Standard Problem Exercise No. 3

Model 3: Detailed Global 3D Model

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Model 3 Summary

- Model 3, a detailed global 3D model applies lessons learned from Models 1 and 2 to continue studying all aspects of SPE
- Pressure only analysis at this time

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Model Geometry and Initial Conditions

- Simulation of friction and pressure-response related changes to tendon stress distribution has been included
- Model includes concrete, all tendons, rebar, and liner. Shear reinforcement was not included in the model, since the structure wall was represented by shell elements.
- Concrete was modeled with 4-node shell elements
- Rebar modeled with embedded subelements, tendons with two-node beam elements, and liner with 4-node shell elements, overlain onto same nodes as concrete shell nodes, but offset by appropriate eccentricity

Model Geometry and Initial Conditions

- Representation of losses was by FE Model's representation of friction
- Every tendon was modeled, and each tendon had a "jacking element" protruding from the tendon end zone
- Due to much greater complexity, the tendon-concrete interaction methodology followed in Model 1 was modified as follows:
  - Every node of the tendons has matching reference node that shares the same space
  - Reference nodes are tied to surface of concrete, and transfer forces and displacements directly to concrete
  - Connector elements are used to constrain the tendon nodes to the reference nodes

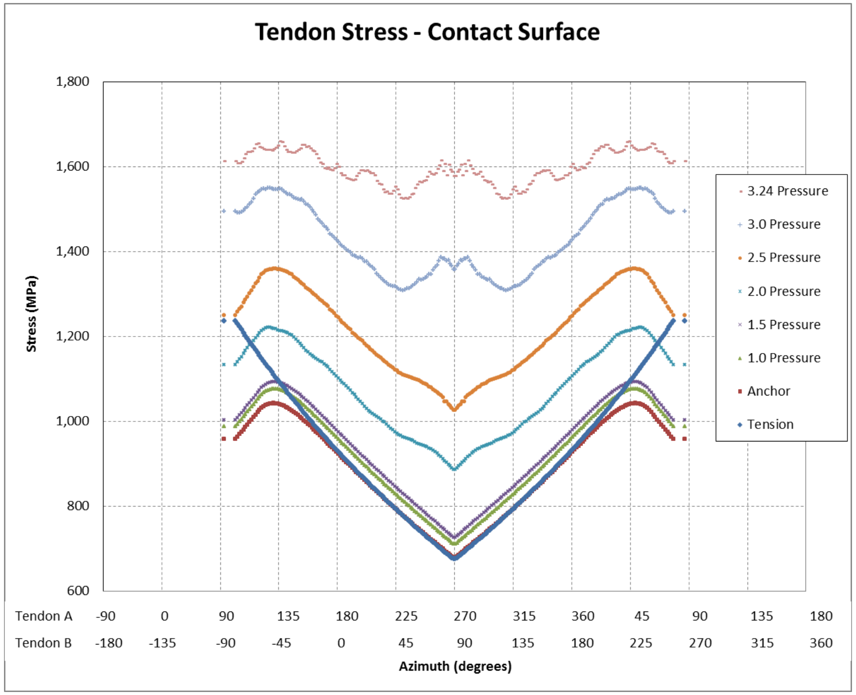
Tendon "Connector" Elements

- "SLOT" type selected
- Slot connectors allow tendon nodes to move only in one direction relative to reference node
- Assigned to be initial tangential direction along the tendon
- Connector elements able to solve for frictional resistance by taking the force normal to the direction of motion and determine whether sticking or slipping occurs
- Traction and normal forces exerted by the tendons are transferred directly to concrete through reference nodes

Model 1 vs. Model 3 Tendon Modeling Comparison

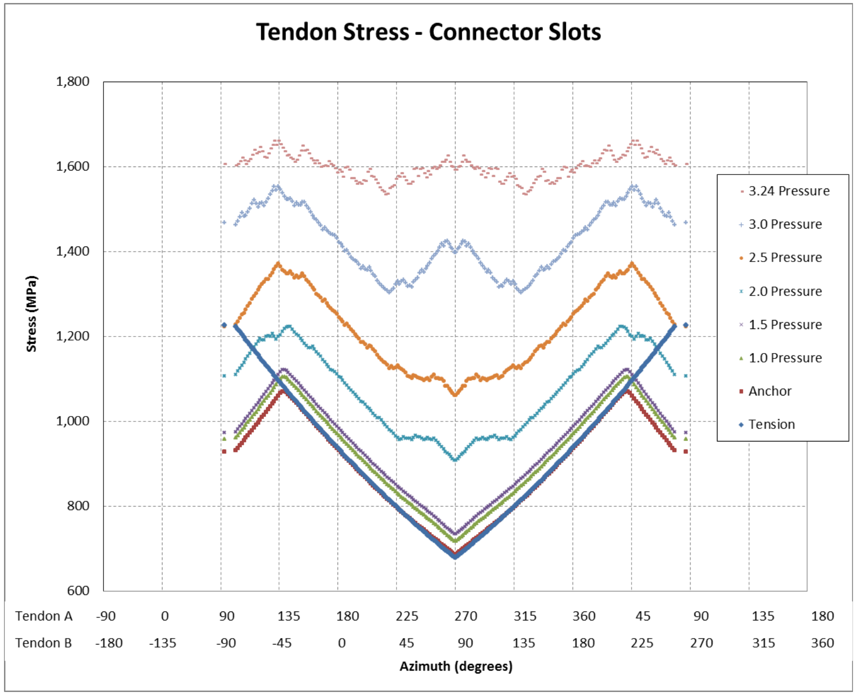
Model 1 Contact Surface

Tendon Stress



Model 1 Connector Slots

Tendon Stress



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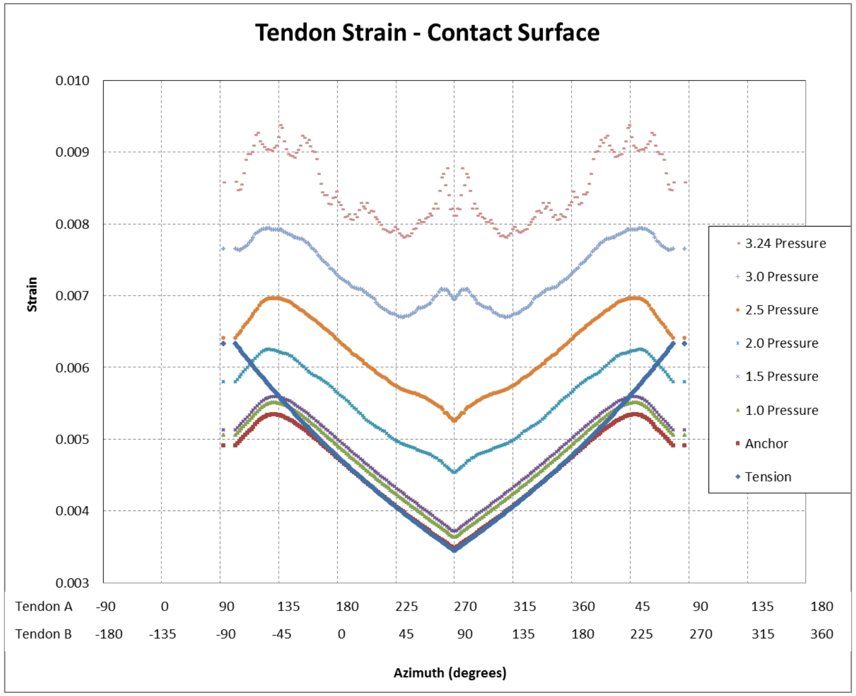
Model 1 vs. Model 3 Tendon Method Comparison

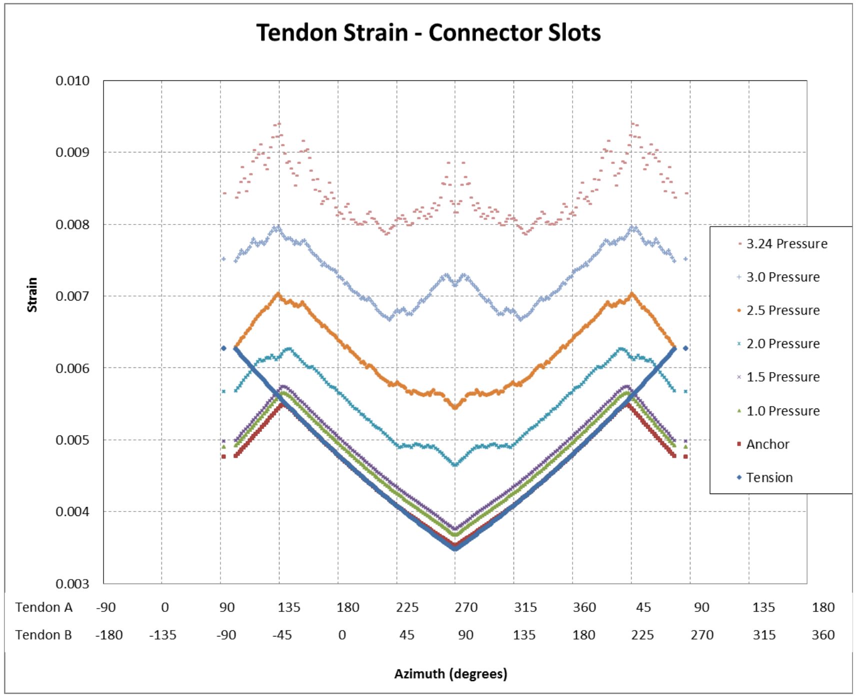
Model 1 Contact Surface

Tendon Strain



Model 1 Connector Slots

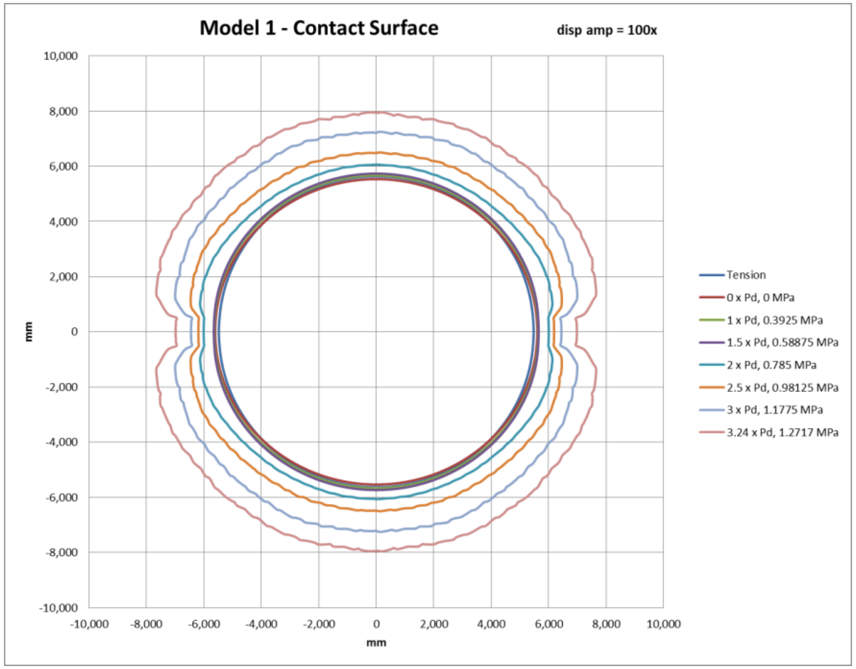
Tendon Strain



Model 1 vs. Model 3 Tendon Method Comparison

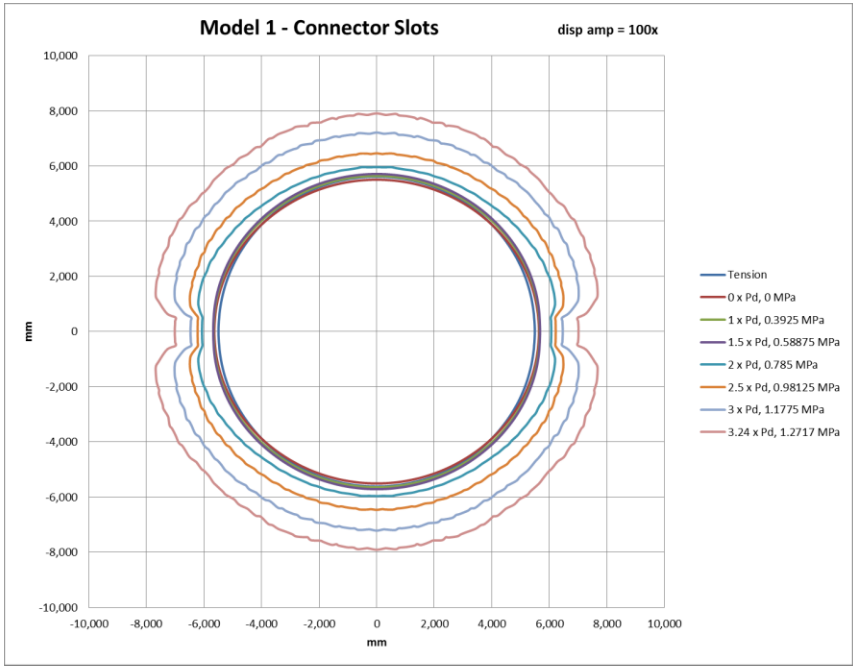
Model 1 Contact Surface

Displacement



Model 1 Connector Slots

Displacement



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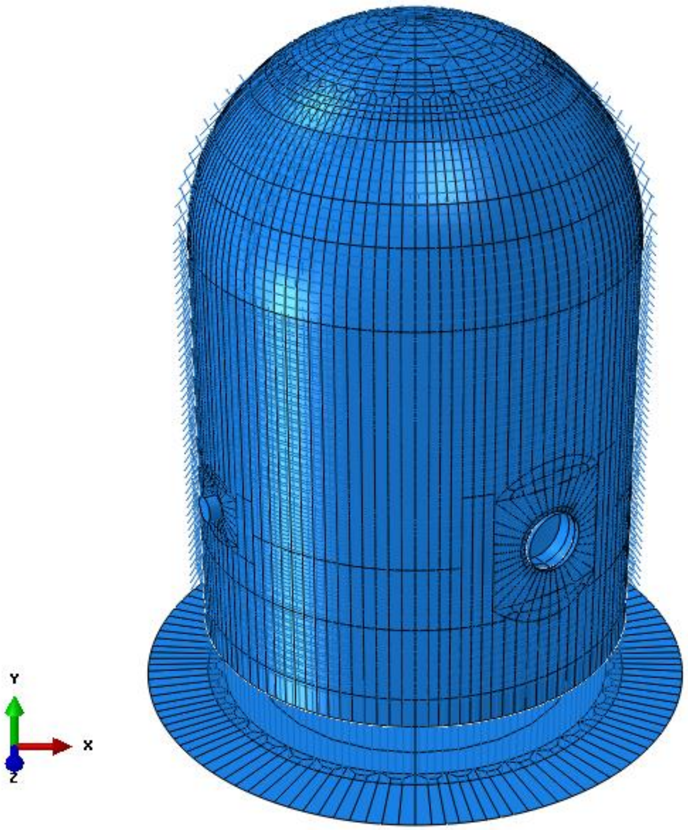
Model 3 Geometry and Initial Conditions

- “jacking elements”
  - Have elastic properties
  - All prestressing is applied through these elements by applying temperature contraction
  - The stresses distribute around the vessel, in the tendons
  - Similar to how ‘real world’ tendons are stressed
  - During prestressing step, ends of jacking elements are rigid-linked to the nearest concrete node
  - Different schemes for jacking, anchor set, and nodal connectivity were attempted before one deemed satisfactory

Model 3 Overview



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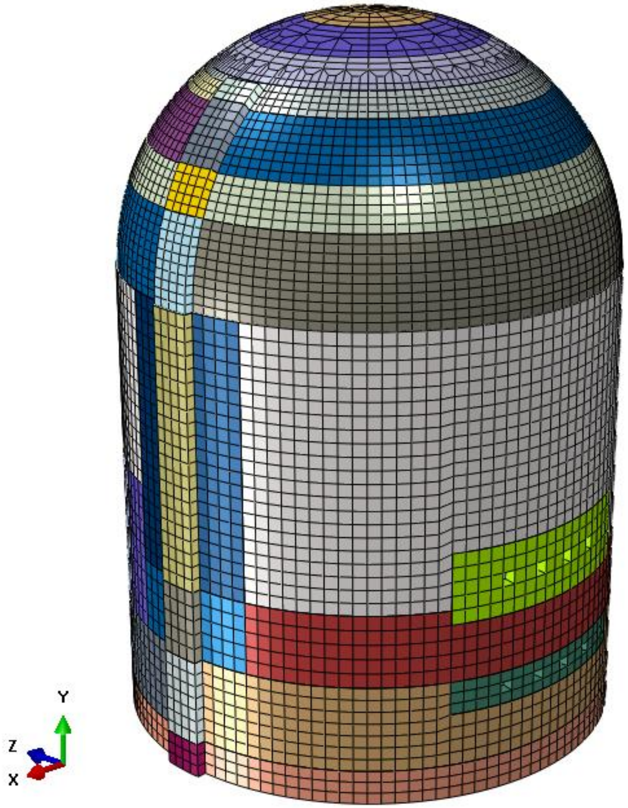
Meshed Concrete Vessel with Various Section Assignments



View of M/S and F/W

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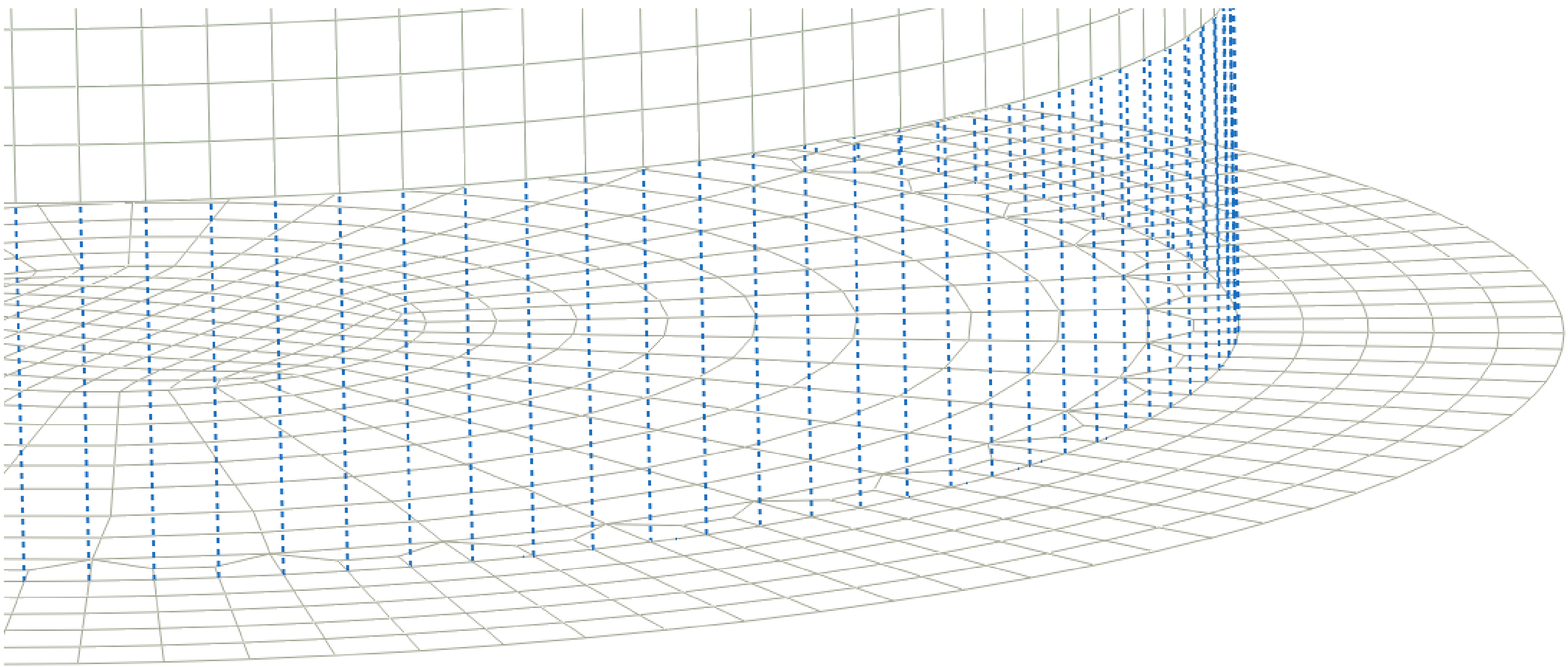
Rigid Links from Bottom of Vessel to Basemat Elements



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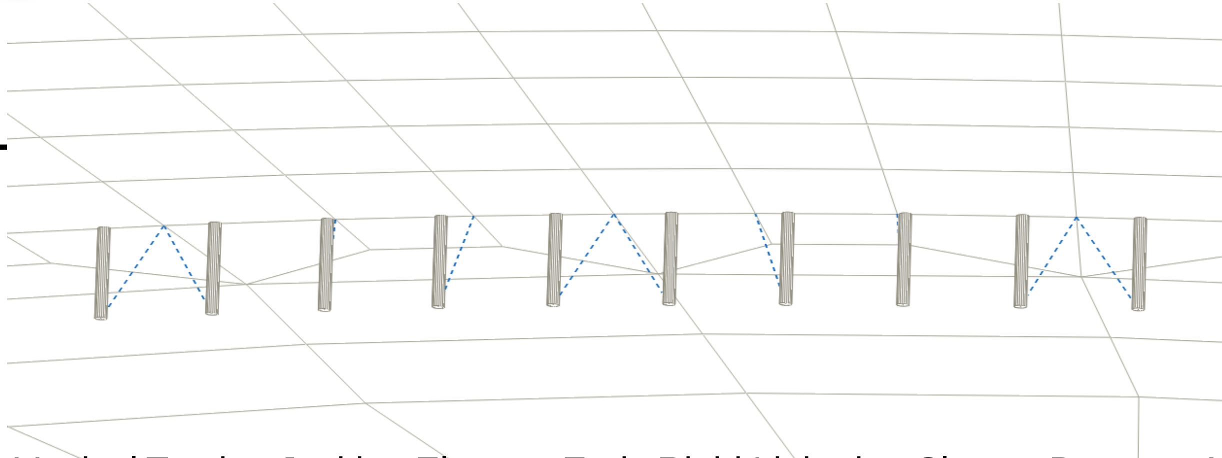
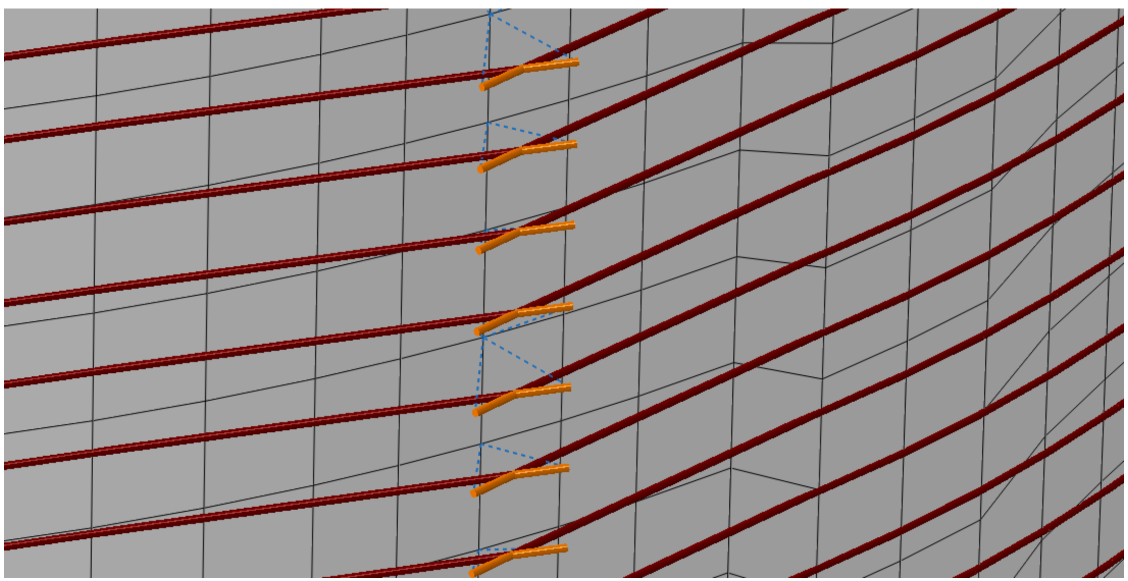


Vertical Tendon Jacking Element Ends Rigid Linked to Closest Basemat Node



Hoop Tendon Jacking Element Ends Tied to Closest Buttress Center Node

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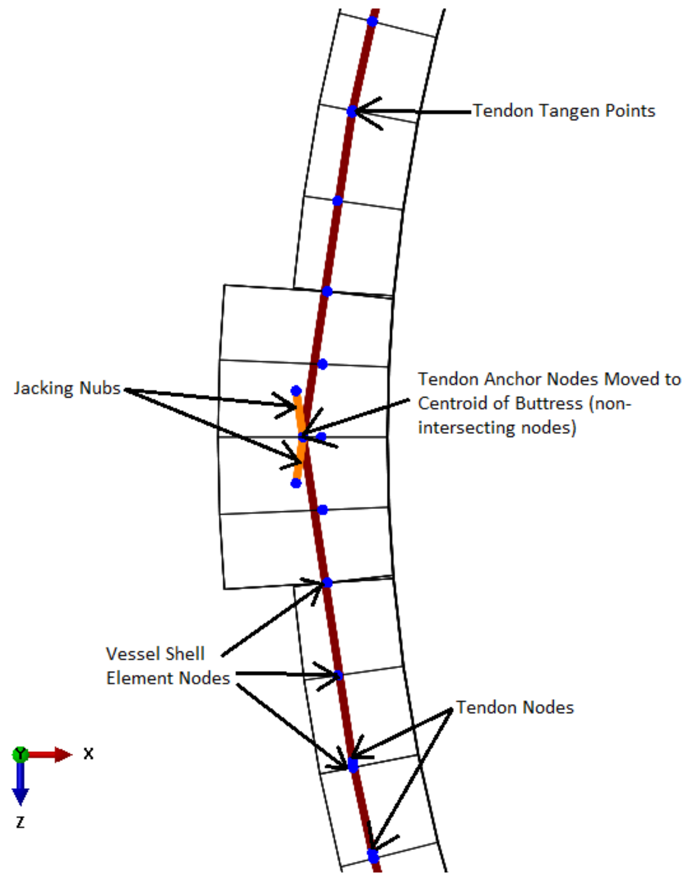
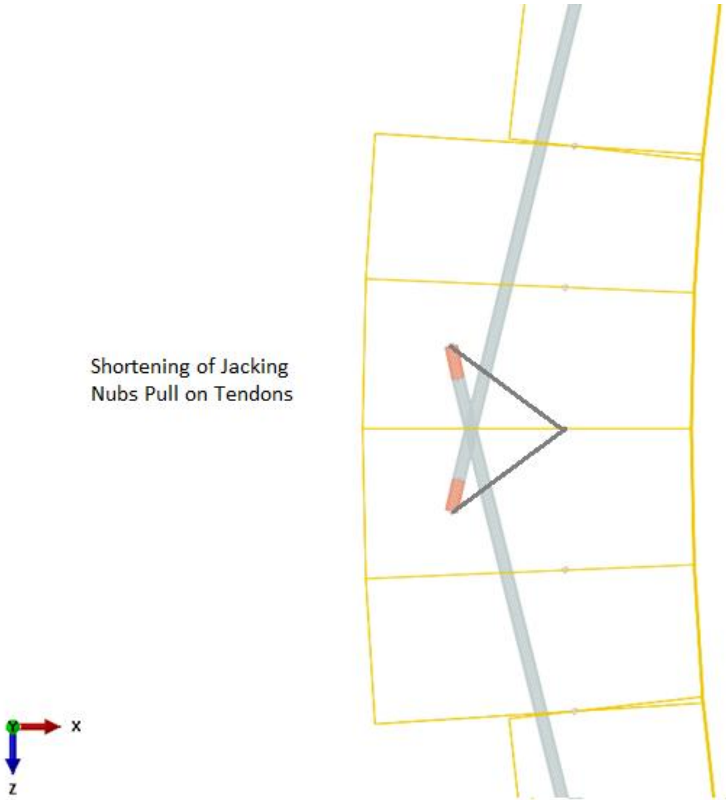
Hoop Tendon Jacking Elements (“nubs”) and Tendon Nodes Shown Relative to Concrete Nodes in the Buttress Region



Deformed Shape of Hoop Tendon Anchor System After "Jacking Loading Step"



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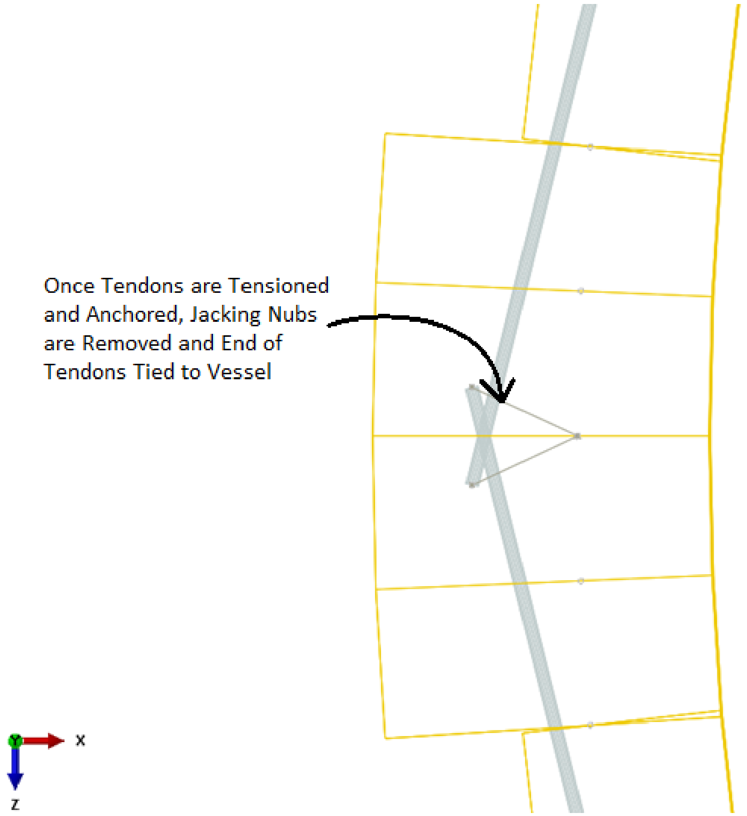
Deformed Shape of Hoop Tendon System After "Anchor Set Step"



