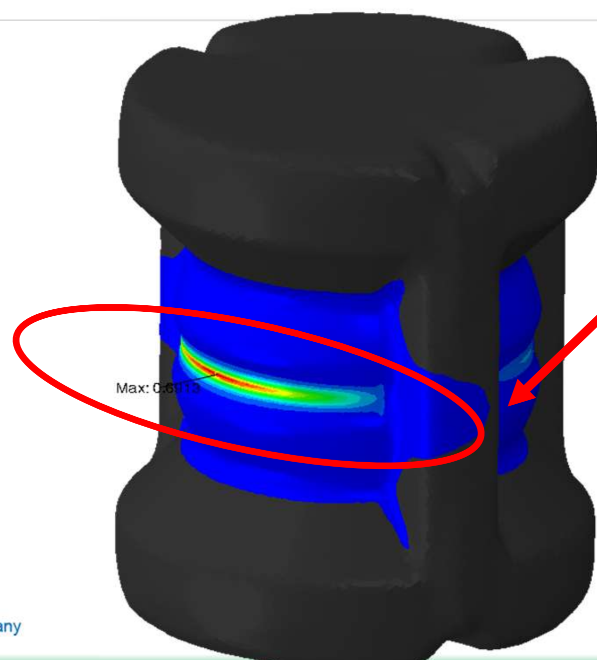
Burst Test Vessel – FEA vs Actual





Actual Burst Pressure = 35,729 psi
~ 6.9% greater than predicted, using minimum specified material properties

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