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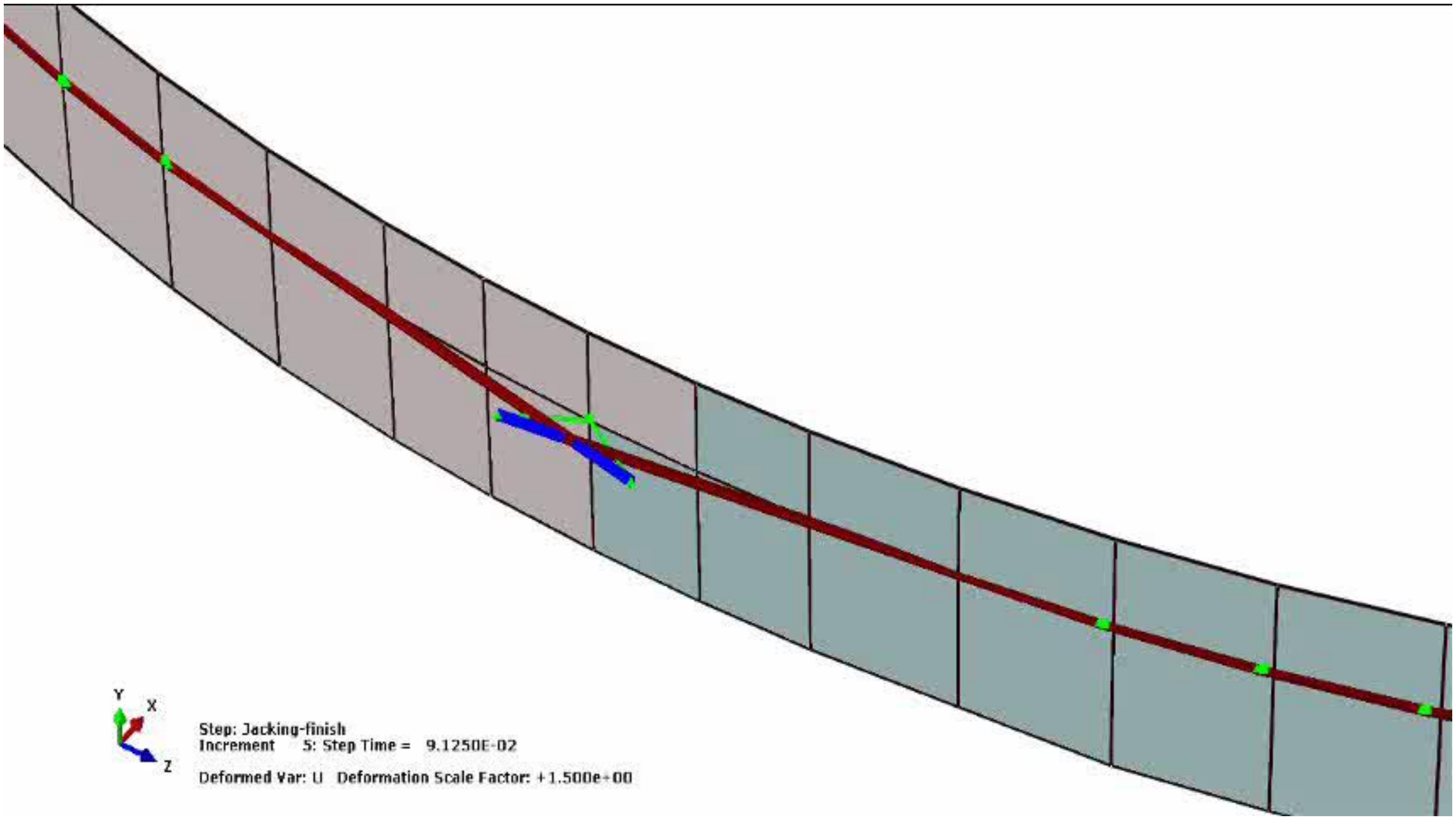
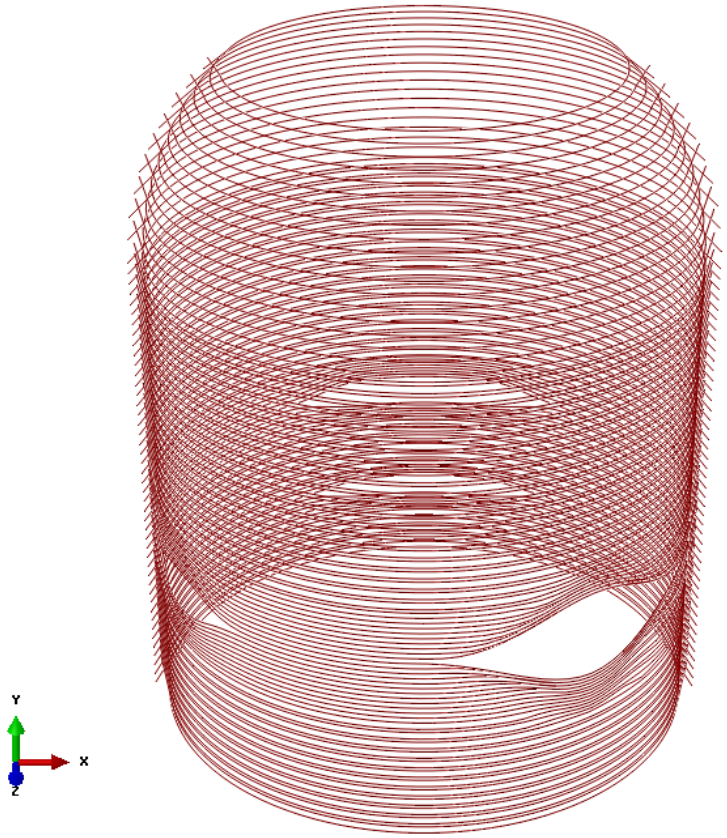
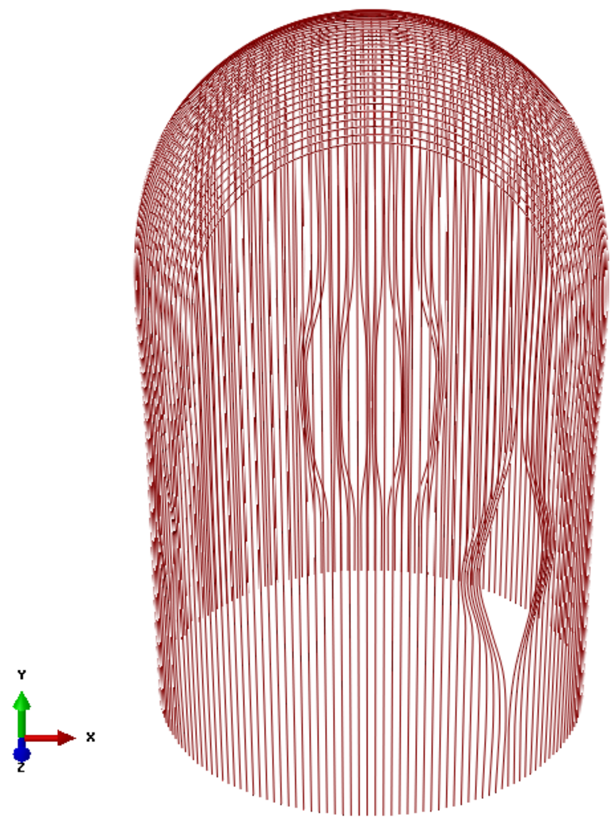
Animation of a Tendon Jacking Area



Hoop Tendon Layout



Vertical Tendon Layout



Analysis Results

<u>Required Output/Results for Model 3:</u>

1. **Description of Failure Prediction Model or Criteria Selected for Use**
2. **Assumptions Made In Geometric Modeling, and Model Description**
3. **Subset of response information defined by "55 standard output locations" of 1:4 Scale PCCV round-robin;**
4. **Contour Plot of Peak Strains in Liner During LST at pressure milestones: P = 0 (prestress applied); 1 x P_d; 1.5 P_d; 2 P_d; 2.5 P_d; 3 P_d; 3.3 P_d; 3.4 P_d; Ultimate Pressure**
5. **Average Strains over 450.45 mm Regions as were shown in Figure 11, locations 3, 4, 5, but with similar locations adjacent to all other penetrations, plotted vs. Pressure. (The intent is for these strains to be over a standardized gage length, which is defined by the spacing between liner anchors.)**

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For direct comparison amongst participants, also requested to plot (Using Excel)

- Liner Strain Magnitudes (Hoop Direction) at Locations Indicated in Figure 11 (of SPE problem statement), versus pressure
- Tendon stress distribution at P = 0 (prestress applied); 1 x P_d; 1.5 P_d; 2 P_d; 2.5 P_d; 3 P_d; 3.3 P_d; 3.4 P_d; Ultimate Pressure for
  - Hoop Tendons # H35, H53, H68
  - Vertical Tendon # V37 and V46
  - Plots of response versus pressure for Standard Output Locations:
- 1-15 (displacements)
- 22-29 (rebar strains)
- 36-42 (liner strains)
- 48-55 (tendon strains and stresses)

(see Table 4-1 in NUREG/CR-6809 for locations of SOL's)

Results by Pressure Milestones at 6.2 m

Milestone	Pressure (MPa)	x Pd
Zero Concrete Hoop Stress (at 0° azimuth)	0.498	1.27
Concrete Hoop Cracking Occurs (at 0° azimuth)	0.624	1.59
Tendon A Reach approx.1% Strain (at 0° azimuth)	1.299	3.31
Tendon B Reach approx.1% Strain (at 0° azimuth)	1.274	3.25

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Analysis Results

- Studying the liner strain plots and comparing to known behaviors from the 1:4 Scale PCCV LST and SFMT, it can be concluded that many similar liner strain "hot spots" exist in the analysis as were observed in the test.
- For example,

  a) near 0-degree azimuth, cylinder midheight,

  b) on either side of the E/H embossment,

  c) on either side of the other penetrations (A/L, M/S, and F/W penetrations)
- One significant exception is the liner strain in the vicinity of the buttresses. This phenomena was observed to minor extent in the test, and not to the extent shown in the analysis.
- Have concluded that the shell modeling approach, and strategy of attaching tendon end to a single concrete node, will tend to cause somewhat larger strains in buttress vicinity than in the actual structure. Thus there remain some trade-offs in accuracy with choosing shell elements and element size, manageable for completing 3D global analysis

Analysis Results, cont'd

- Tendon stress distribution plots show friction modeling strategy for Model 3 is very effective, and stress distributions after jacking and after anchorage are in reasonable agreement with design expectations and with observations and measurements from the test
- Hoop tendon strain contours indicate at 3.6Pd, the largest tendon strains occur in the 0-6 degree midheight zone of the cylinder and in the 135-degree zone of the cylinder, and that these strains are approximately 1.73%
- In the SFMT, the first tendon failures were observed to occur in the 0-6-degree midheight zone of the cylinder, and it has been inferred (though not directly measured) that the tendon strains were of approximately this magnitude (approximately 2%) when the first tendons ruptured
- So Model 3 predicted (and PCCV SFMT observed) failure pressure is $3.6P_d$; if tendons were able to achieve 3.8% strains, failure pressure would be $3.8P_d$

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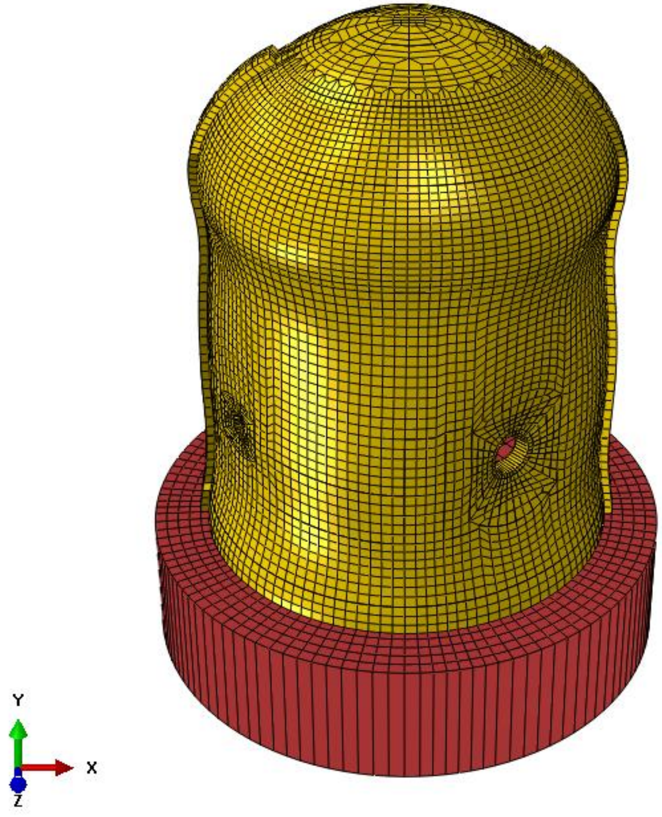
Deformed Shape after Tendon Anchorage. Deformation Scale x 500



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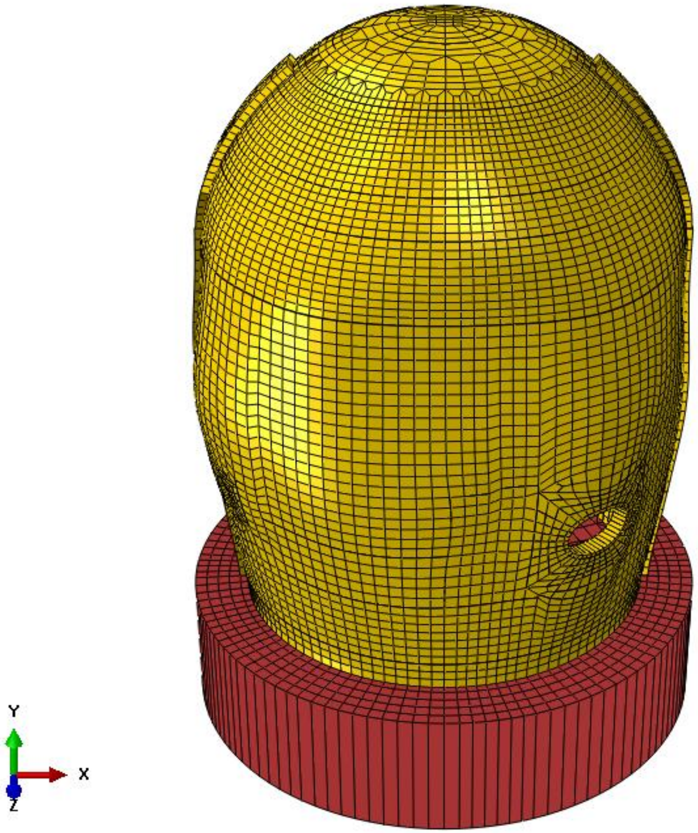
Deformed Shape at 3.6 x Pd. Deformation Scale x 20



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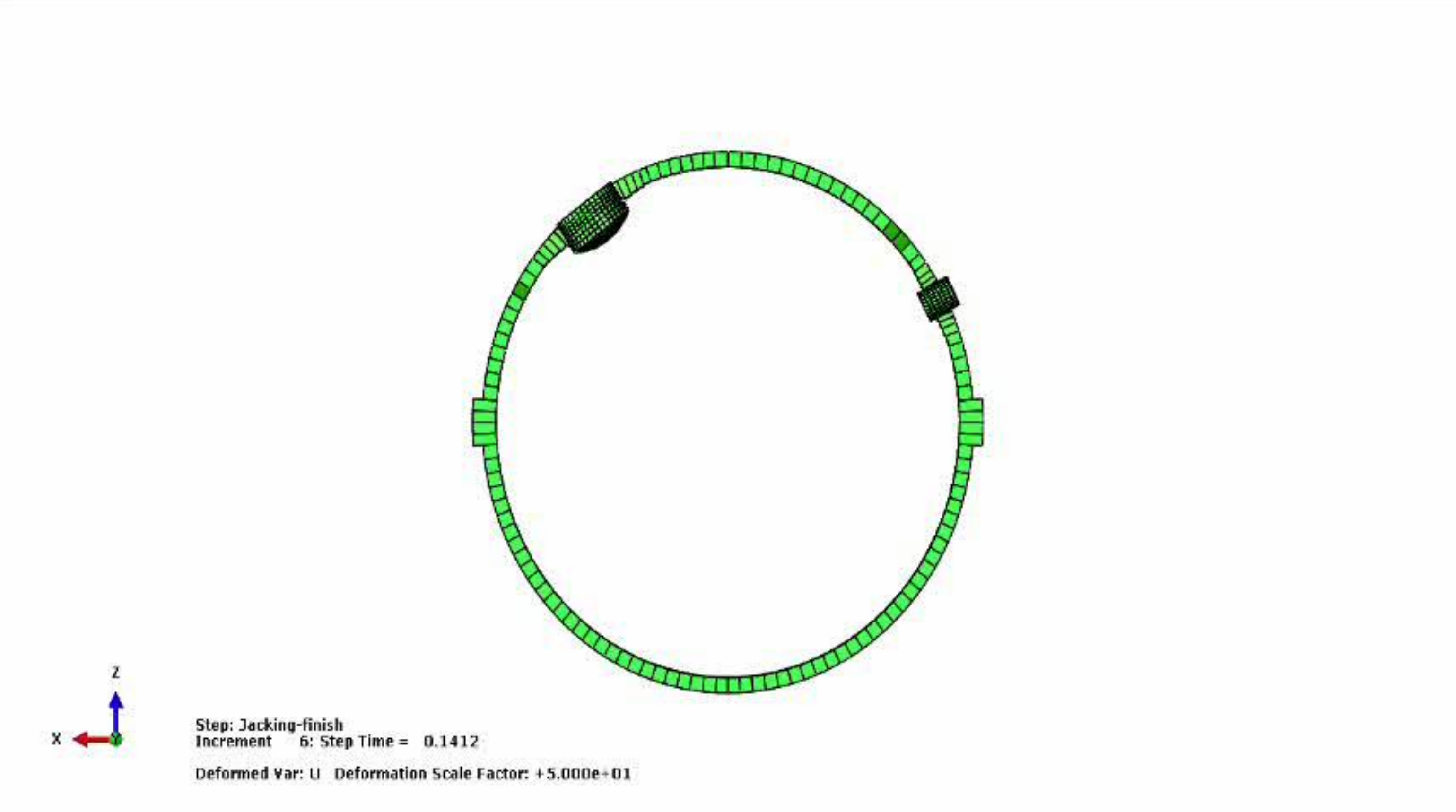
Animation of a "Plan-View" Slice at a Model Elevation of 4.68m



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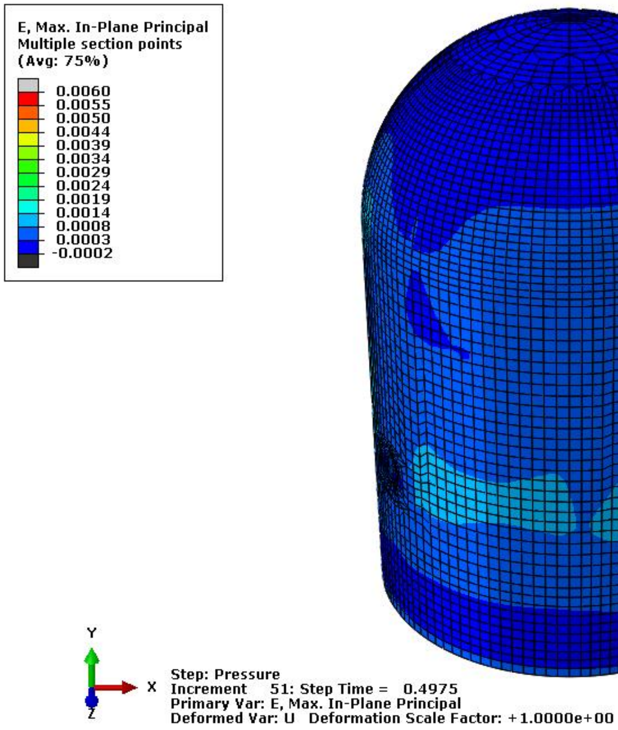
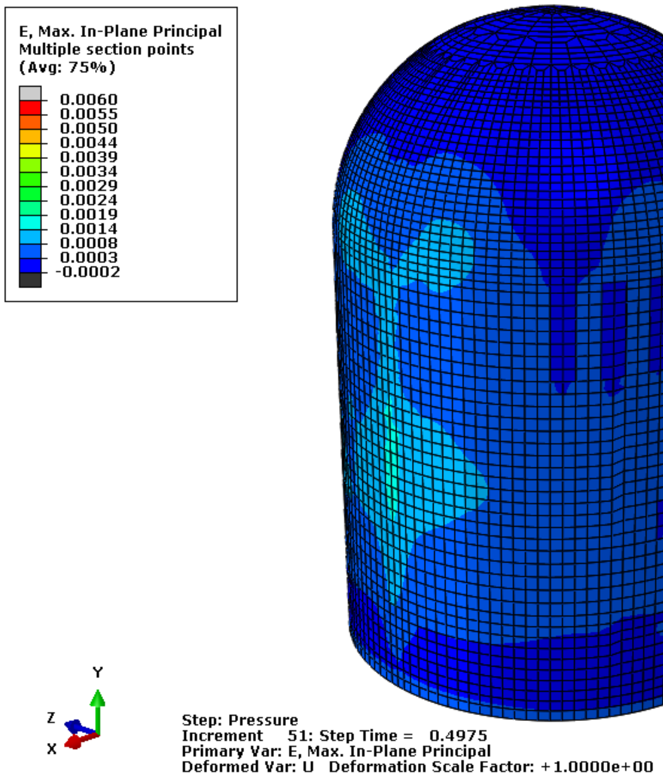
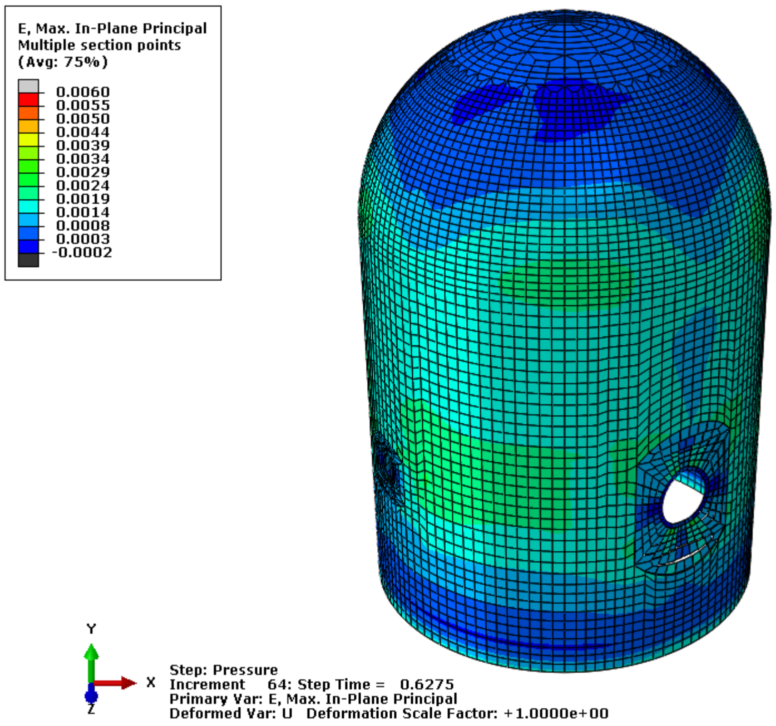
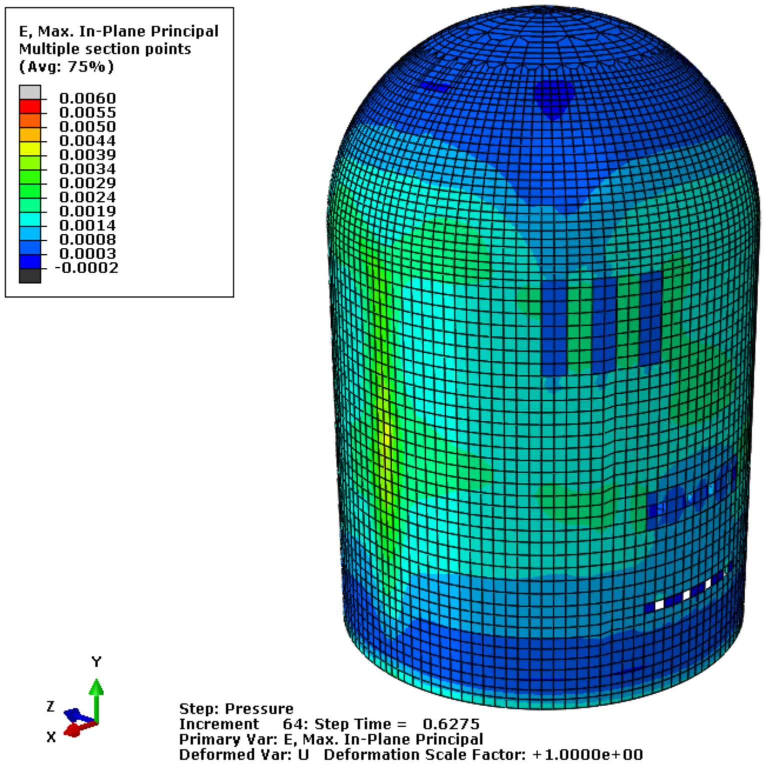
Max Principal Strain in Liner at 2.0 x Pd



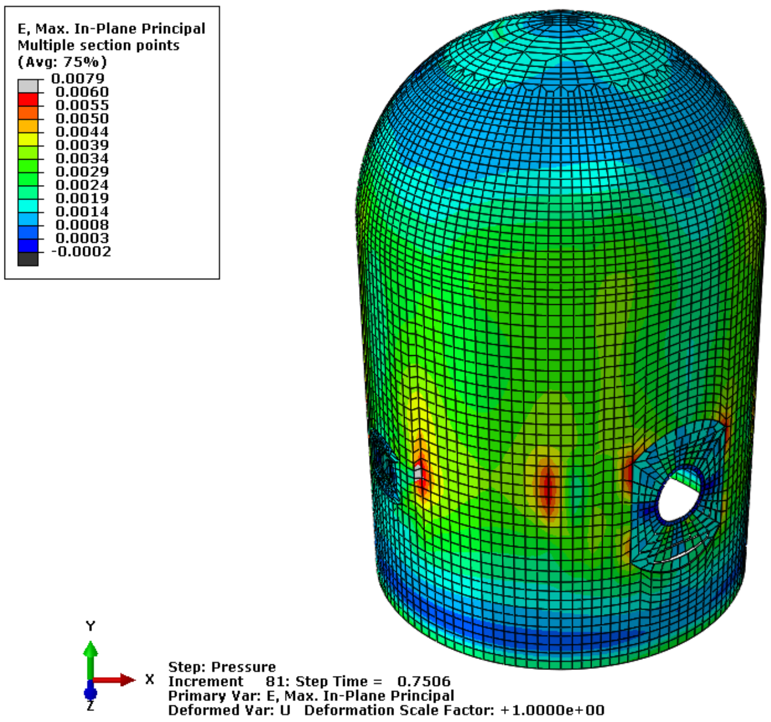


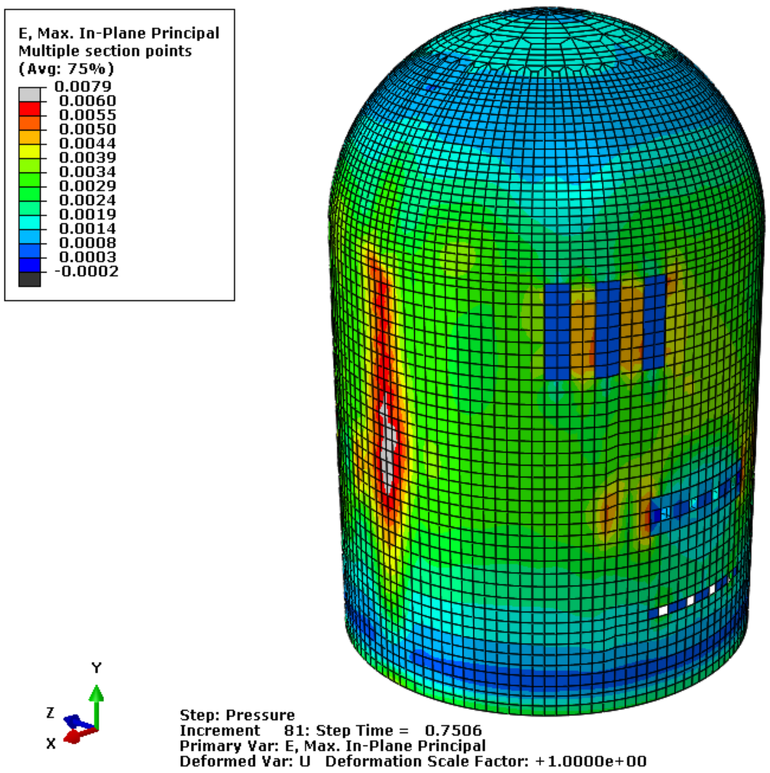
Max Principal Strain in Liner at 2.5 x Pd



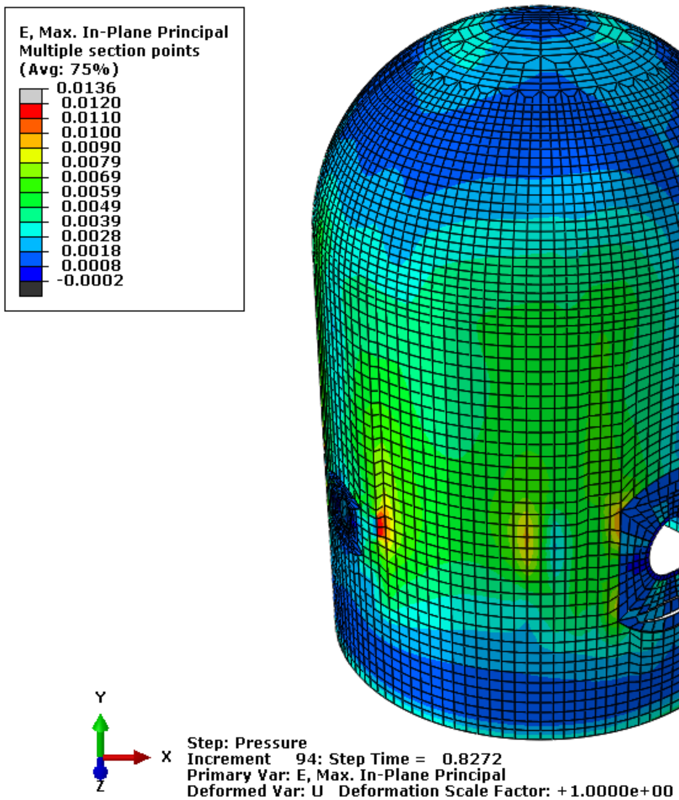


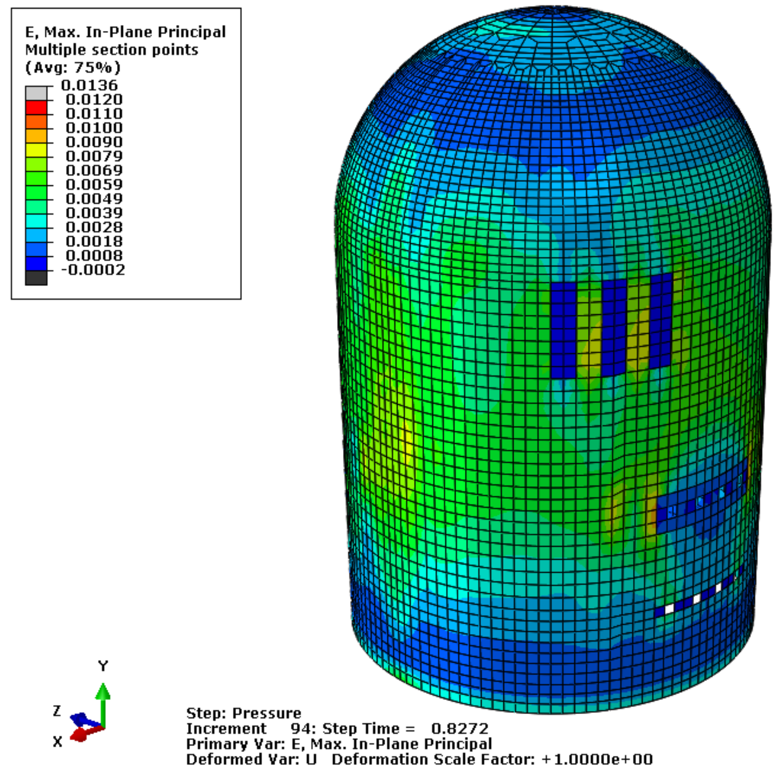
Max Principal Strain in Liner at 3.0 x Pd



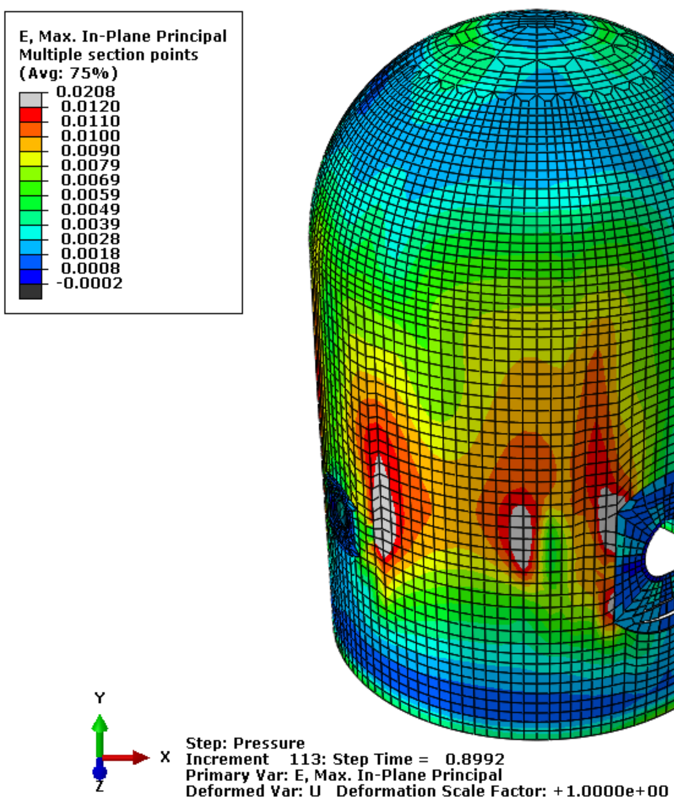


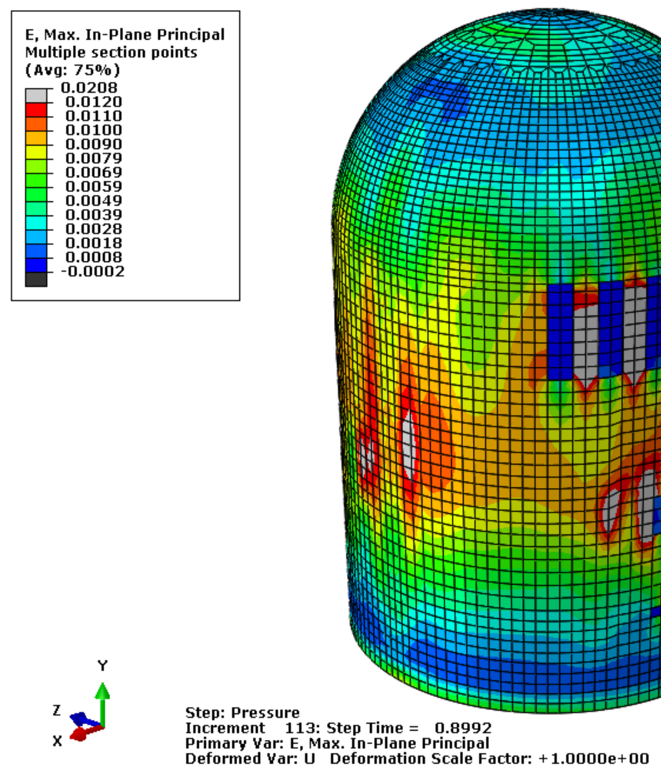
Max Principal Strain in Liner at 3.3 x Pd. (Higher Contour Color Limits)





Max Principal Strain in Liner at 3.6 x Pd





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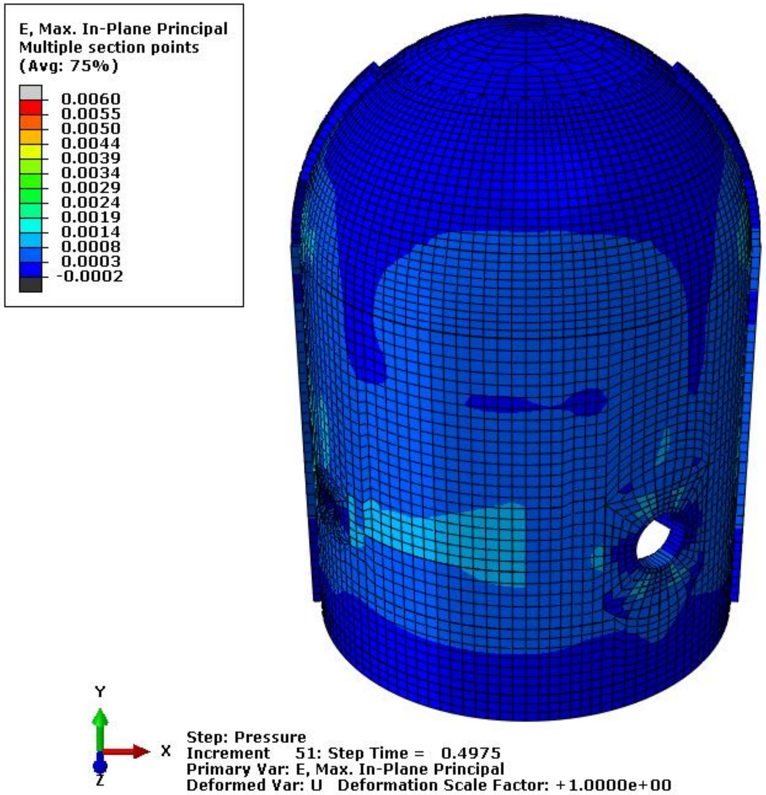
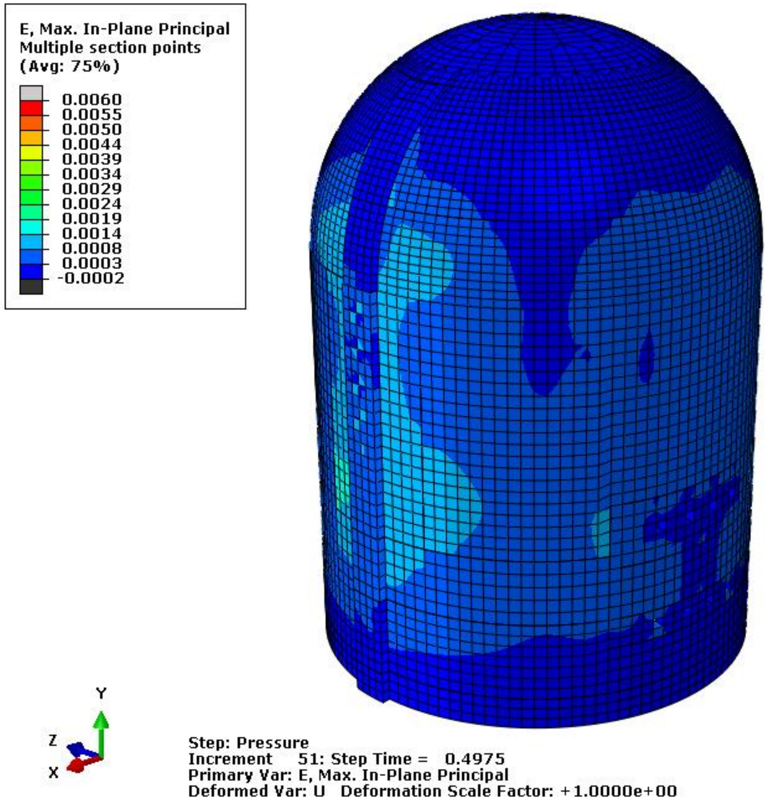
Max Principal Membrane Strain in Concrete at 2.0 x Pd





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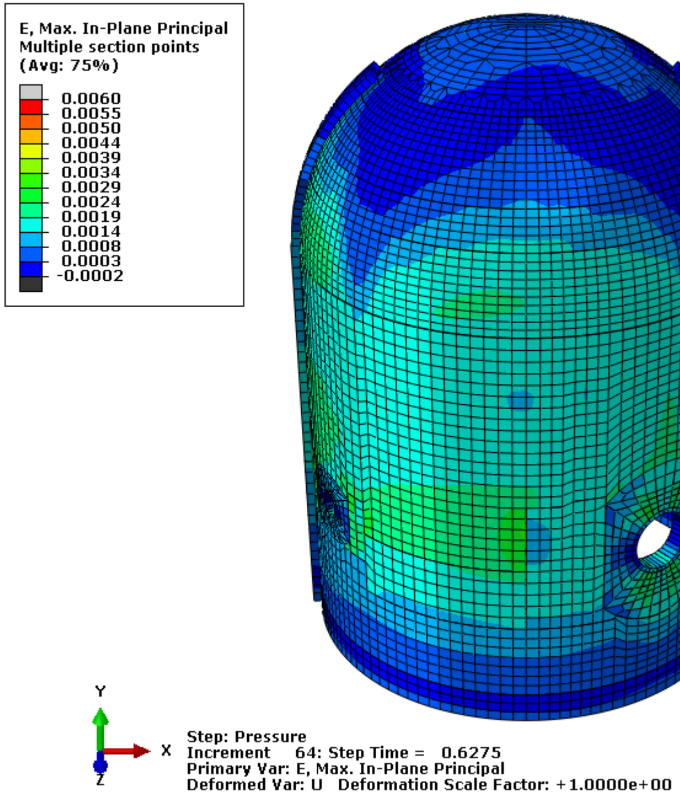
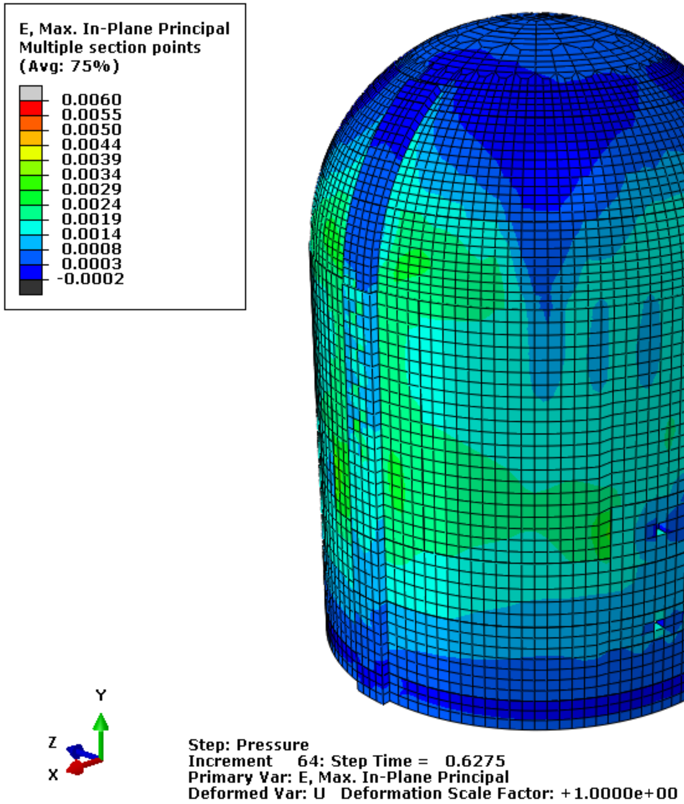
Max Principal Membrane Strain in Concrete at 2.5 x Pd





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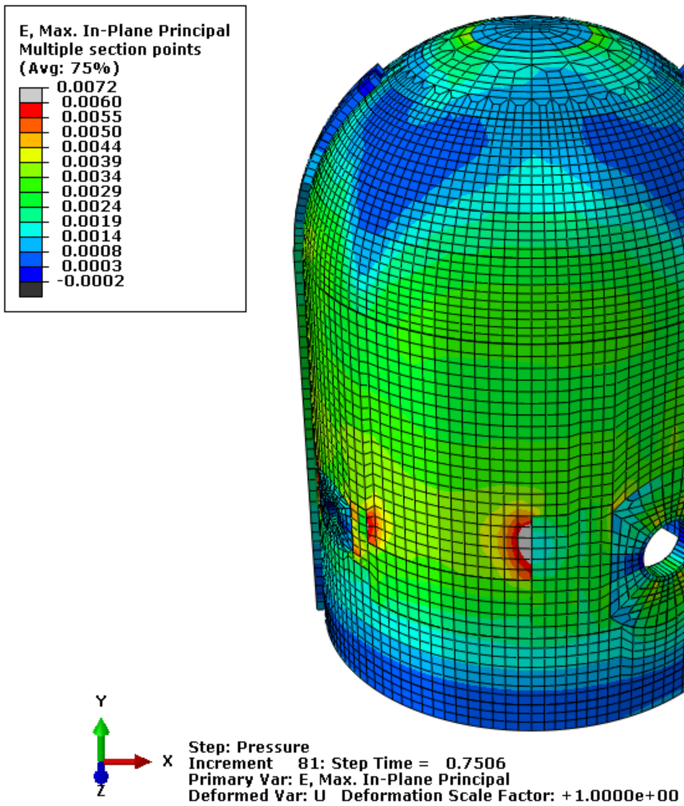
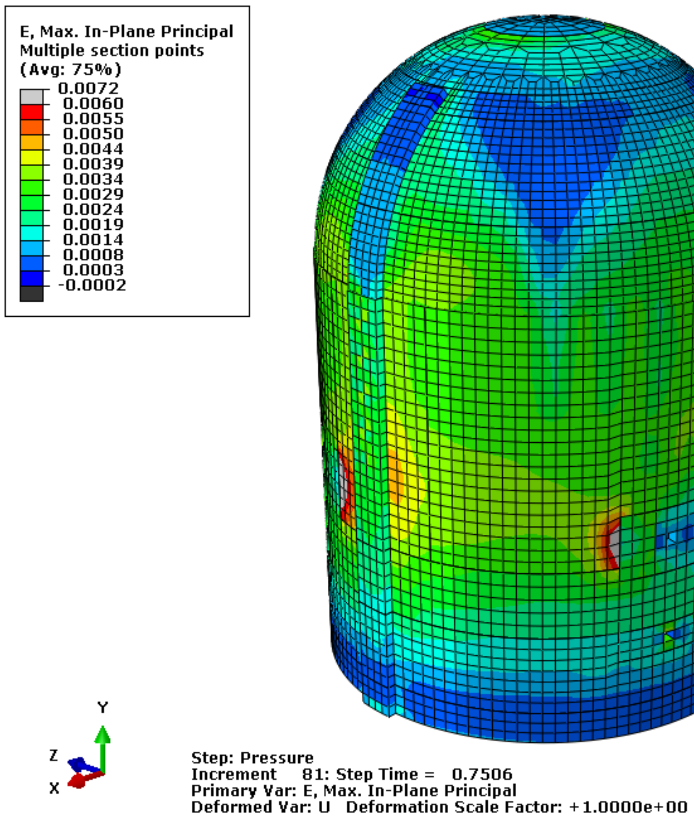
Max Principal Membrane Strain in Concrete at 3.0 x Pd





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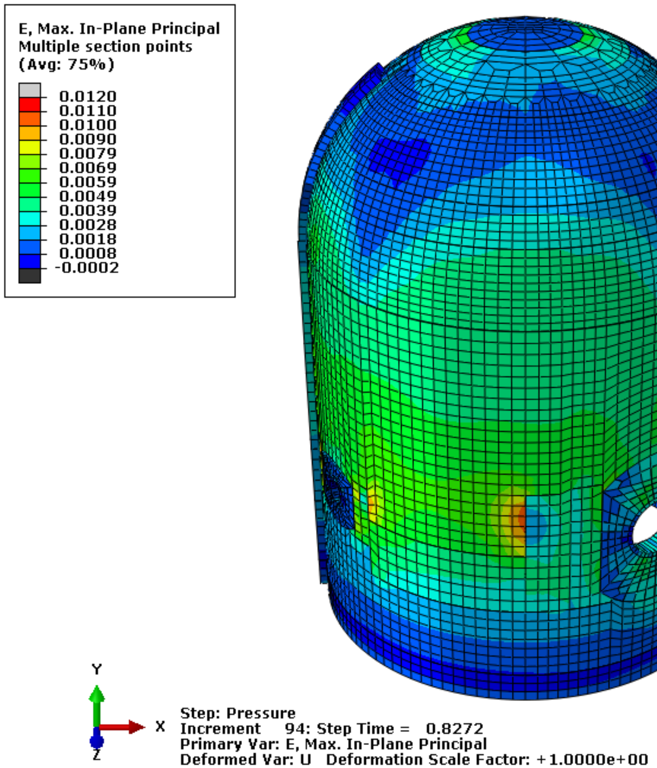
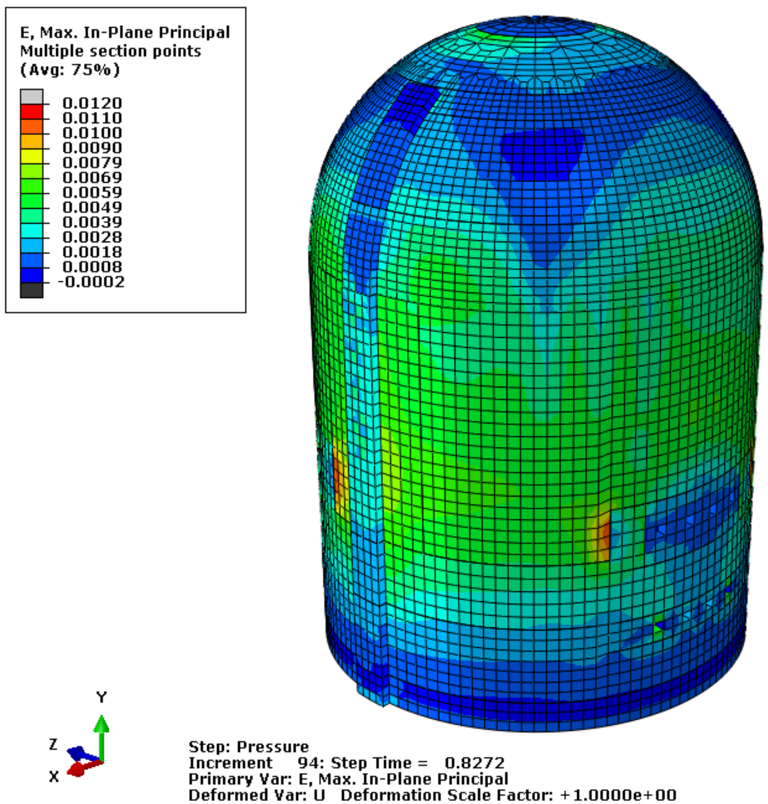
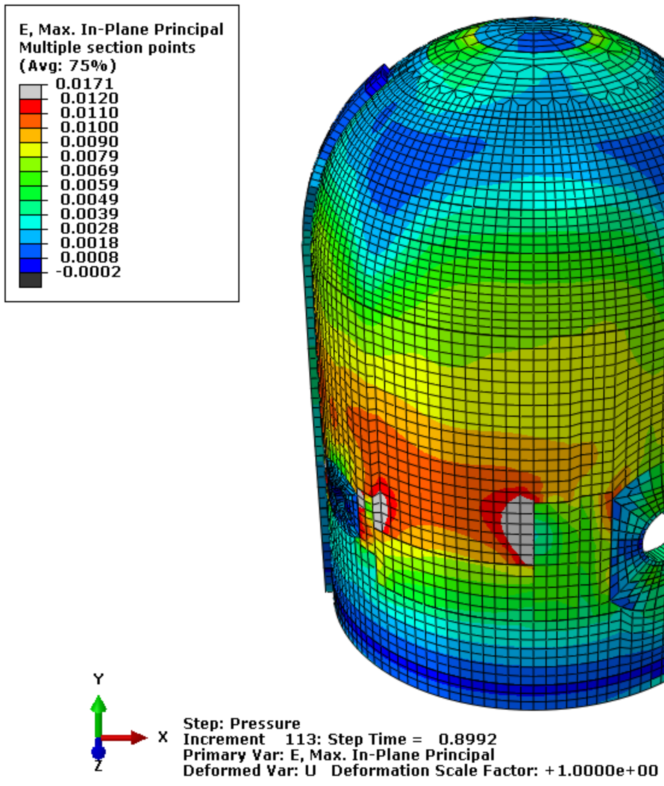
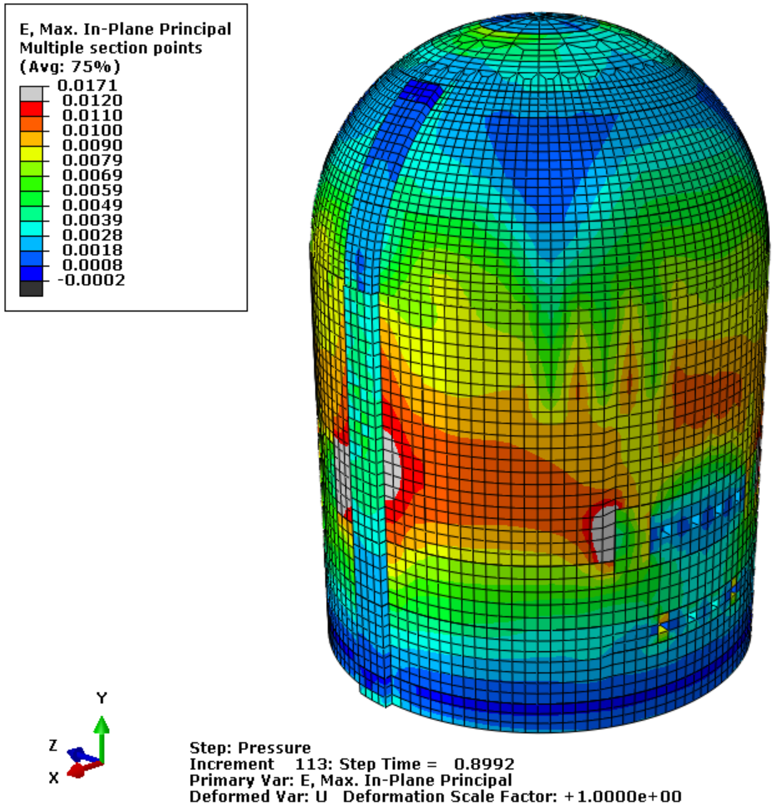
Max Principal Membrane Strain in Concrete at 3.3 x Pd



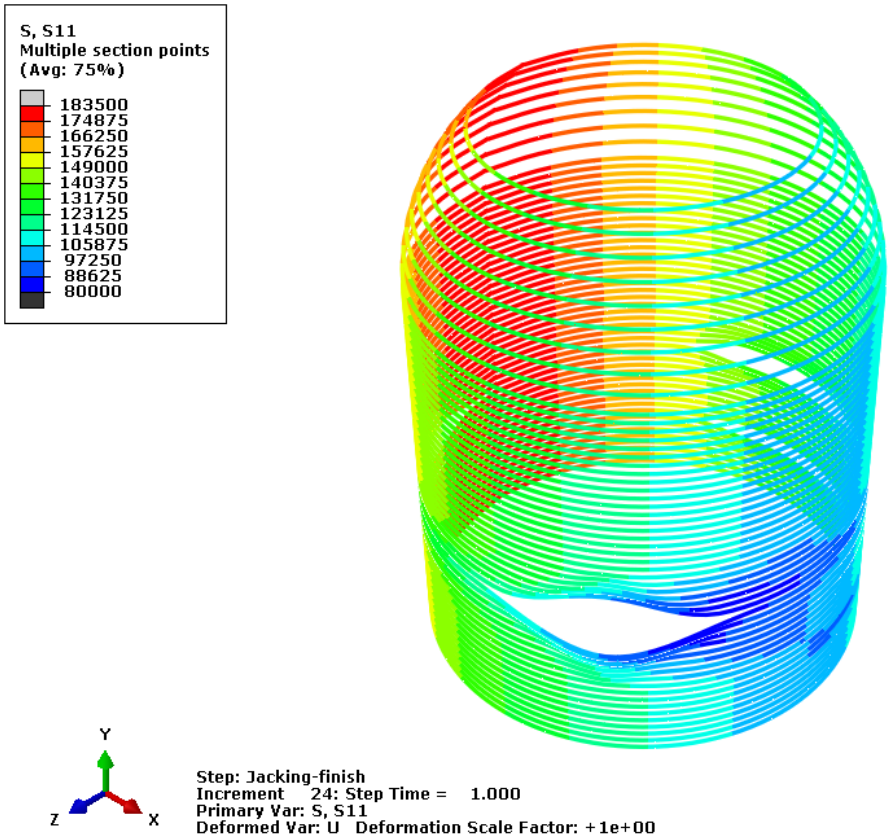


Max Principal Membrane Strain in Concrete at 3.6 x Pd

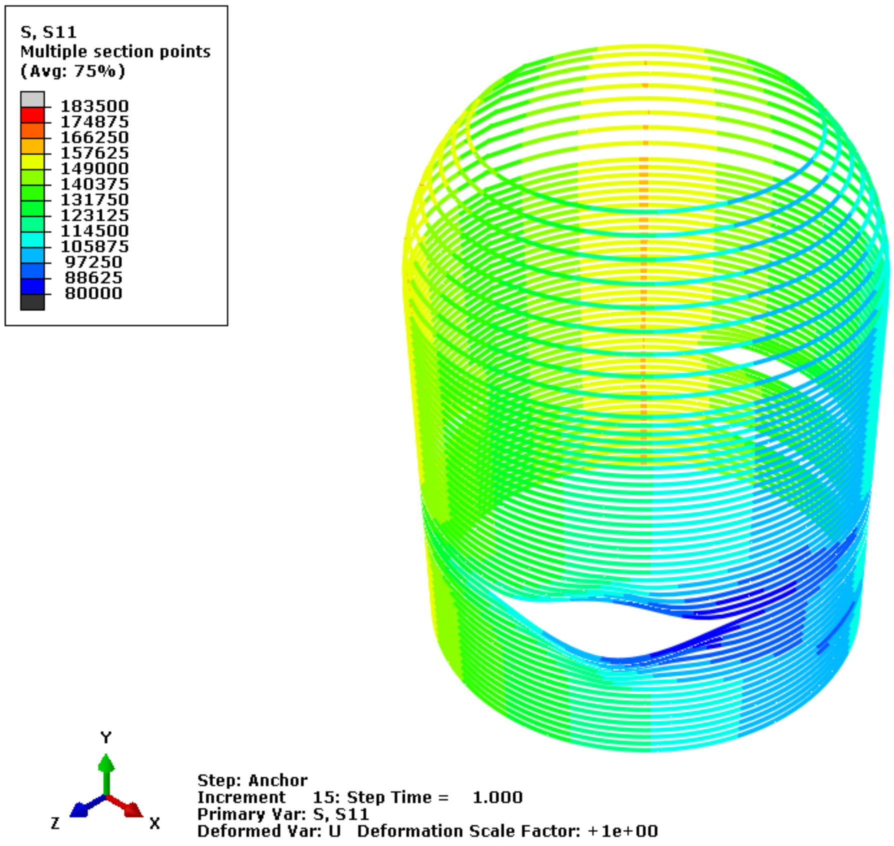




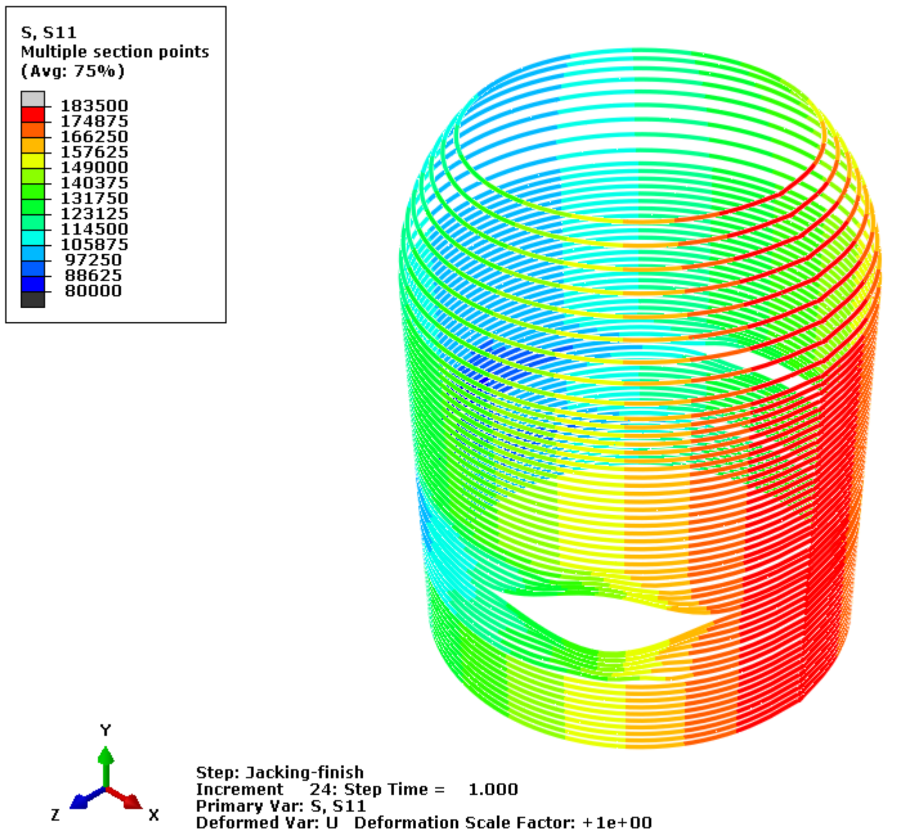
Stress in Hoop Tendons Anchored at 90˚ after Jacking before Anchorage



Stress in Hoop Tendons Anchored at 90° after Anchorage



Stress in Hoop Tendons Anchored at 270°
after Jacking before Anchorage



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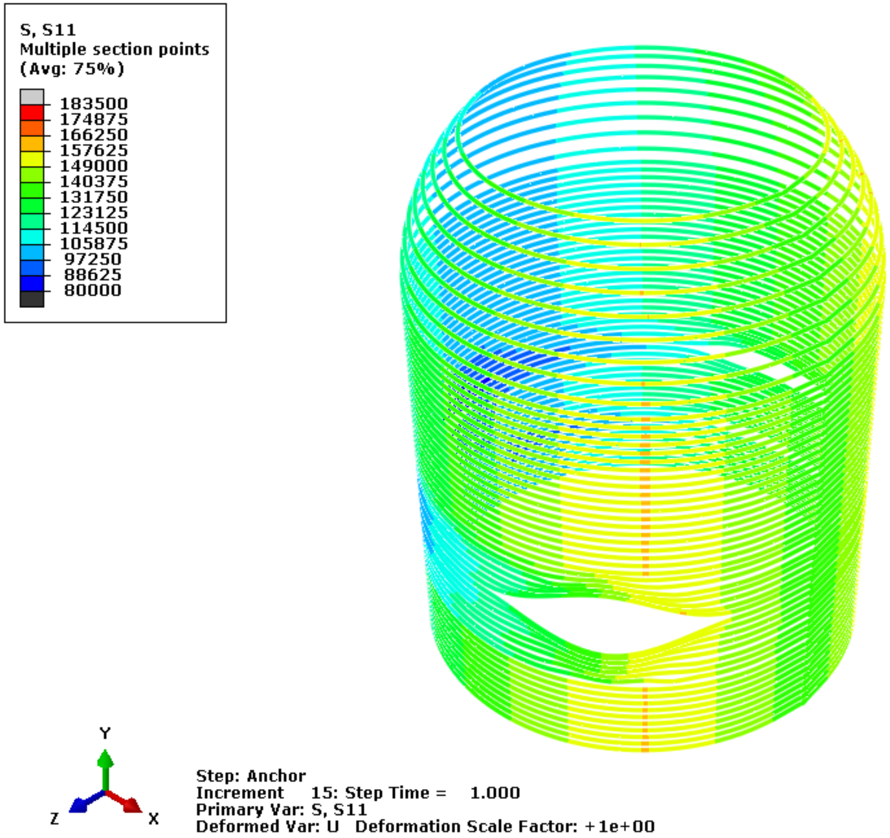
Stress in Hoop Tendons Anchored at 270° after Anchorage



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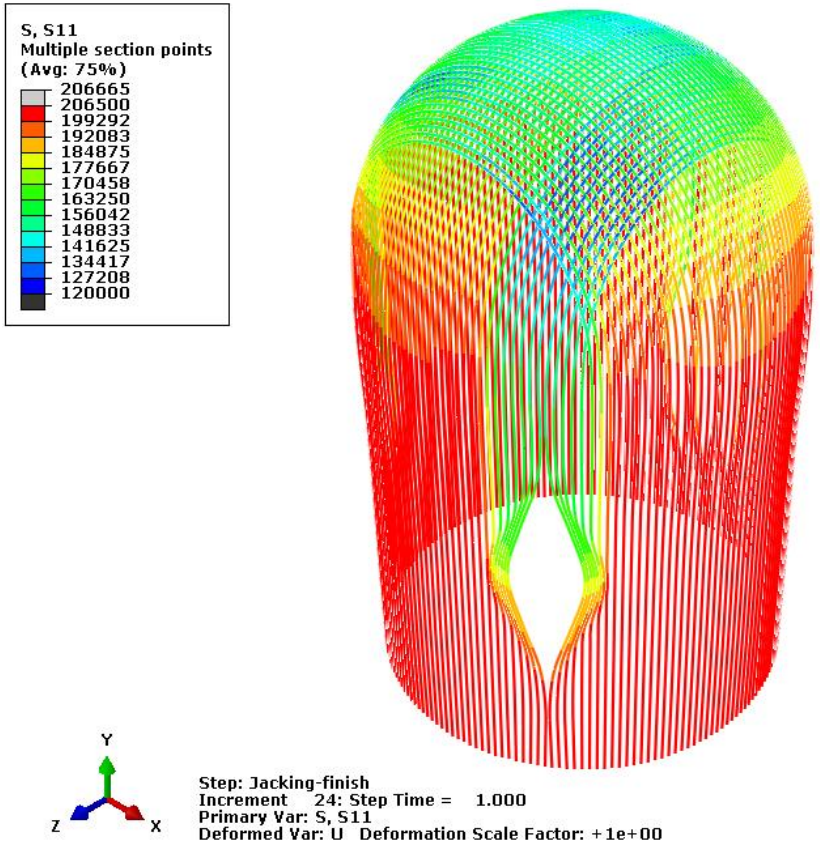
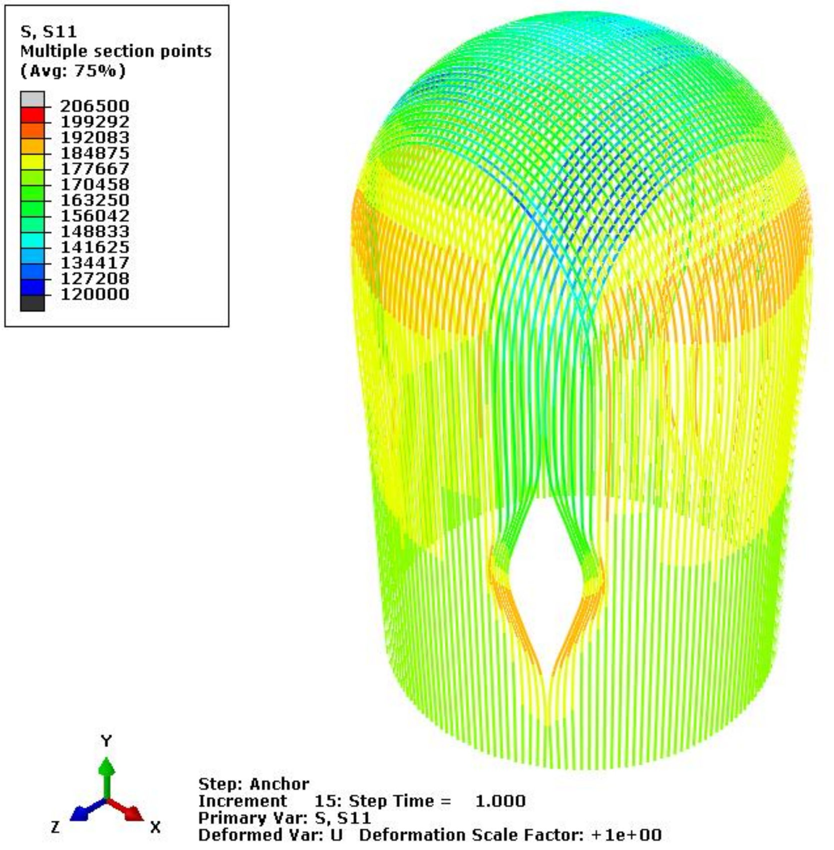
Stress in Vertical Tendons after Jacking before Anchorage

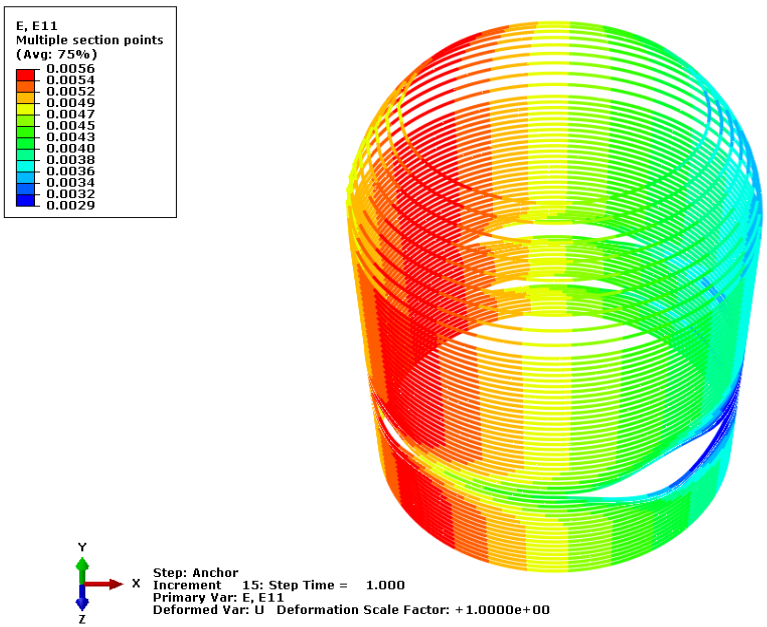


Stress in Vertical Tendons after Anchorage

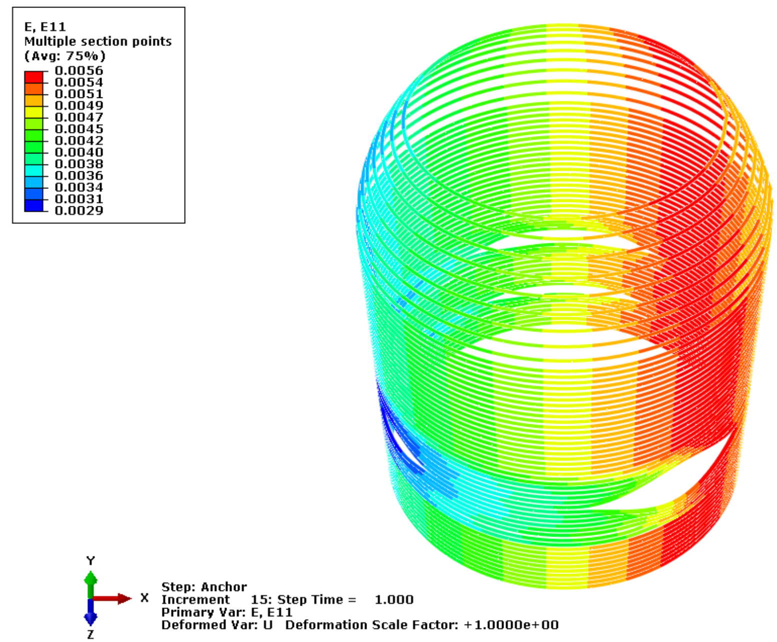


Strain in Hoop Tendons

Anchored at 90° after Anchorage

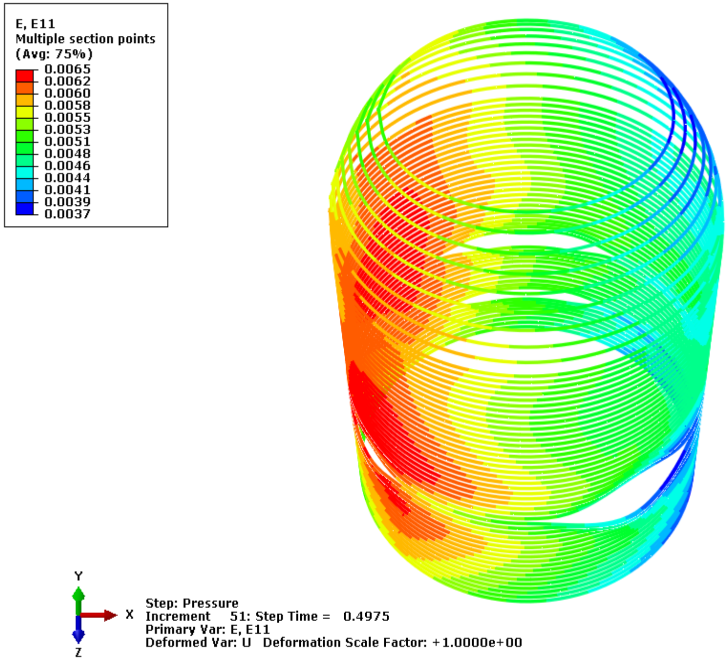


Anchored at 270° after Anchorage

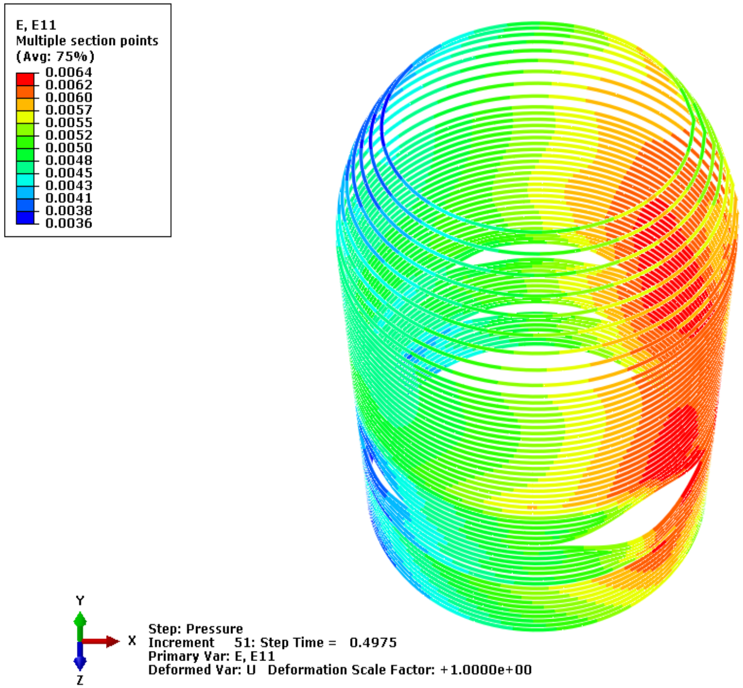


Strain in Hoop Tendons

Anchored at 90° at 2.0 x Pd

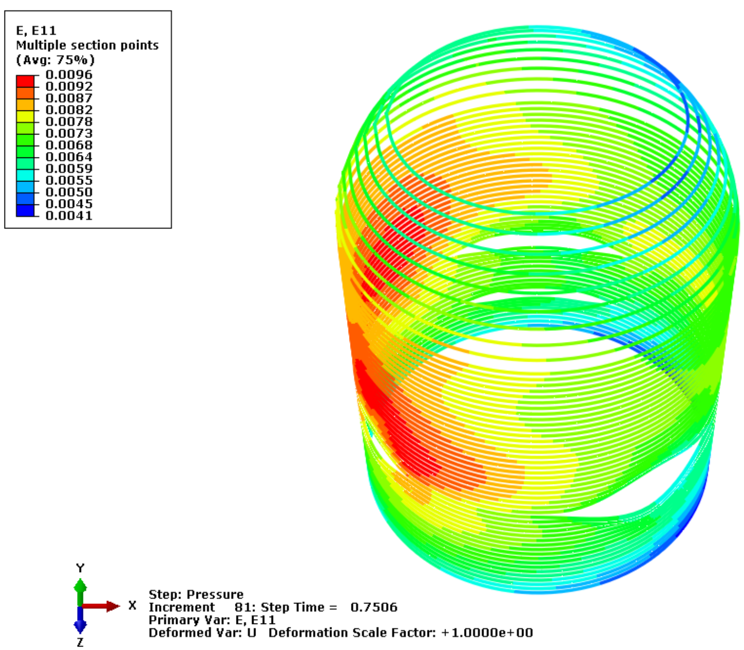


Anchored at 270° at 2.0 x Pd

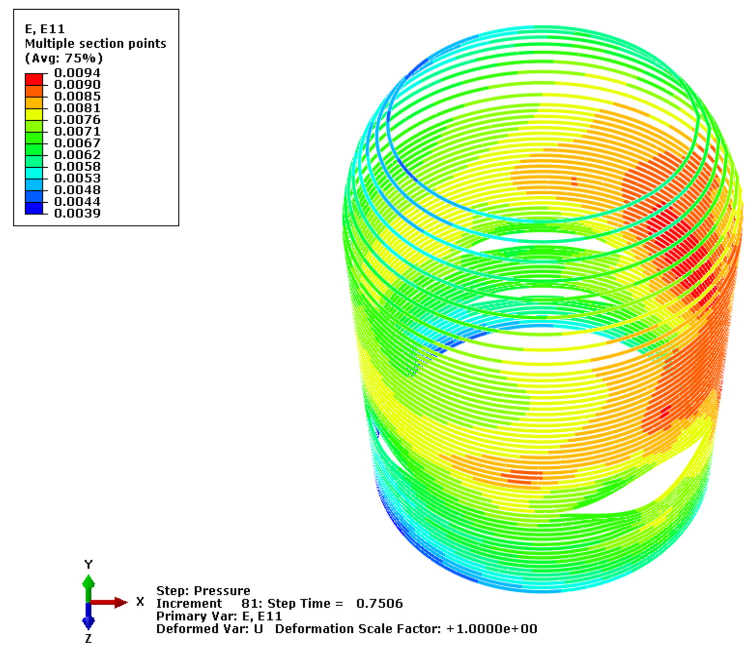


Strain in Hoop Tendons

Anchored at 90° at 3.0 x Pd



Anchored at 270° at 3.0 x Pd



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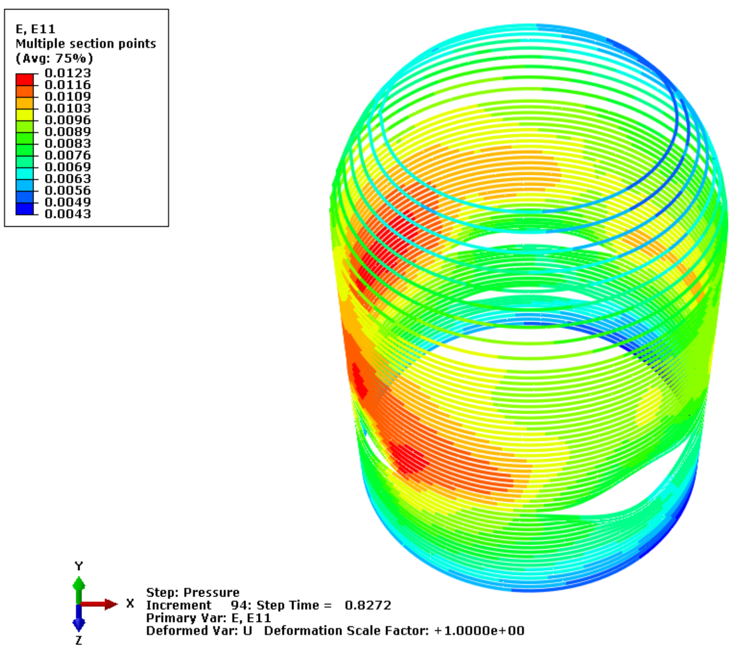
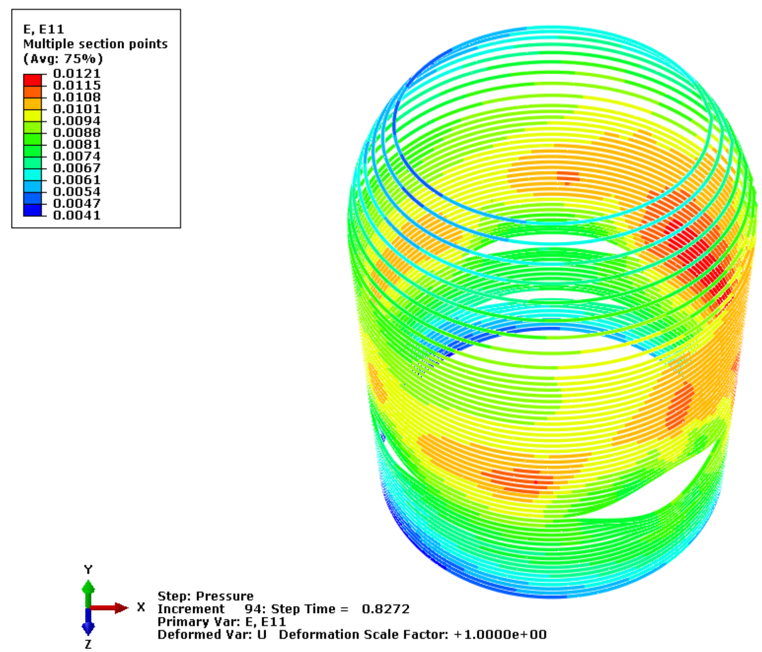
Strain in Hoop Tendons

Anchored at 90° at 3.3 x Pd



Anchored at 270° at 3.3 x Pd



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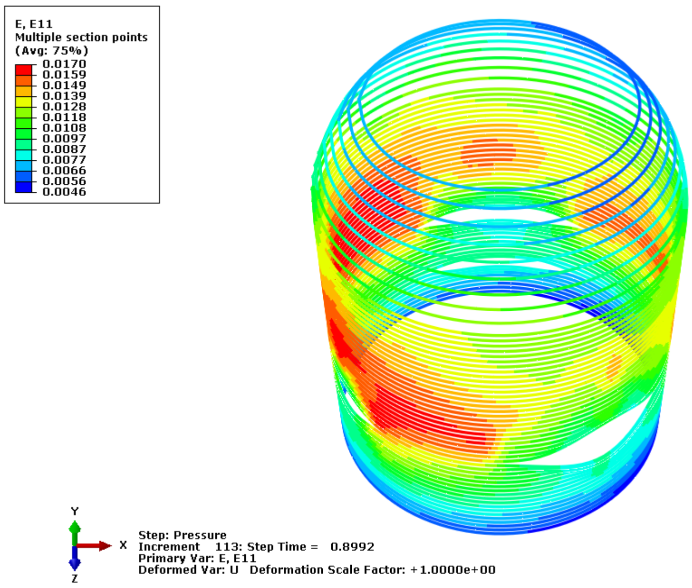
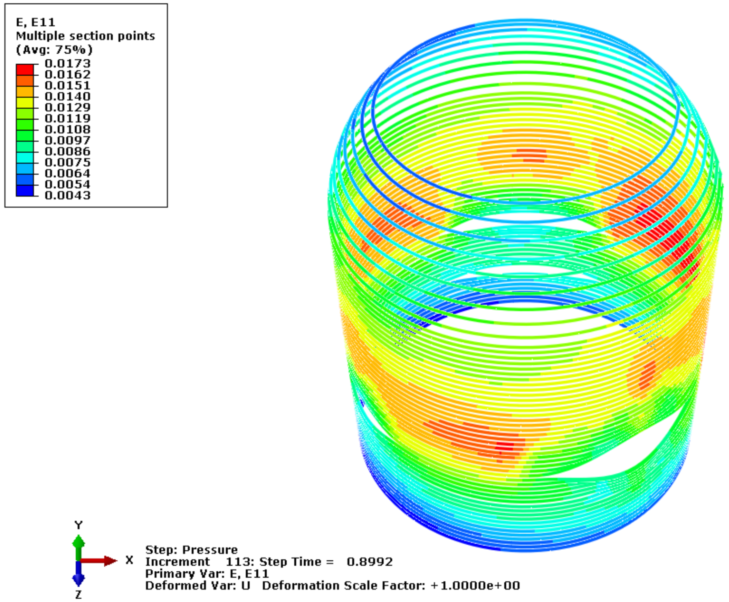
Strain in Hoop Tendons

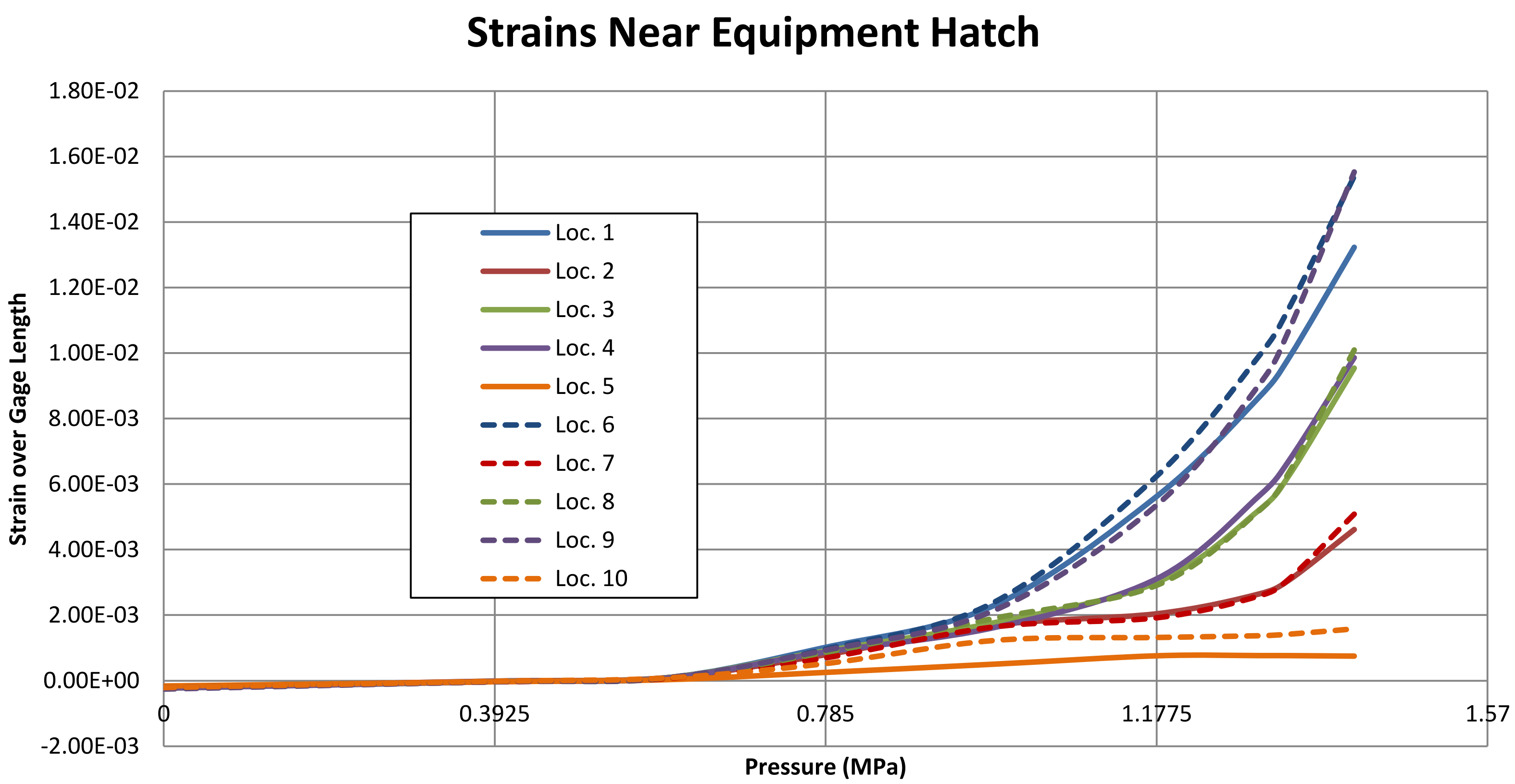
Anchored at 90˚ at 3.6 x Pd



Anchored at 270˚ at 3.6 x Pd



Strains over Selected Gage Length Near E/H



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Analysis Results, cont'd

- **For Model 2, it was shown that at selected gage lengths in the vicinity of liner strain concentrations (like welds and anchors), liner strains of 0.003 may be sufficient to create a tear**
- **Such strain levels are shown to exist in the global Model 3 analysis at locations exhibiting liner tearing in the 1:4 Scale PCCV model test**

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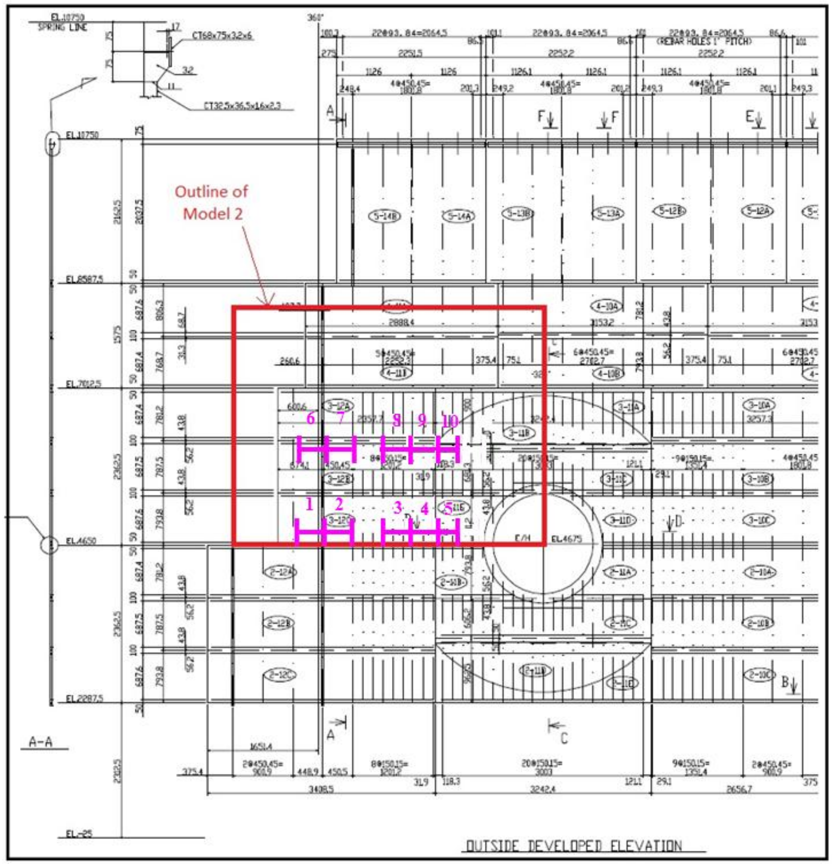
Liner (E/H) View Showing Strain Reports (cut from Page A-28 of NUREG/CR-6810)



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Sol Comparisons, Model 3 Analysis vs. Test

- For most fundamental response quantities such as midheight displacement of the cylinder (at free-field, buttress, and E/H, for example), the analysis compares well to the test measurements
- Some of the response quantities which are

  1) very small, or

  2) have limitations based on the shell element modeling employed, such as displacements at the wall-base juncture, show some noticeable differences between analysis and test
- Exploring these similarities and differences can be a subject of discussion today

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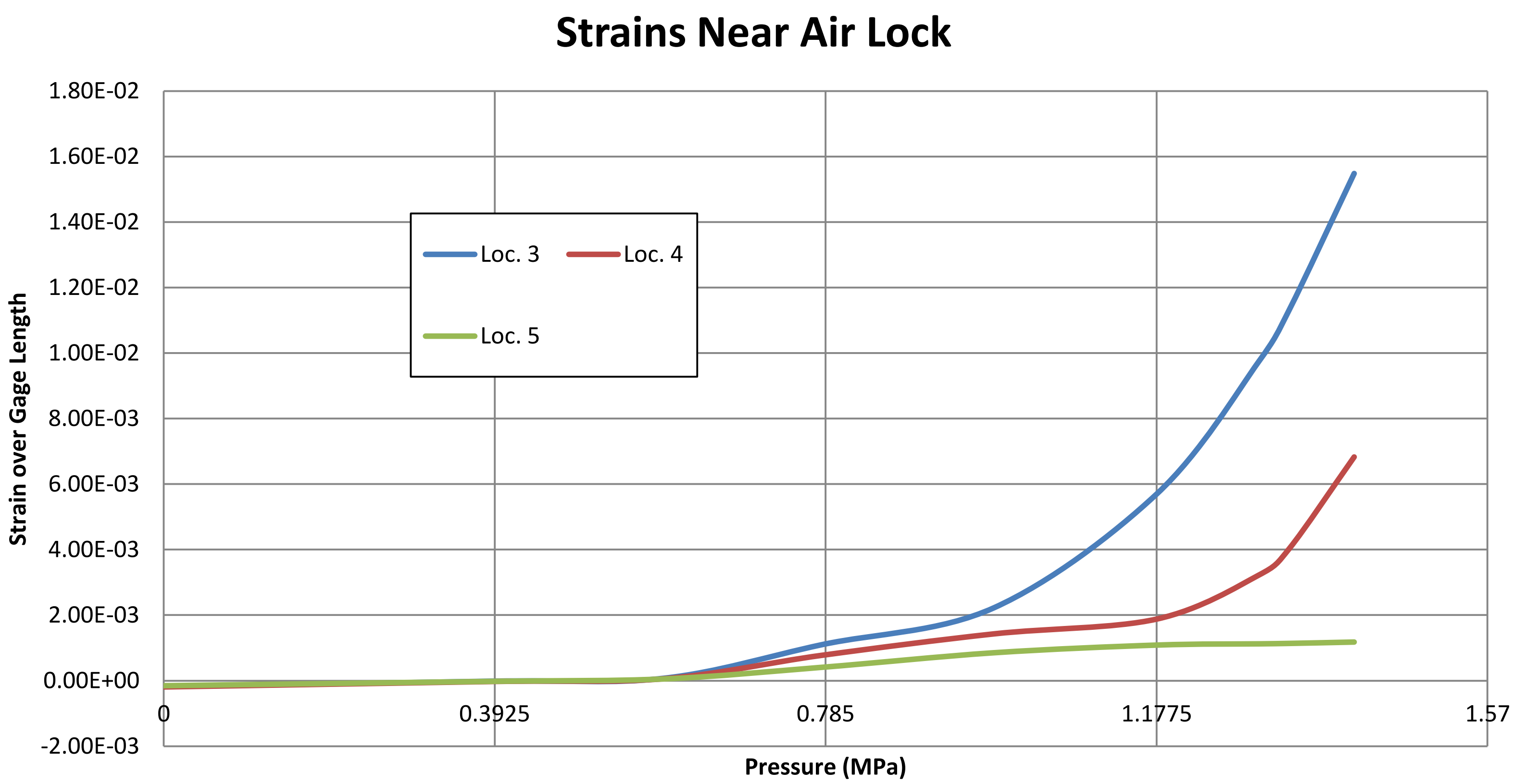
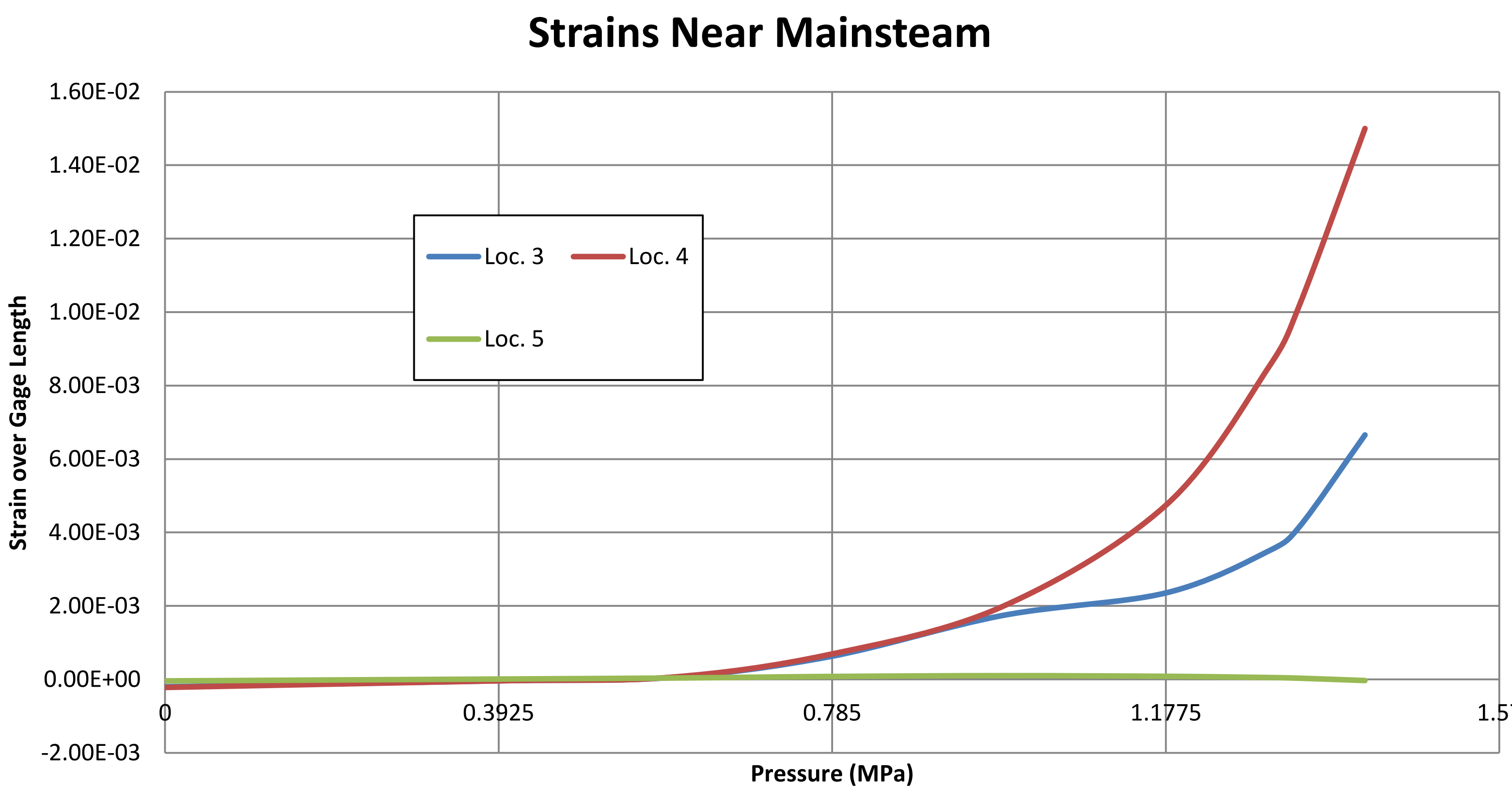
Strains over Selected Gage Length Near A/L



Strains over Selected Gage Length Near M/S



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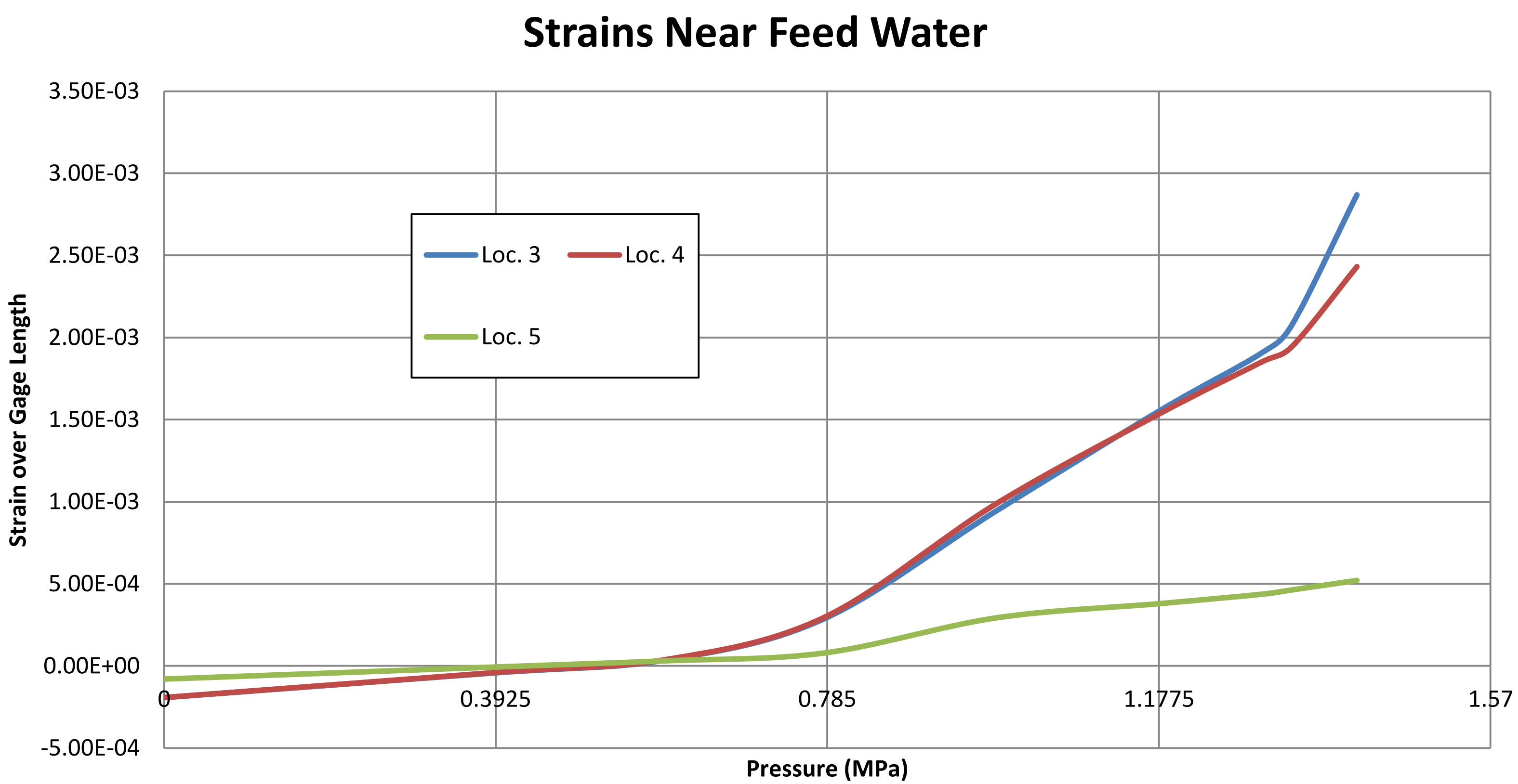
Strains over Selected Gage Length Near F/W



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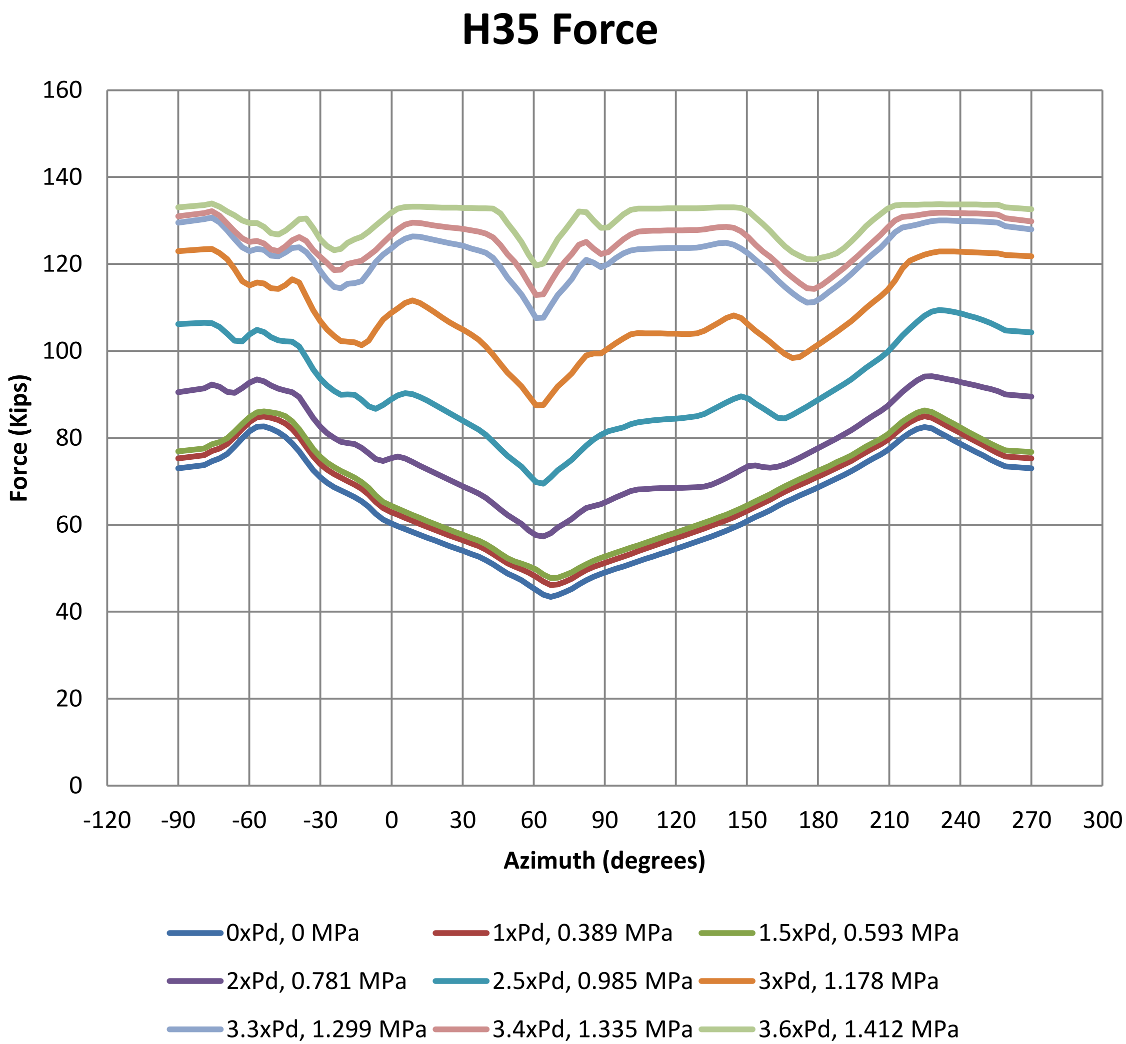
Abaqus Analysis – Hoop Tendon H35 Force



Analysis Results

- For the hoop tendons, the trends agree well between the analysis and test
- For the vertical tendons the general stress levels and effects of friction show similar trends, but there are some differences in stress distribution observed in the dome, between the analysis and the test

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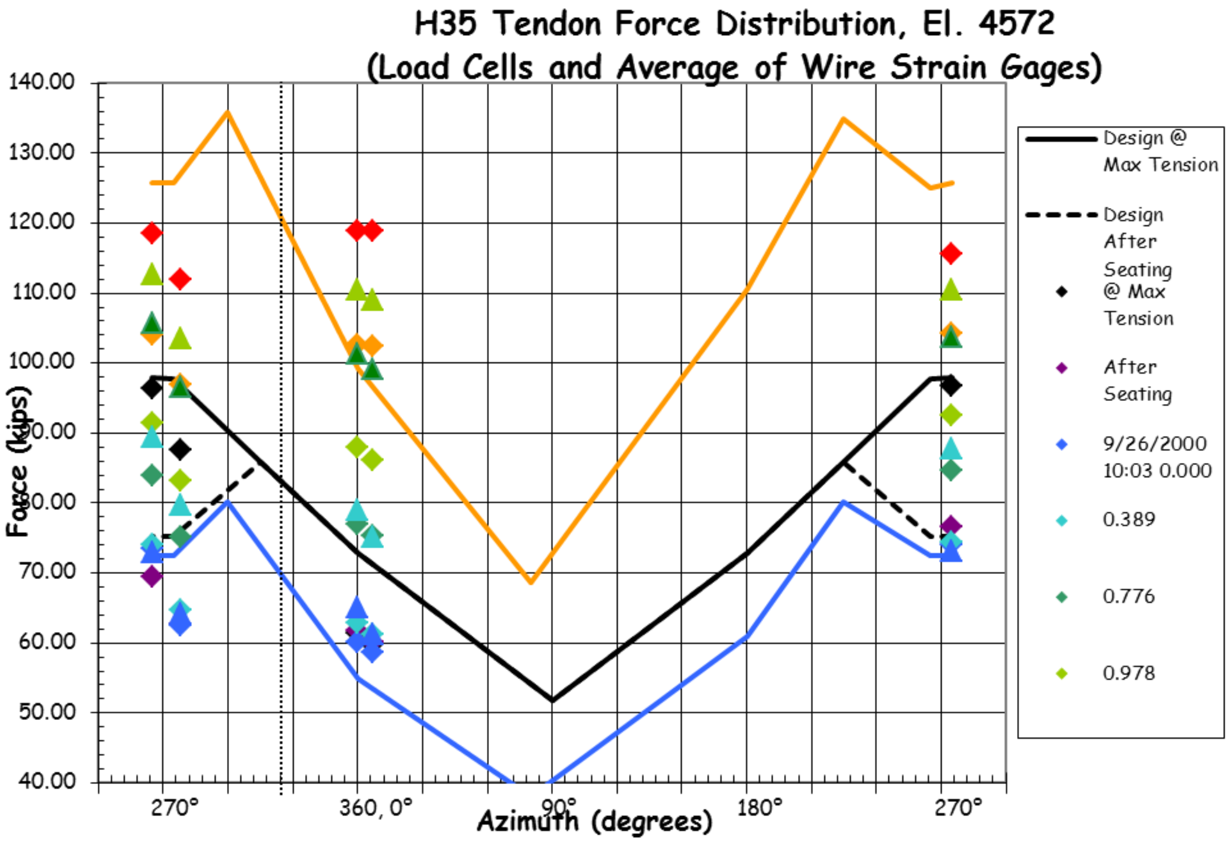
LST Test – Hoop Tendon H35 Force



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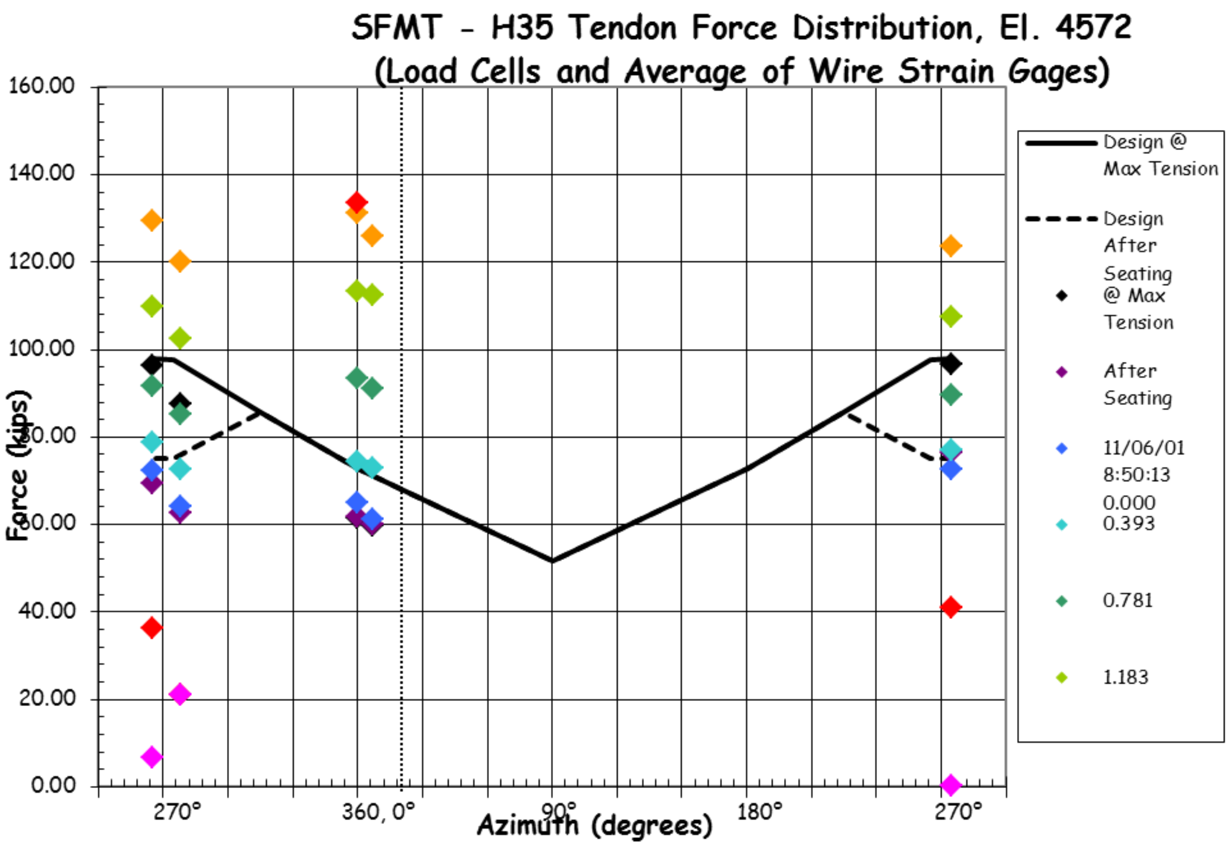
SFMT Test – Hoop Tendon H35 Force



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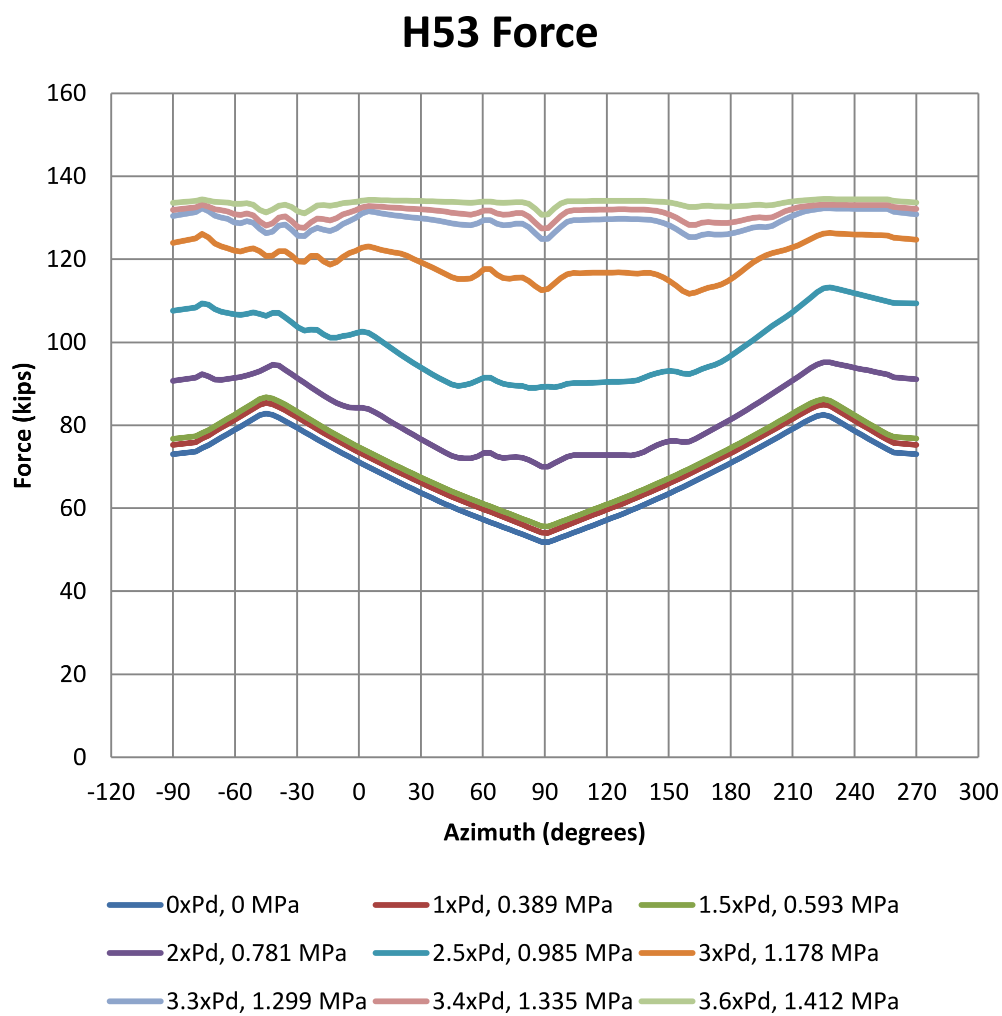
Abaqus Analysis – Hoop Tendon H53 Force



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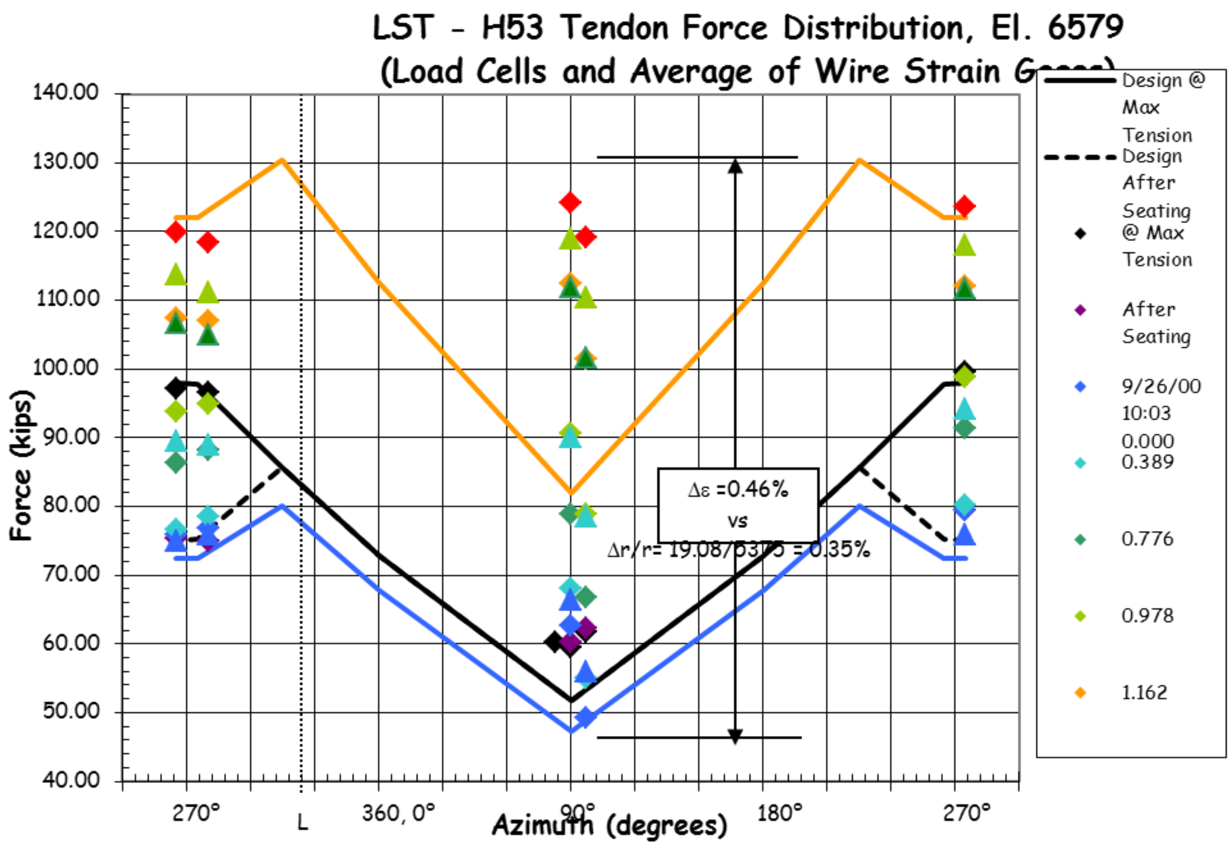
LST Test – Hoop Tendon H53 Force



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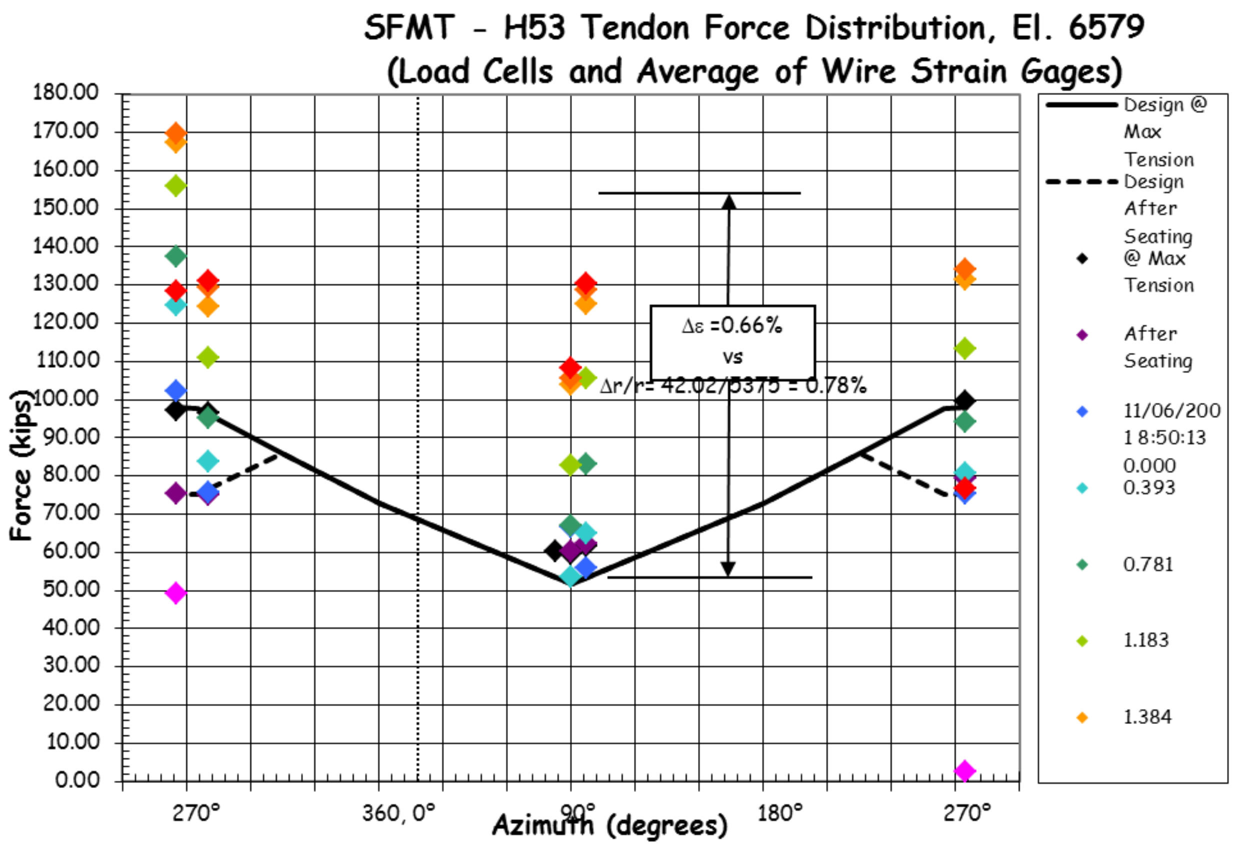
SFMT Test – Hoop Tendon H53 Force



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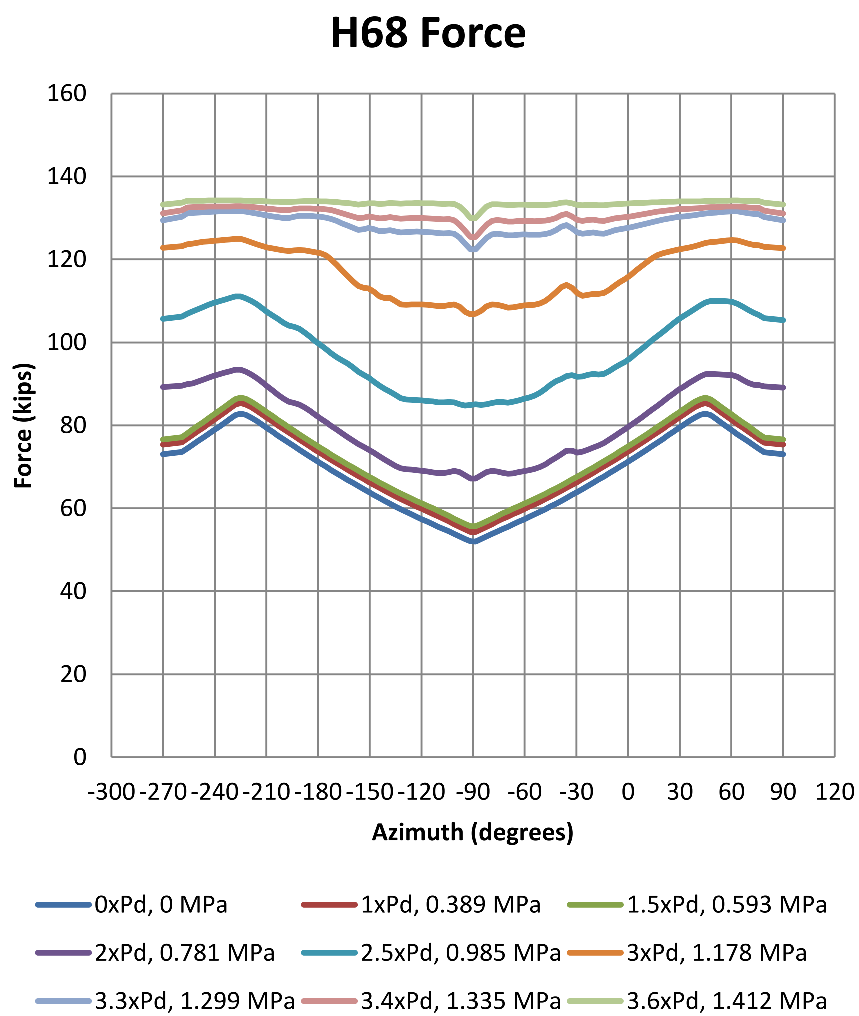
Abaqus Analysis – Hoop Tendon H68 Force



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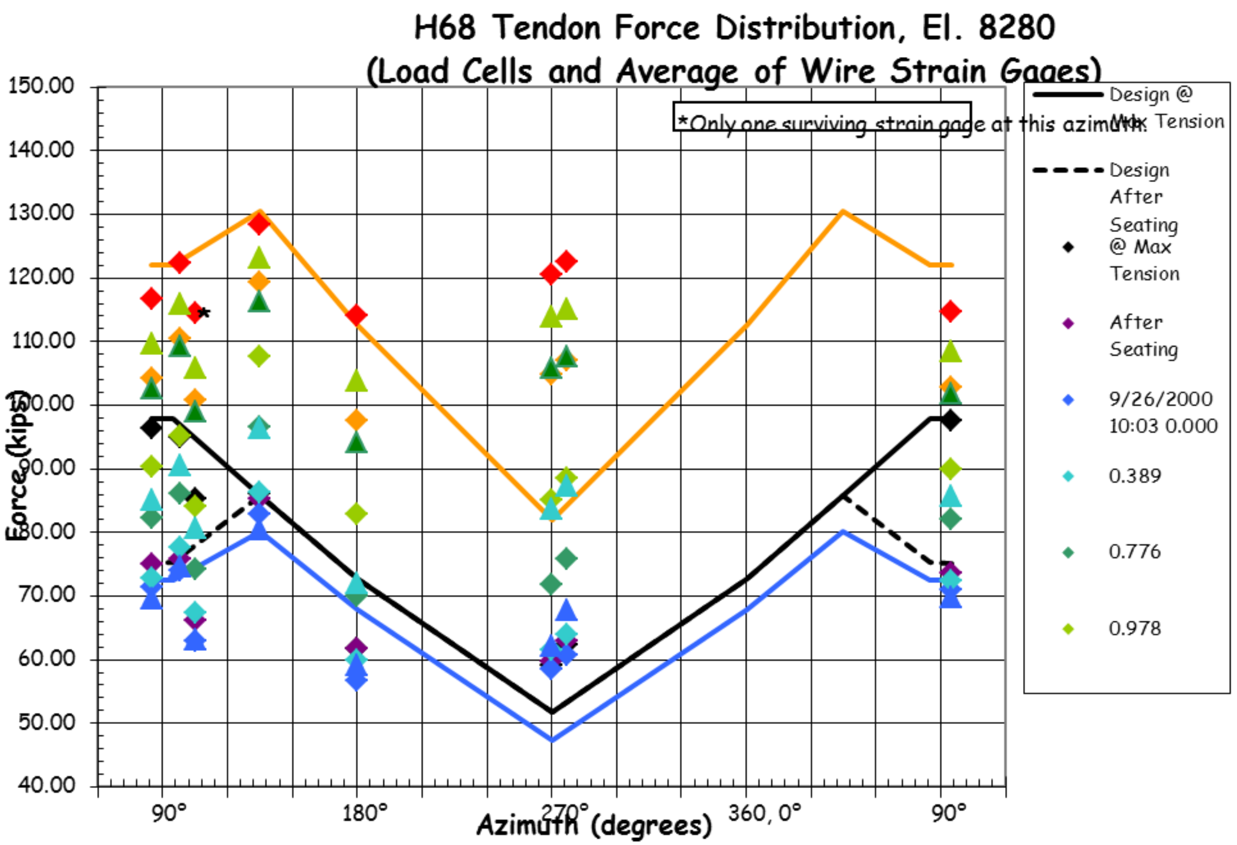
LST Test – Hoop Tendon H68 Force



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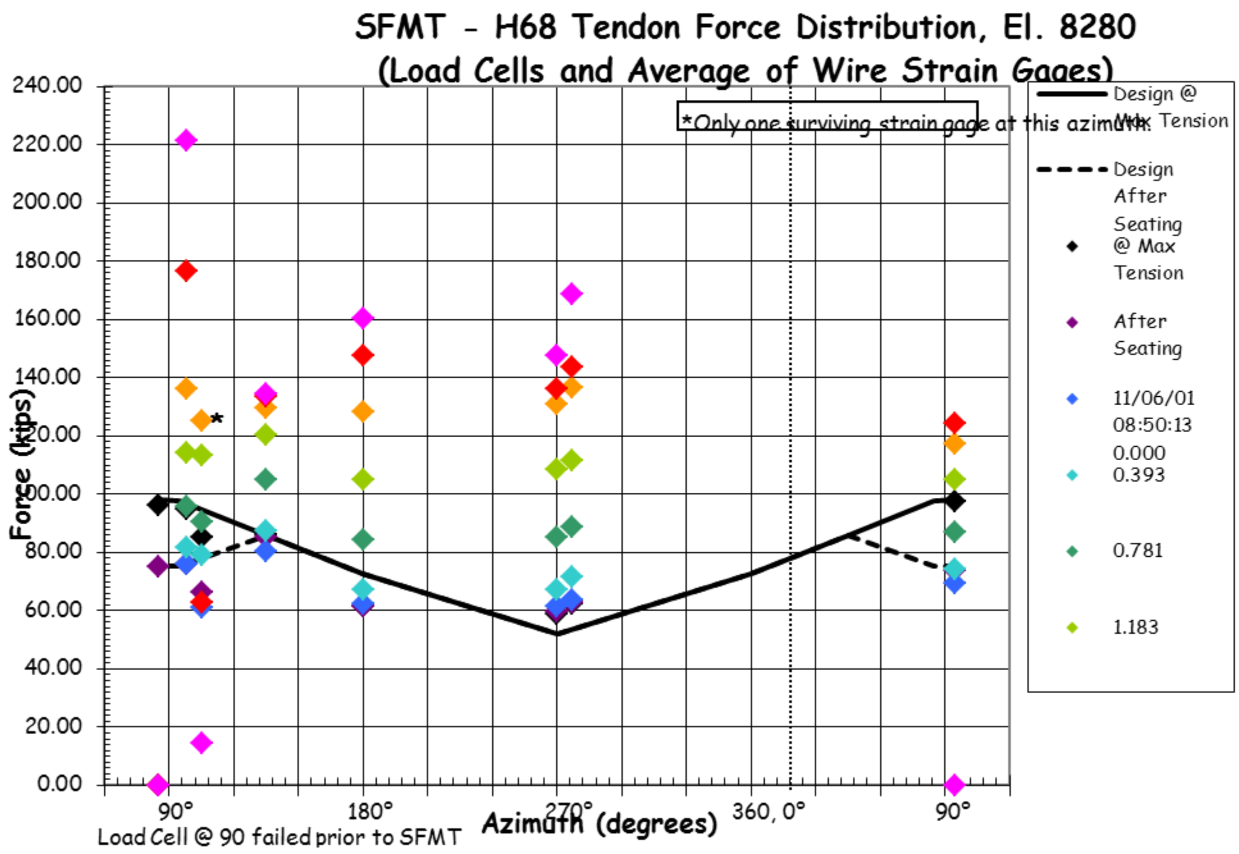
SFMT Test – Hoop Tendon H68 Force



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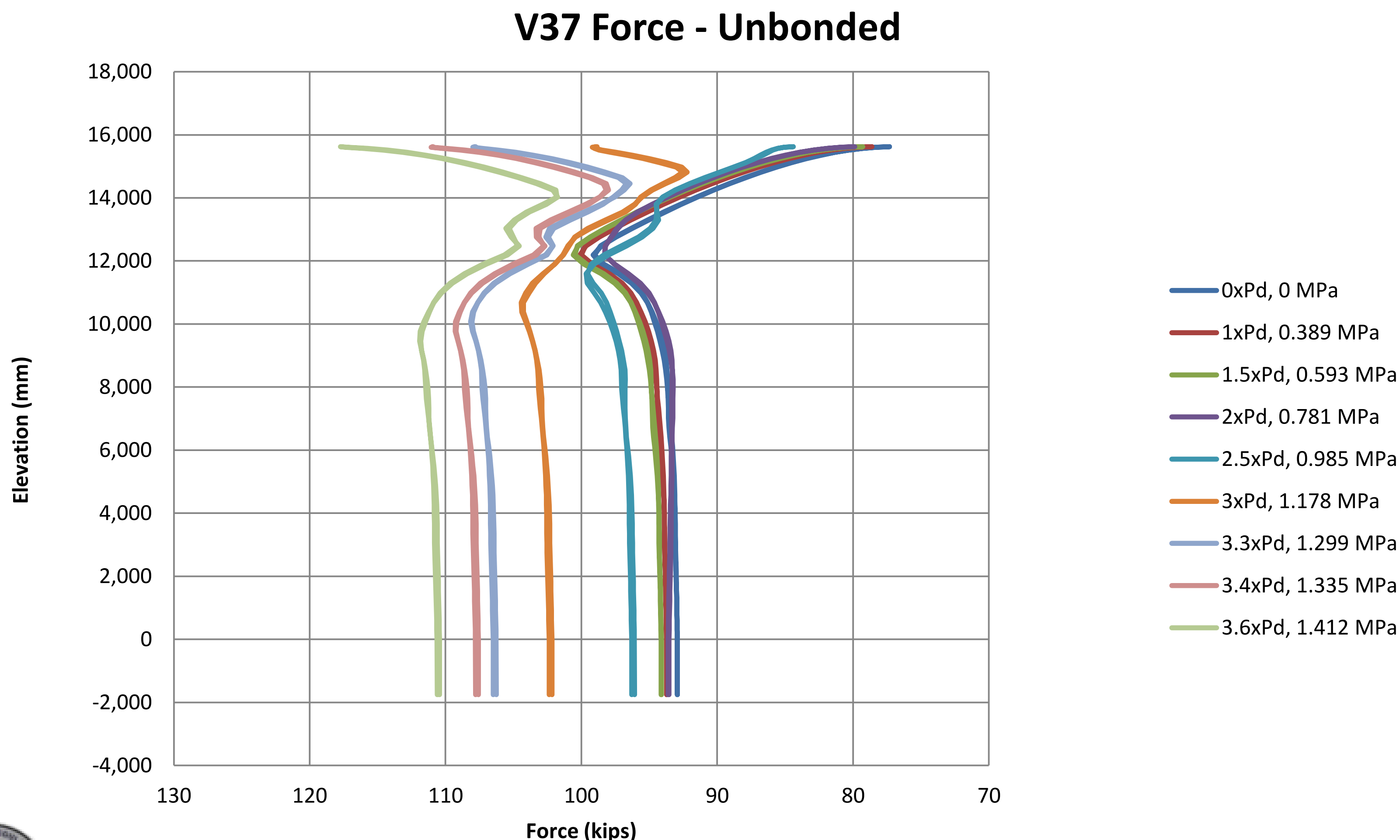
Abaqus Analysis – Hairpin Tendon V37 Force



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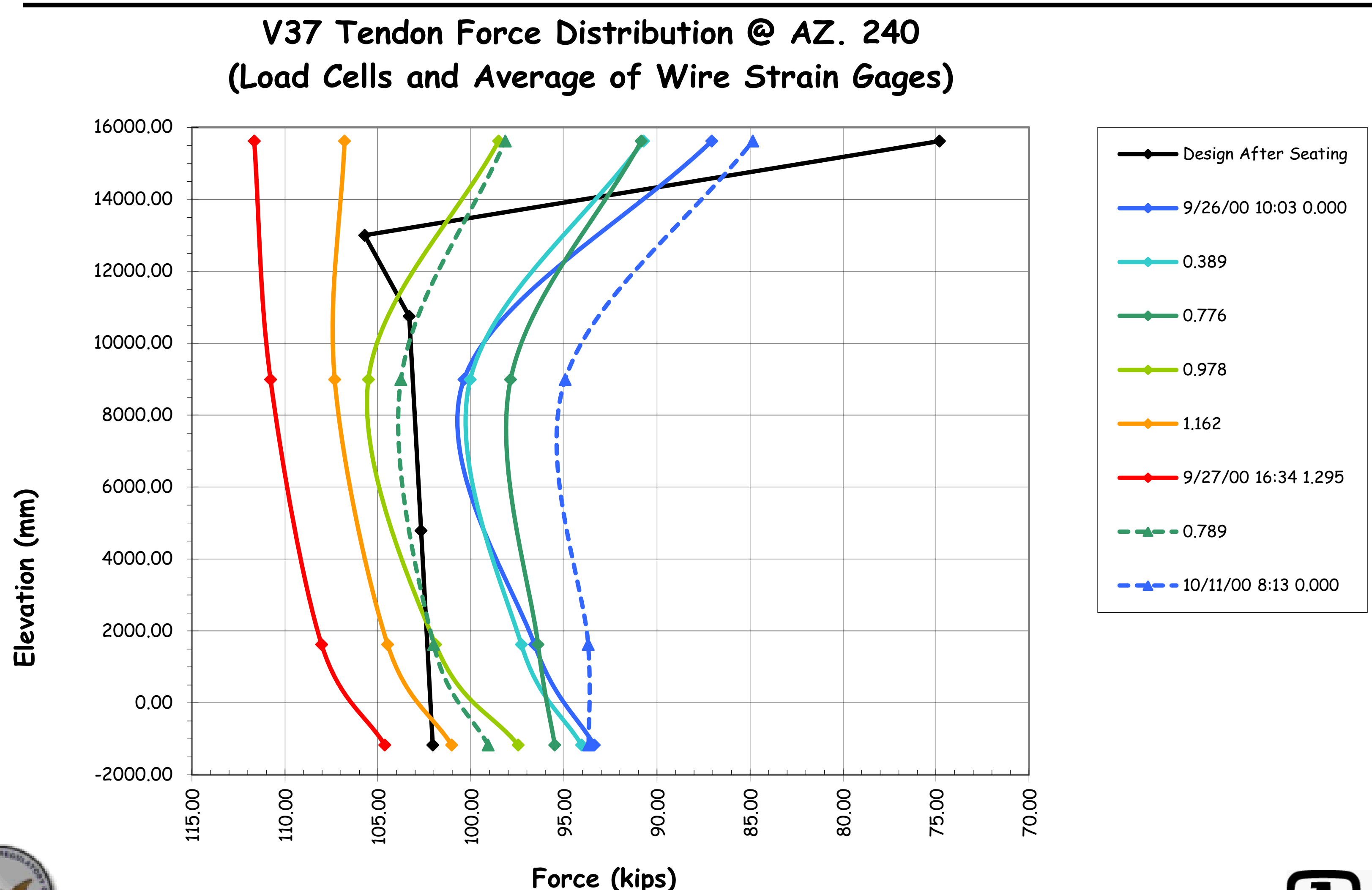
LST Test – Hairpin Tendon H37 Force



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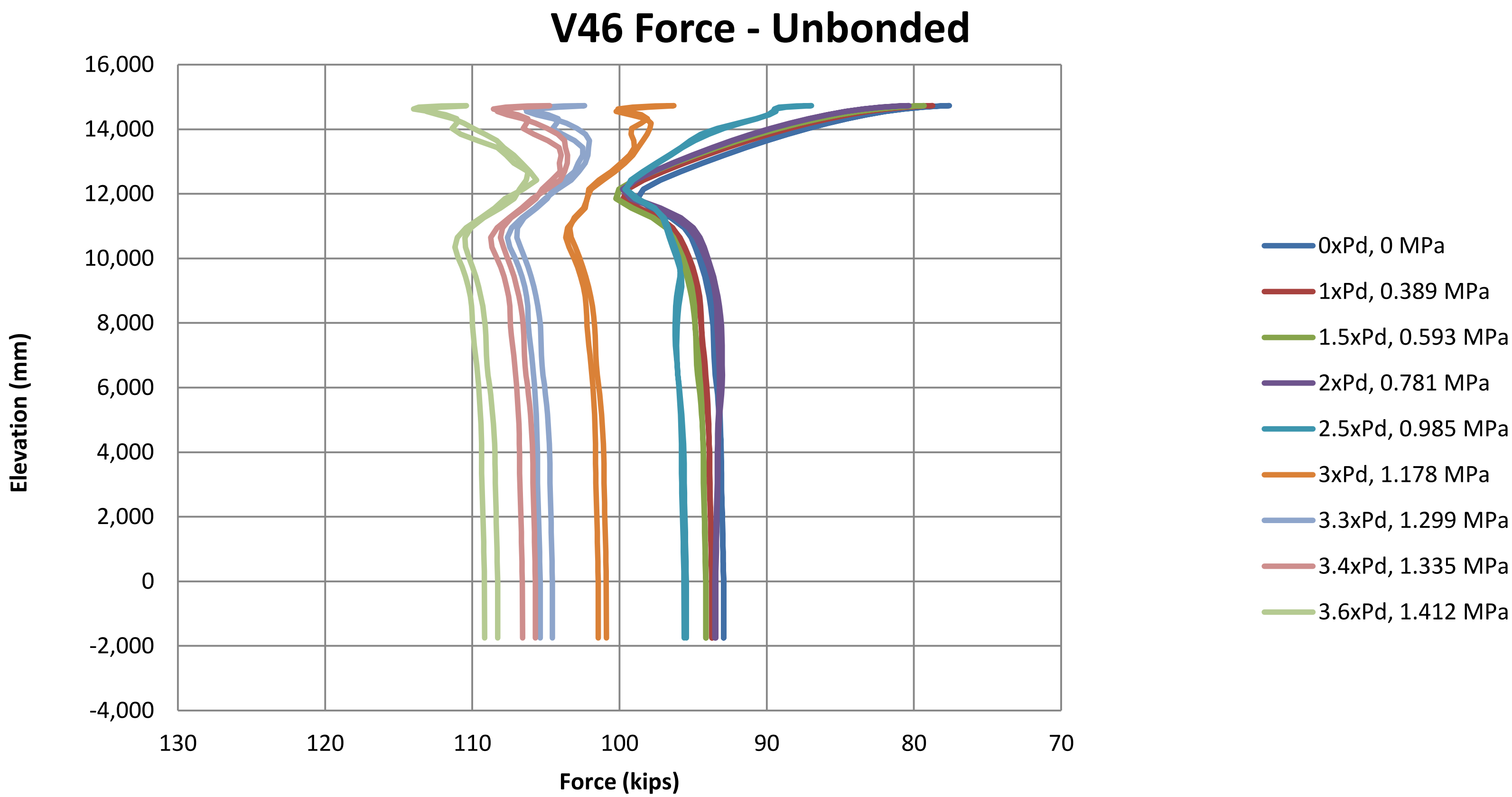
Abaqus Analysis – Hairpin Tendon V46 Force



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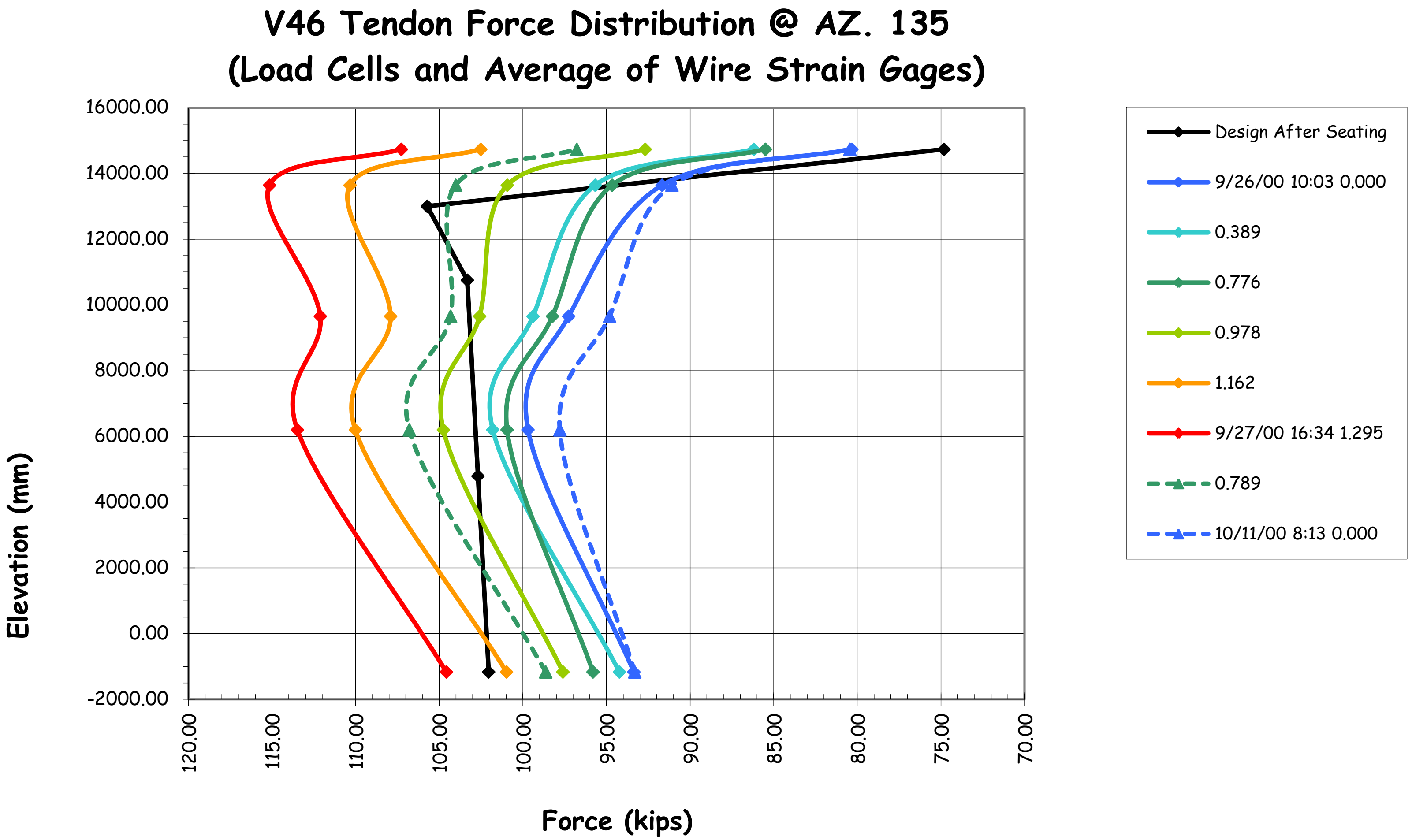
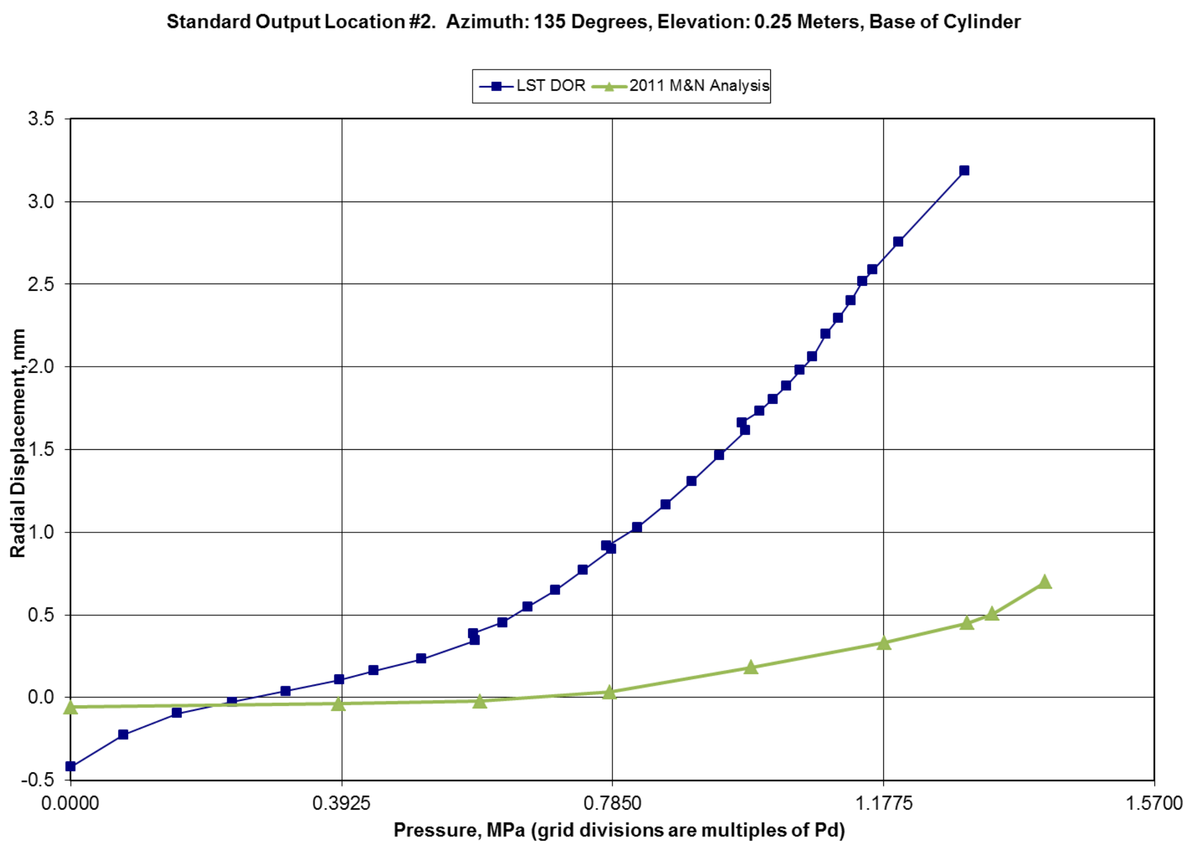
LST Test – Hairpin Tendon H46 Force





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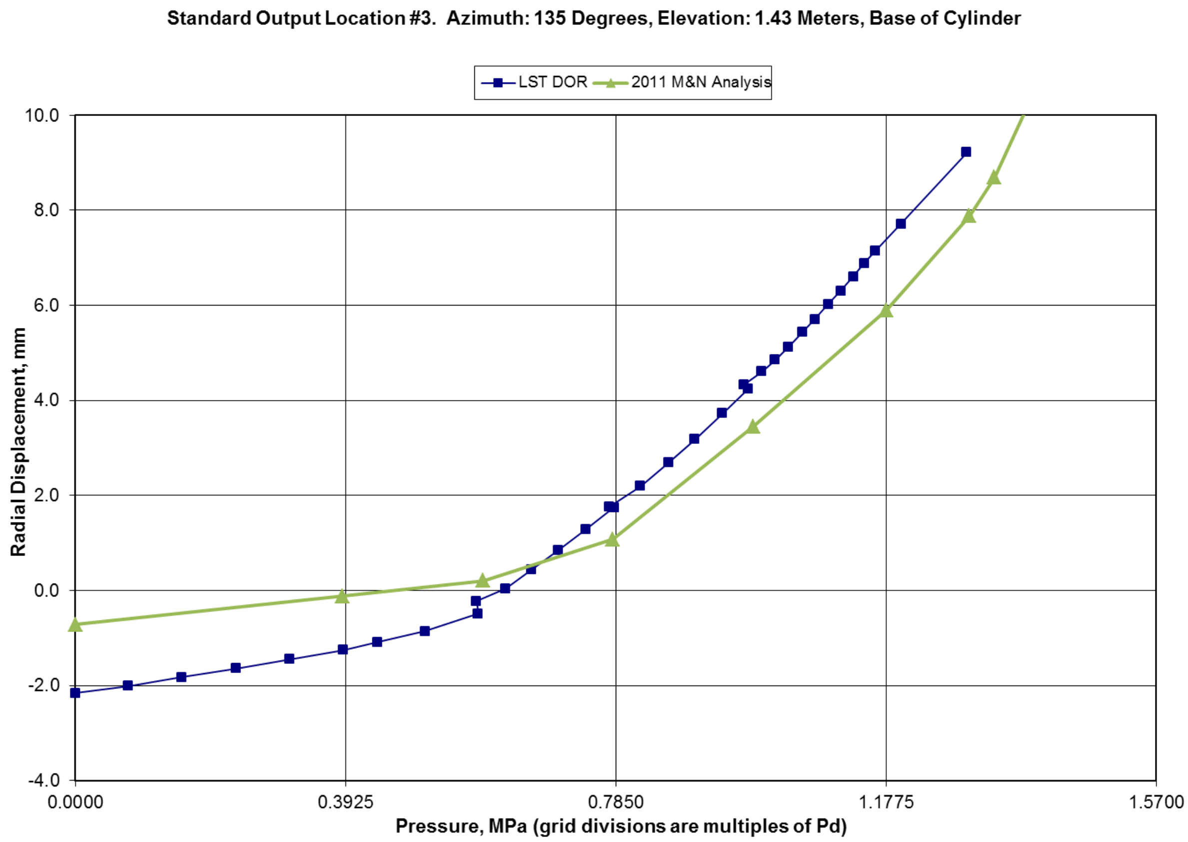
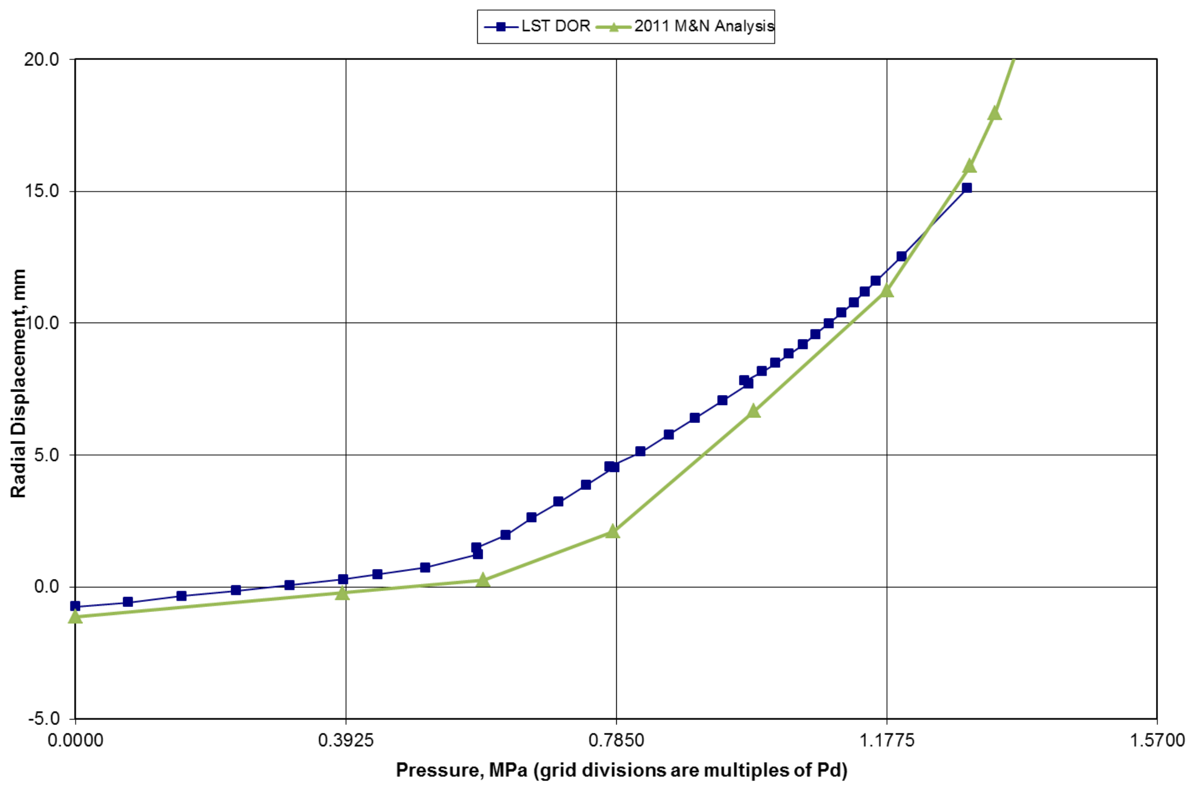

Standard Output Location #3. Azimuth: 135 Degrees, Elevation: 1.43 Meters, Base of Cylinder
LST DOR
2011 M&N Analysis
Radial Displacement, mm
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)

Standard Output Location #4. Azimuth: 135 Degrees, Elevation: 2.63 Meters, Base of Cylinder



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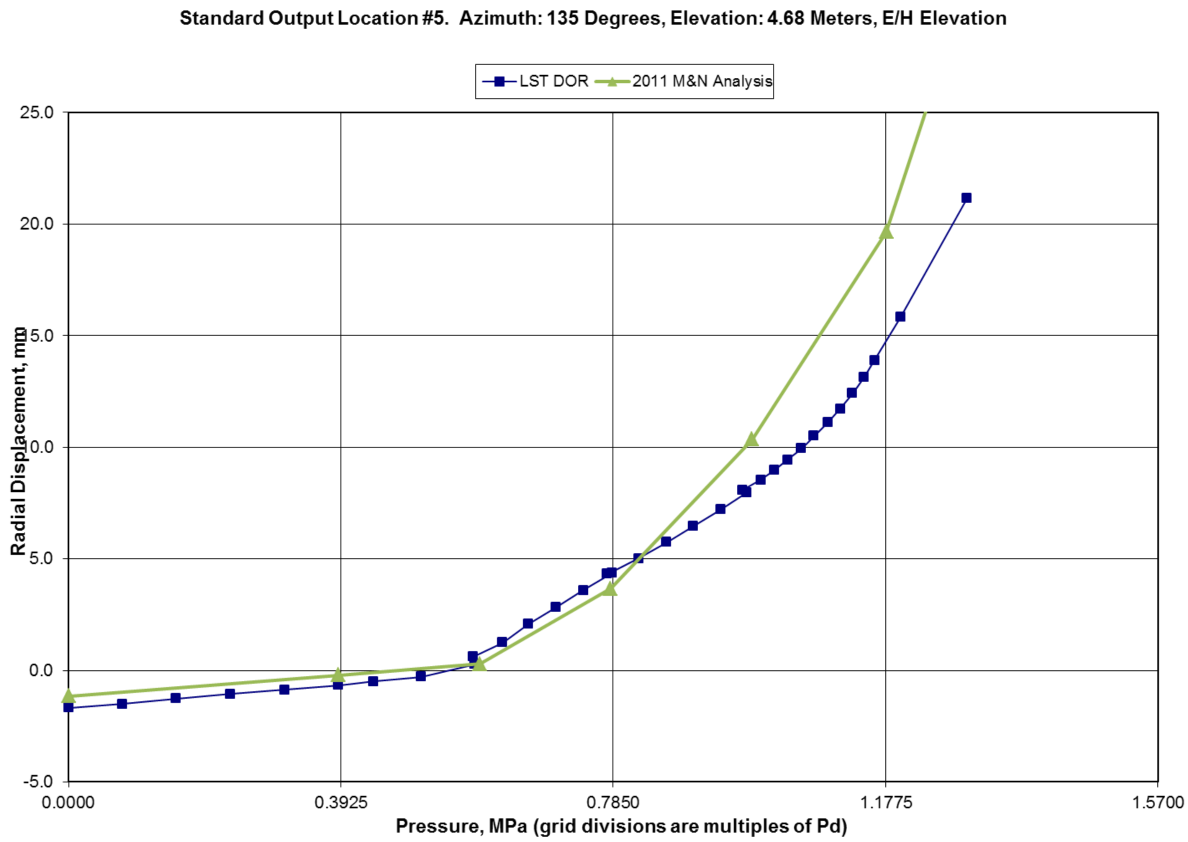

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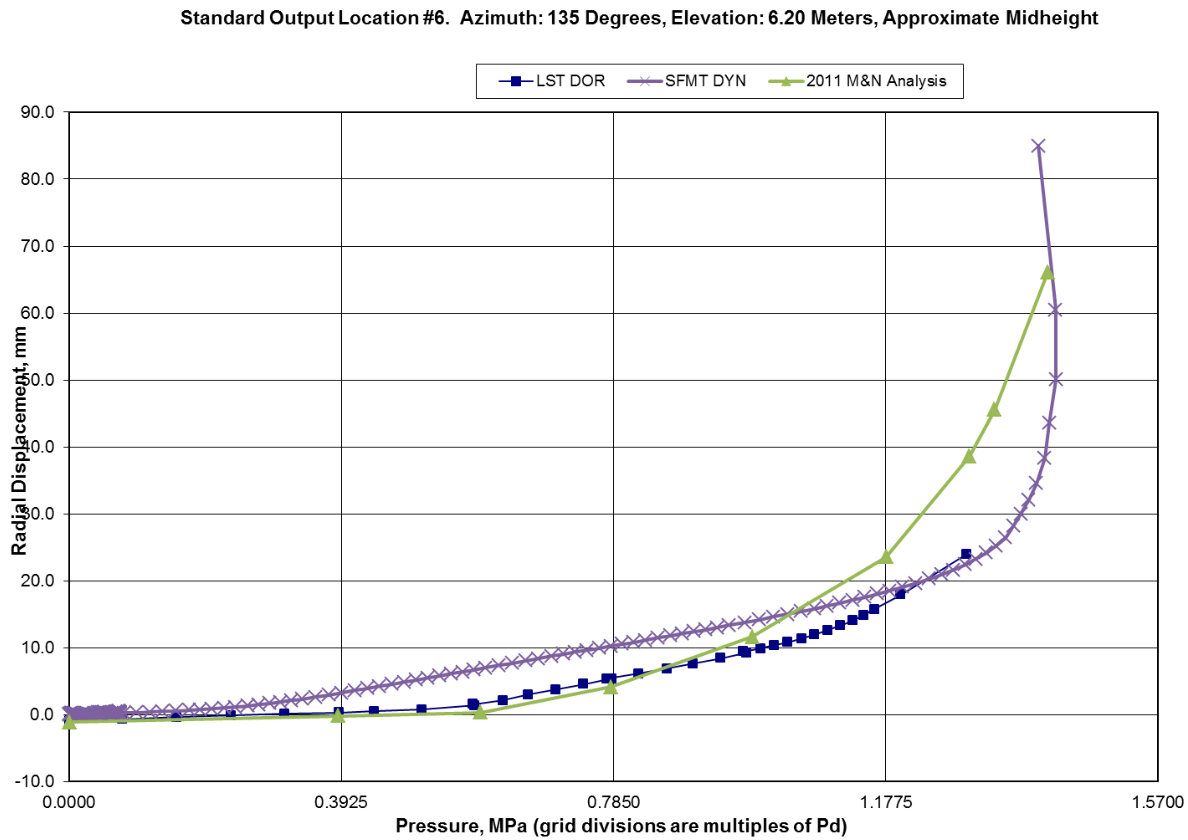

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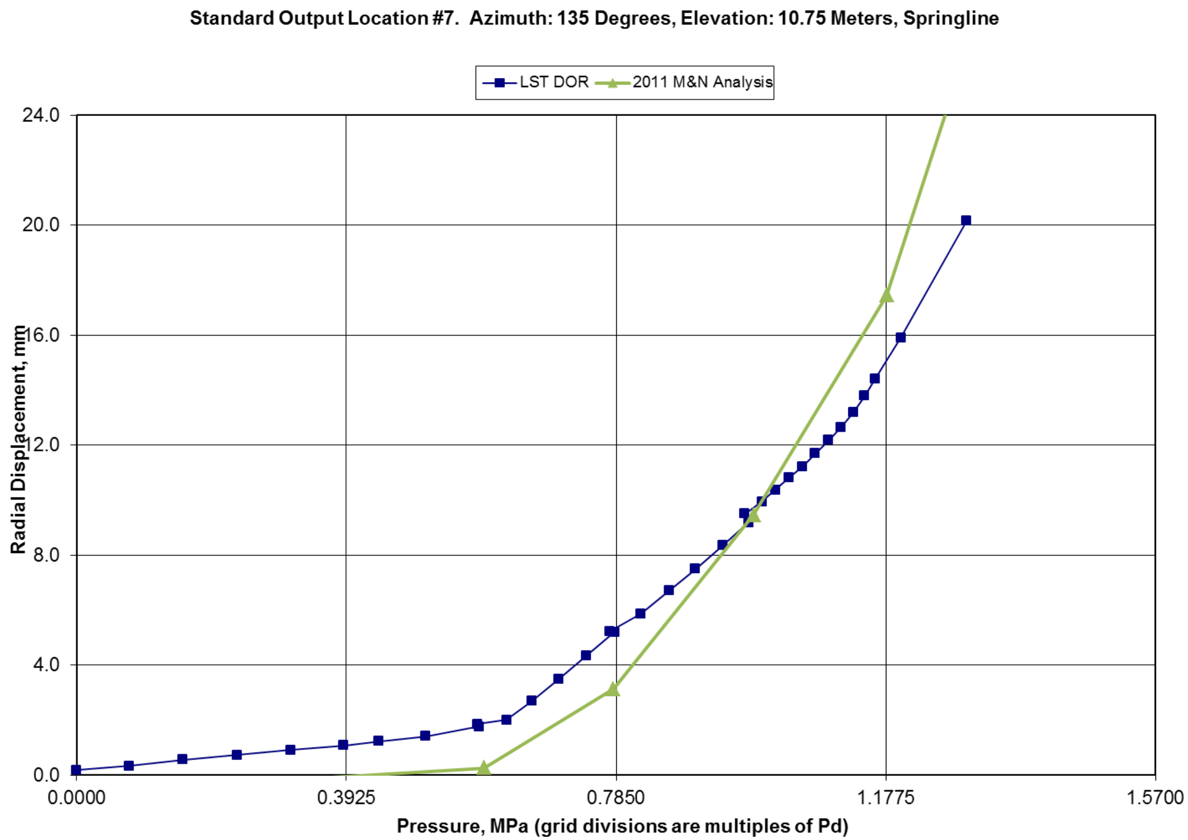

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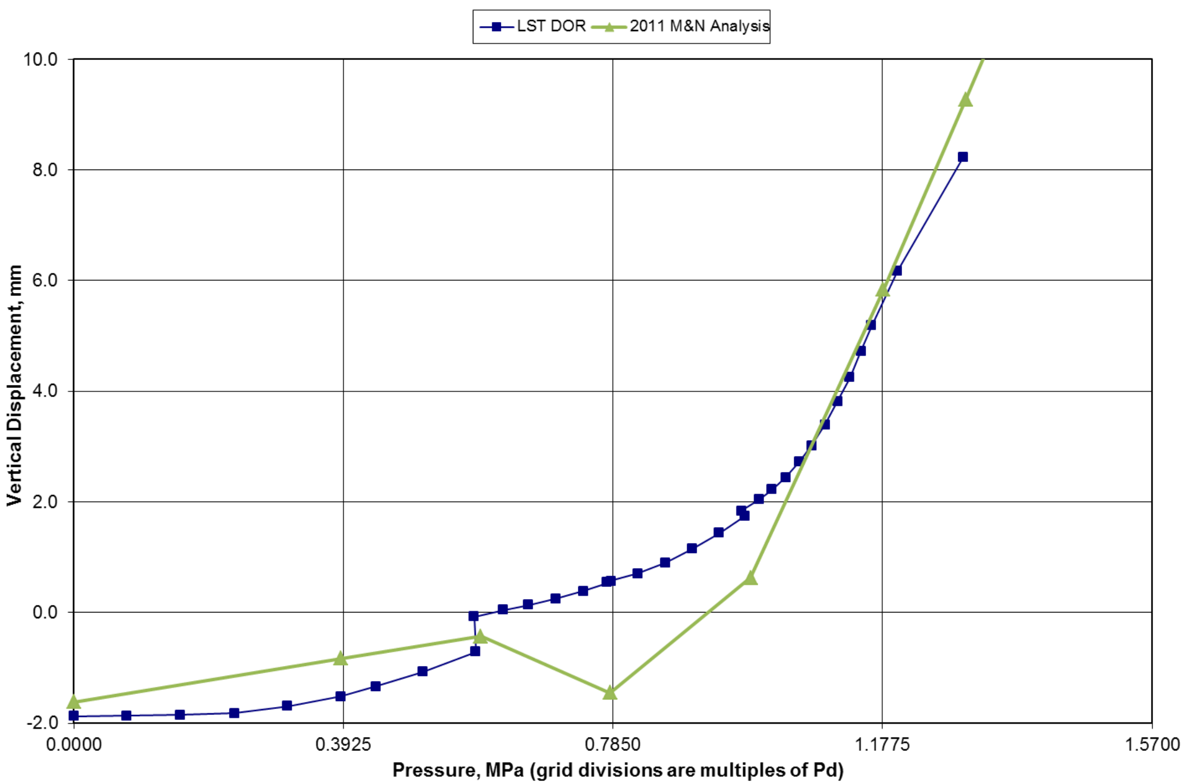
Standard Output Location #8. Azimuth: 135 Degrees, Elevation: 10.75 Meters, Springline



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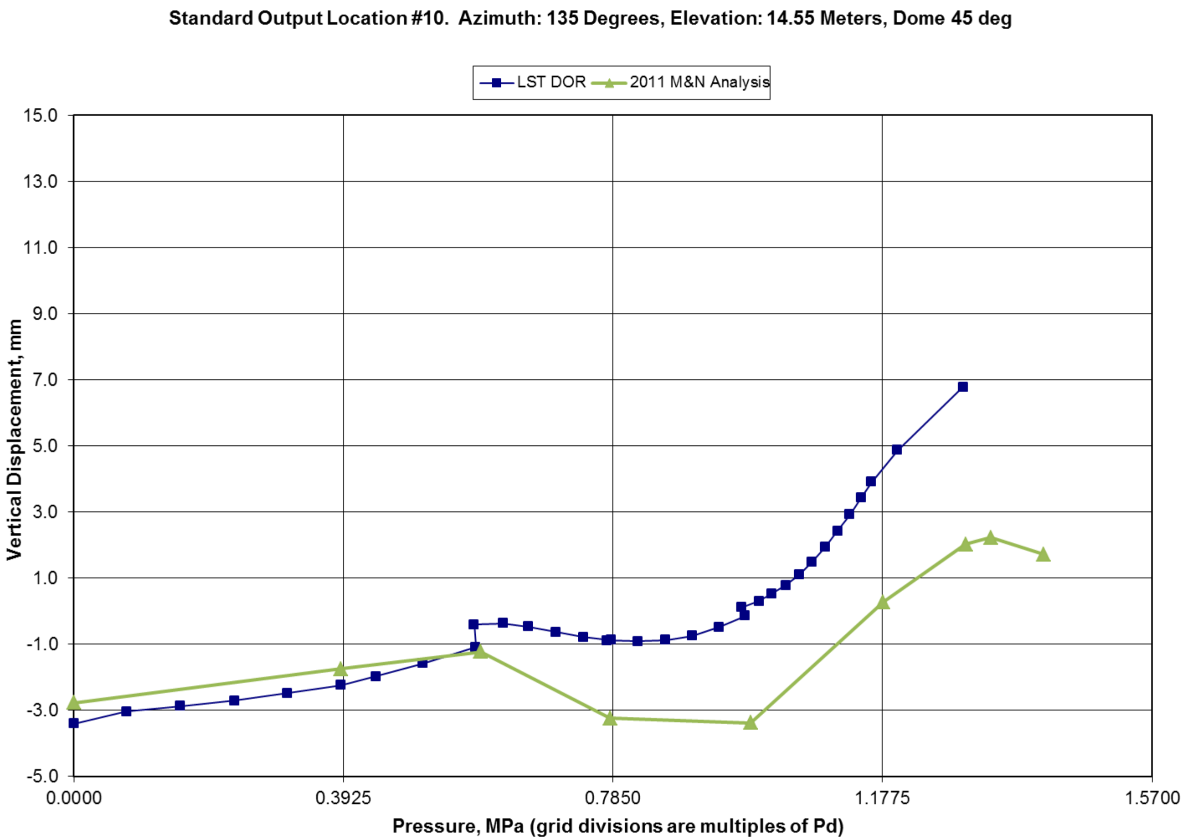

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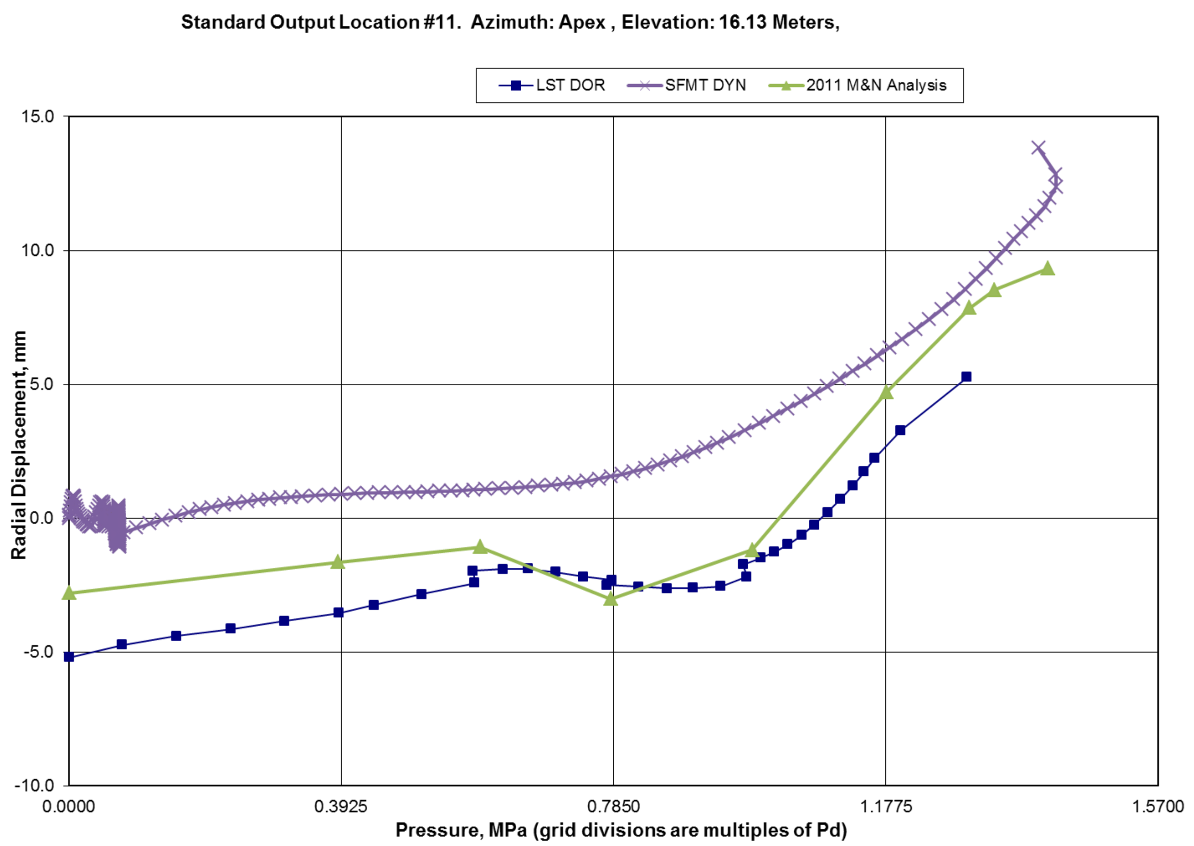
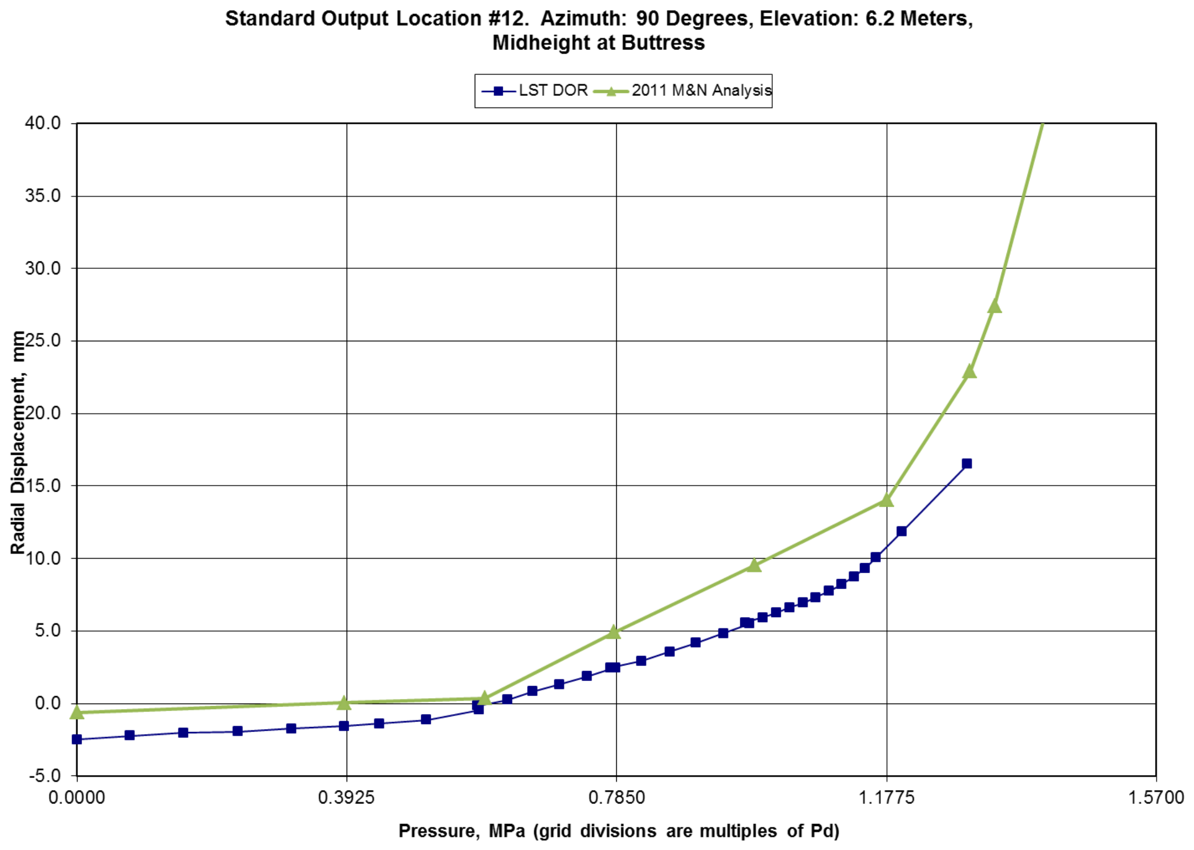
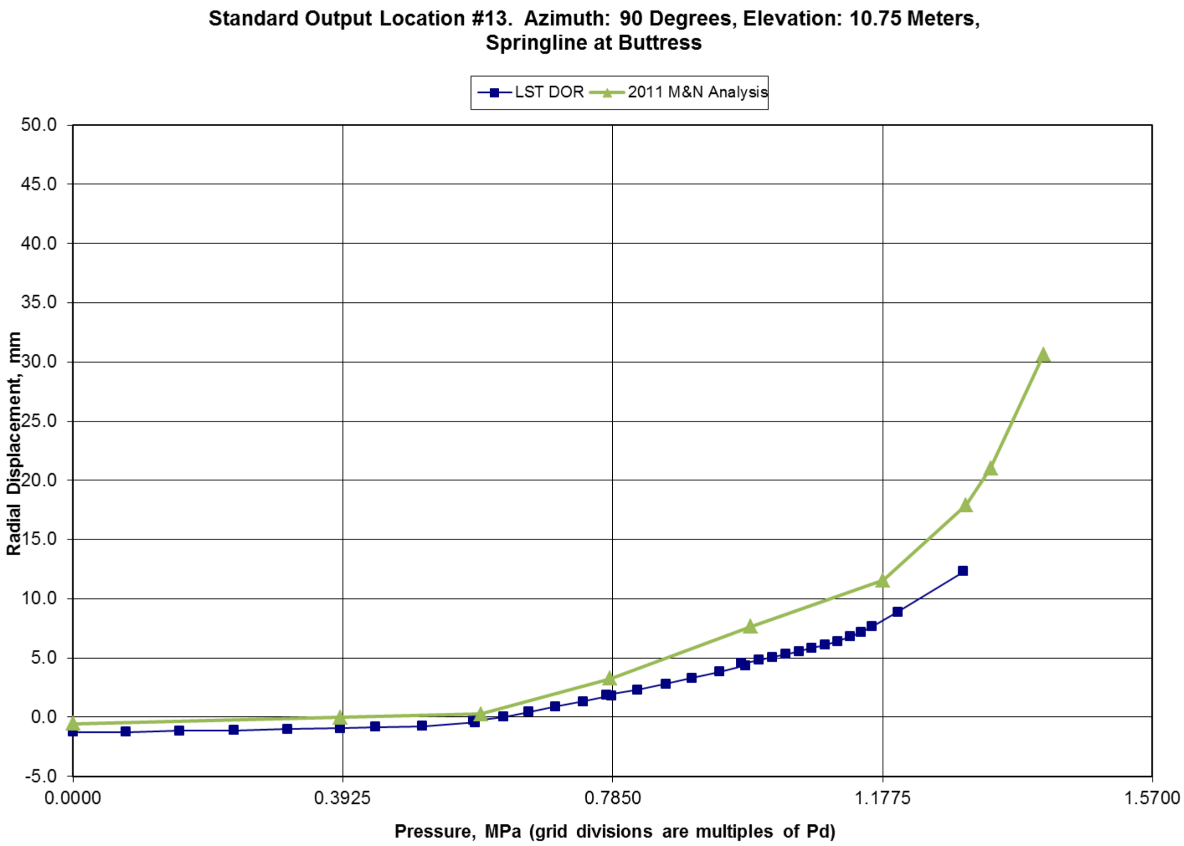

Standard Output Location #11. Azimuth: Apex , Elevation: 16.13 Meters,
LST DOR
SFMT DYN
2011 M&N Analysis
15.0
10.0
5.0
0.0
-5.0
-10.0
Radial Displacement, mm
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)


Standard Output Location #12. Azimuth: 90 Degrees, Elevation: 6.2 Meters, Midheight at Buttress
LST DOR
2011 M&N Analysis
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
Radial Displacement, mm
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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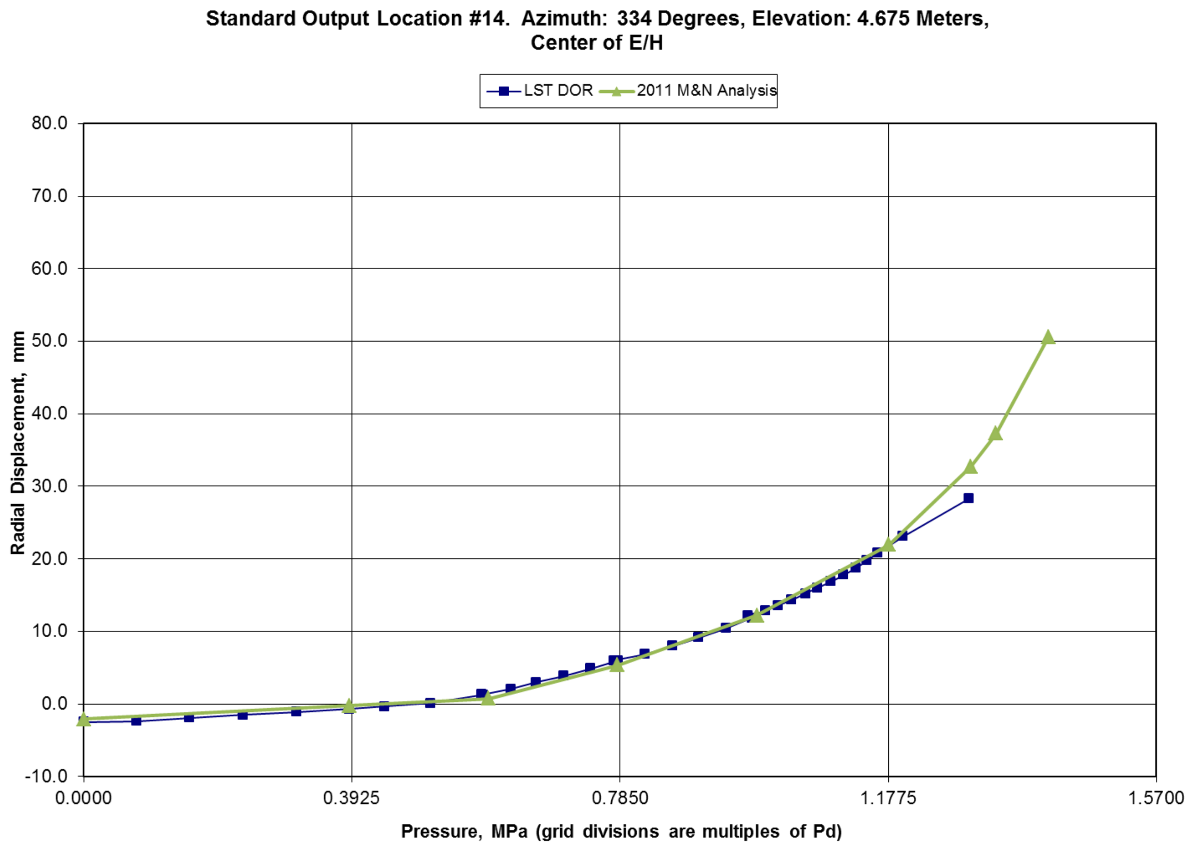

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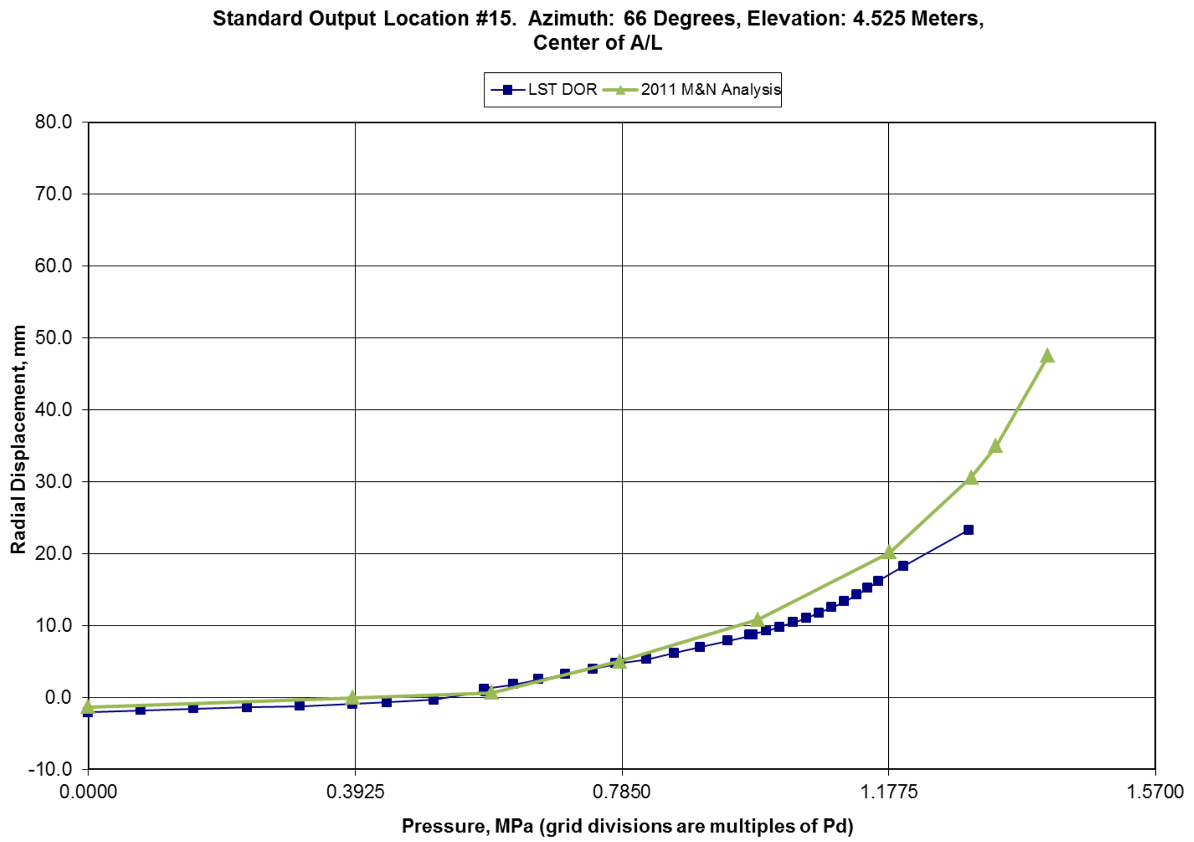
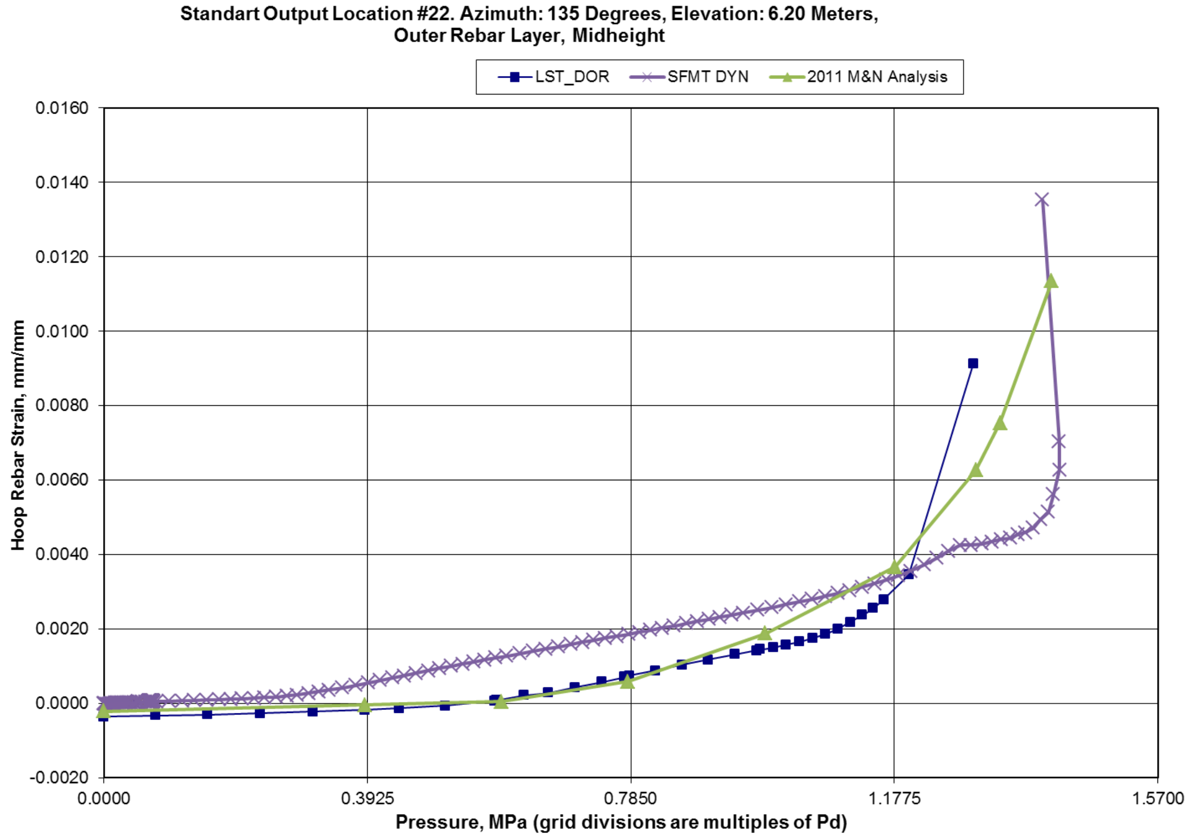

Standard Output Location #15. Azimuth: 66 Degrees, Elevation: 4.525 Meters, Center of A/L
LST DOR
2011 M&N Analysis
Radial Displacement, mm
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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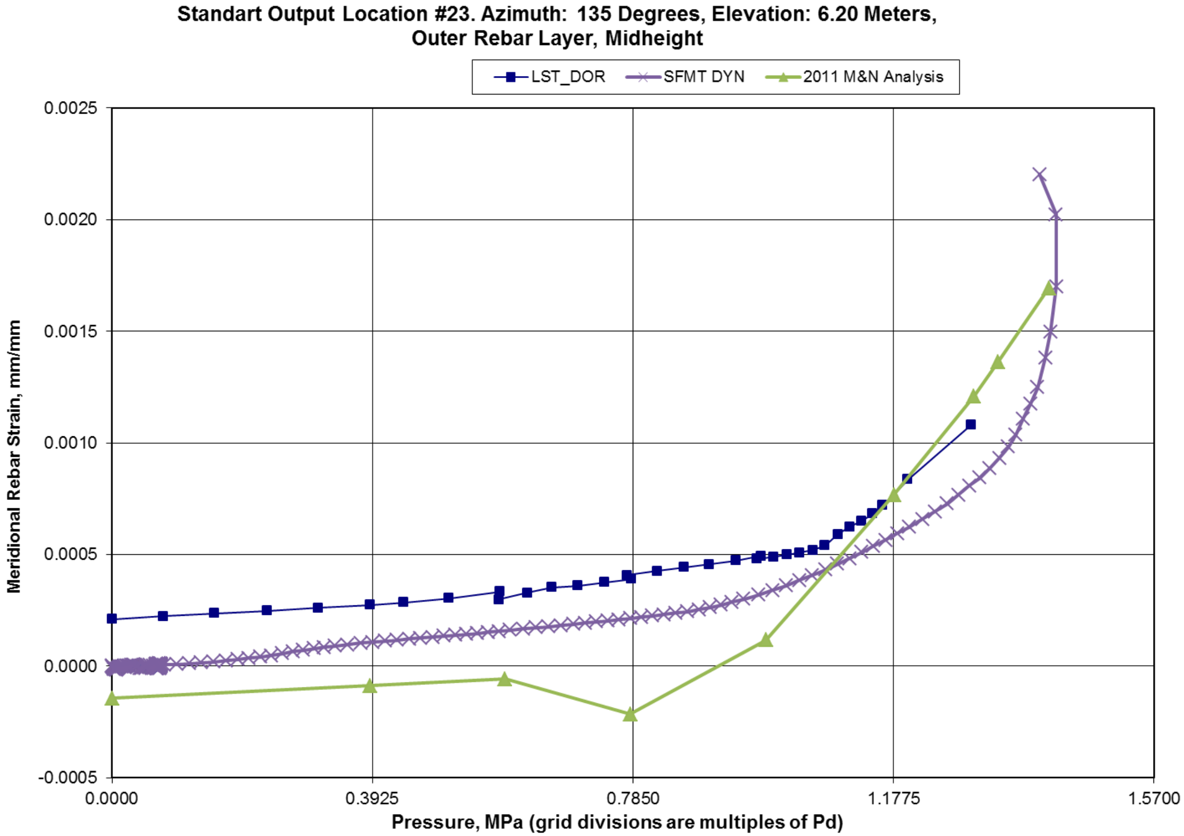
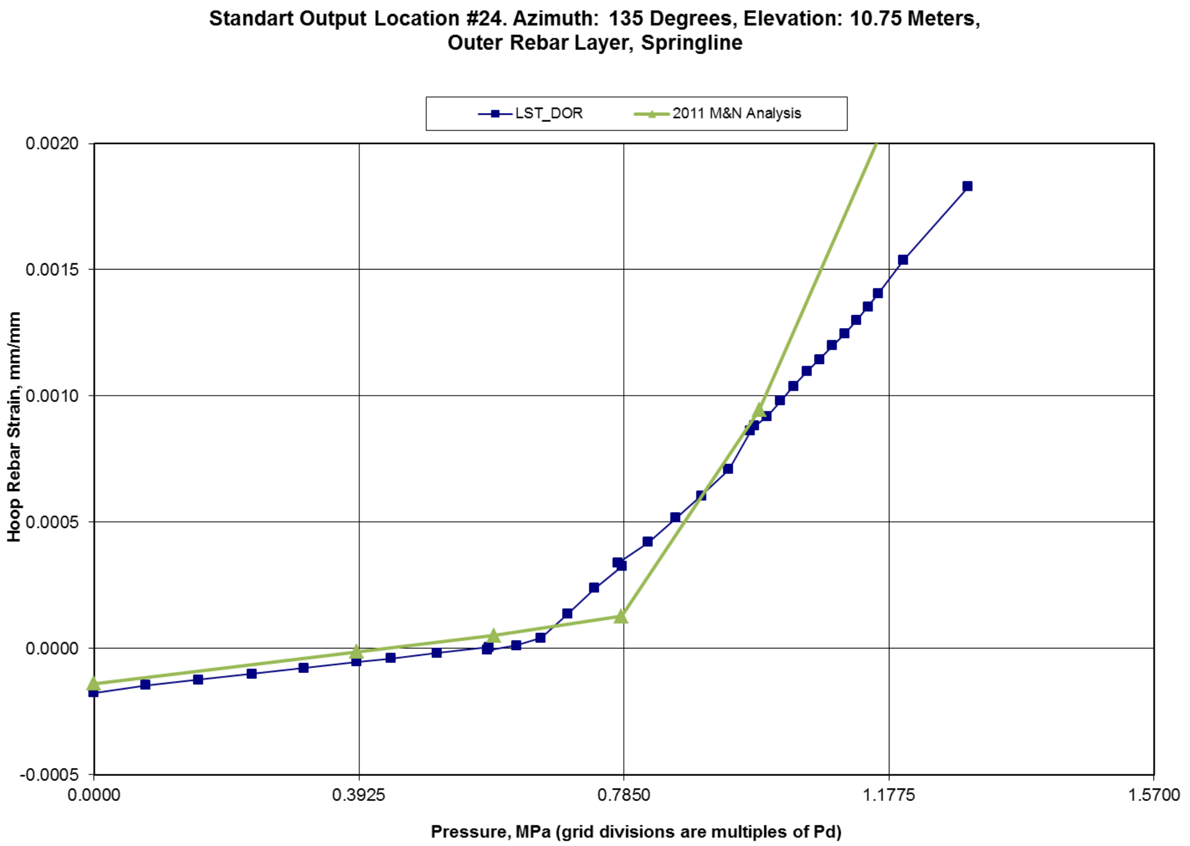


Standart Output Location #23. Azimuth: 135 Degrees, Elevation: 6.20 Meters,
Outer Rebar Layer, Midheight
LST_DOR
SFMT DYN
2011 M&N Analysis
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
Meridional Rebar Strain, mm/mm
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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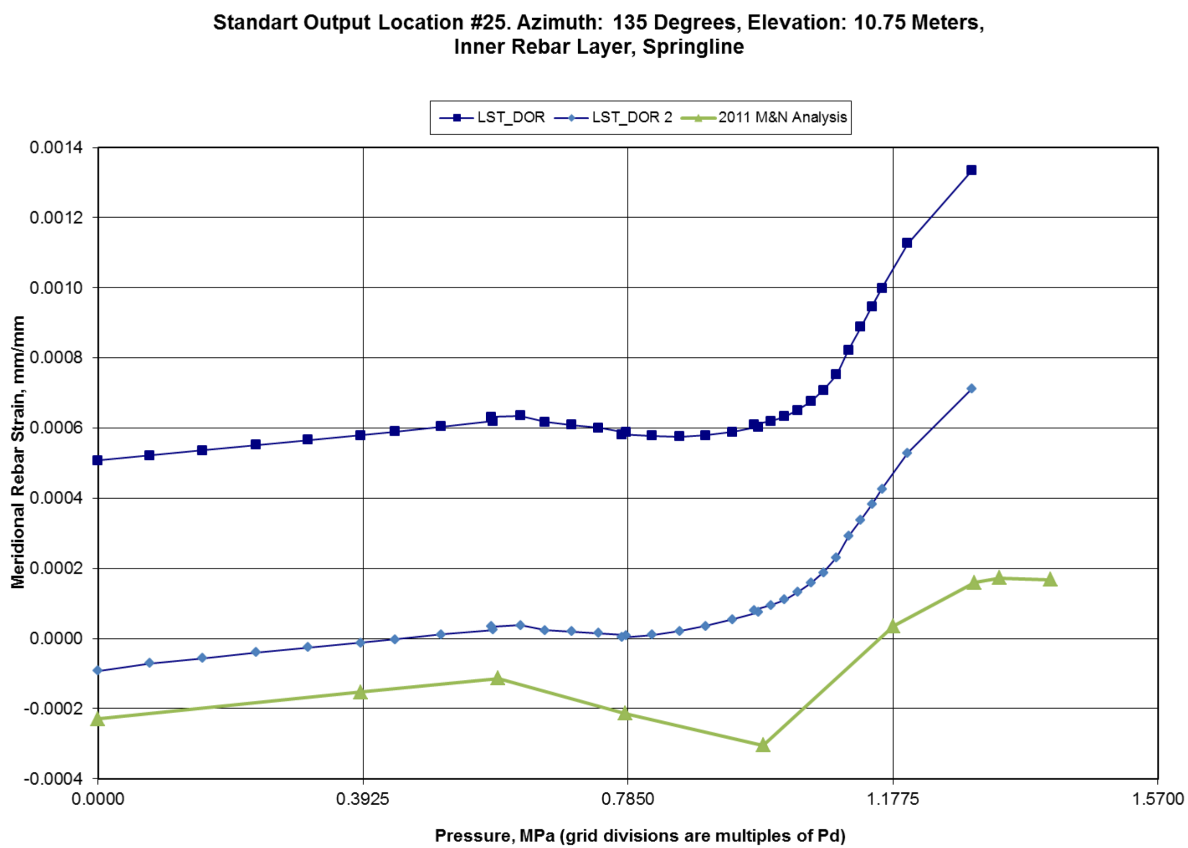
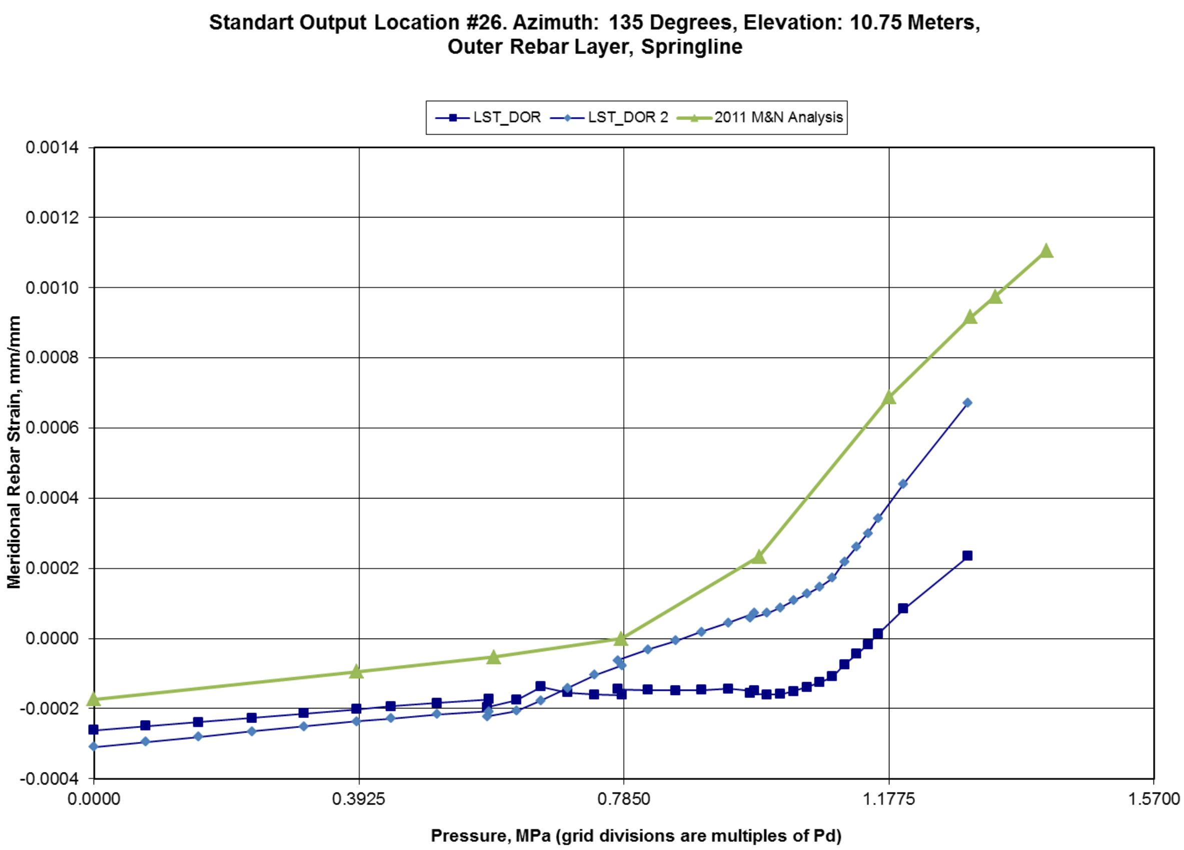

Standart Output Location #25. Azimuth: 135 Degrees, Elevation: 10.75 Meters,
Inner Rebar Layer, Springline
LST_DOR
LST_DOR 2
2011 M&N Analysis
Meridional Rebar Strain, mm/mm
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
-0.0004
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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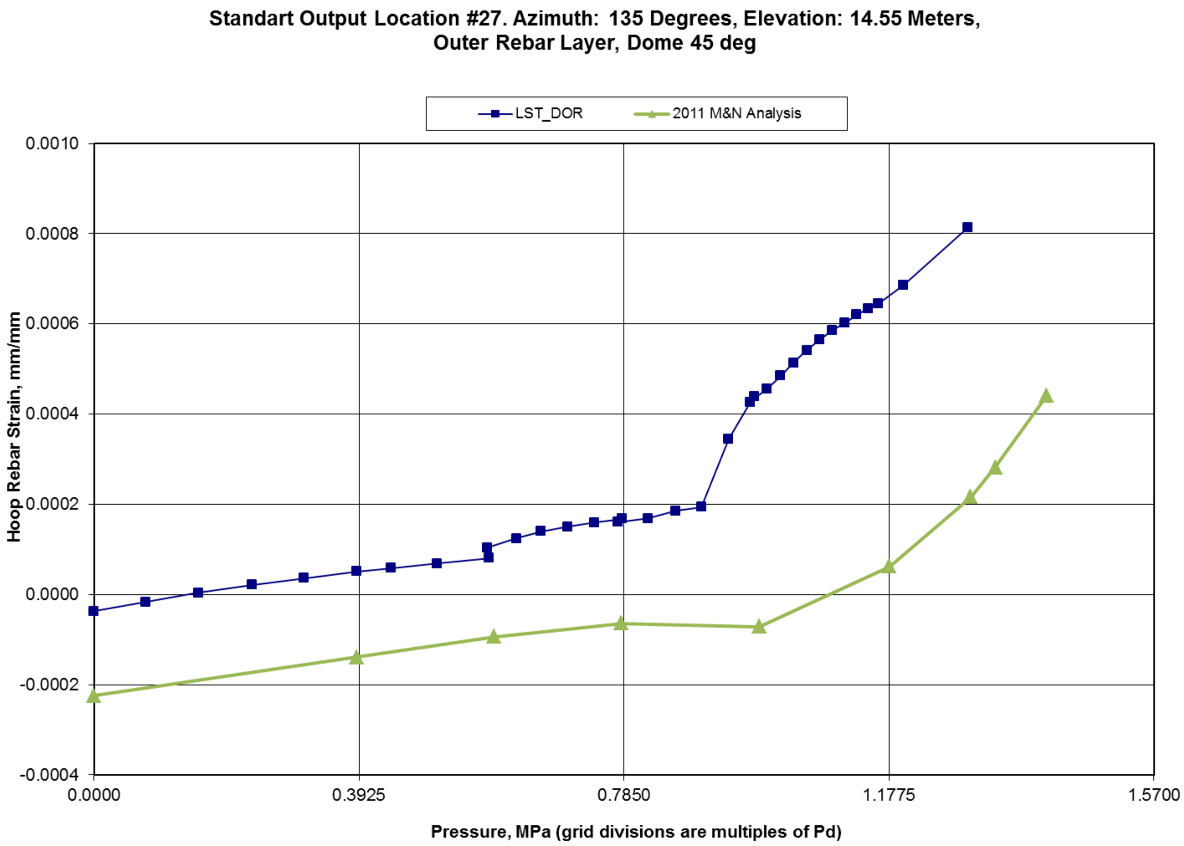

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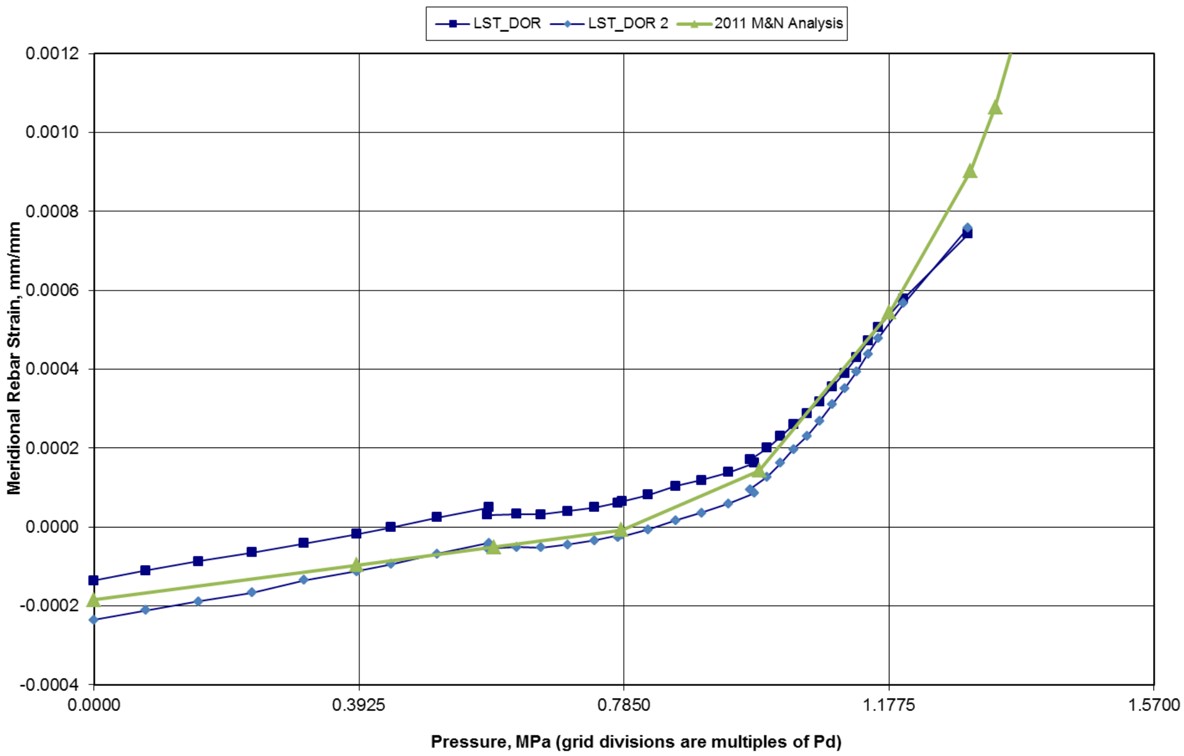
Standart Output Location #28. Azimuth: 135 Degrees, Elevation: 14.55 Meters,
Inner Rebar Layer, Dome 45 deg



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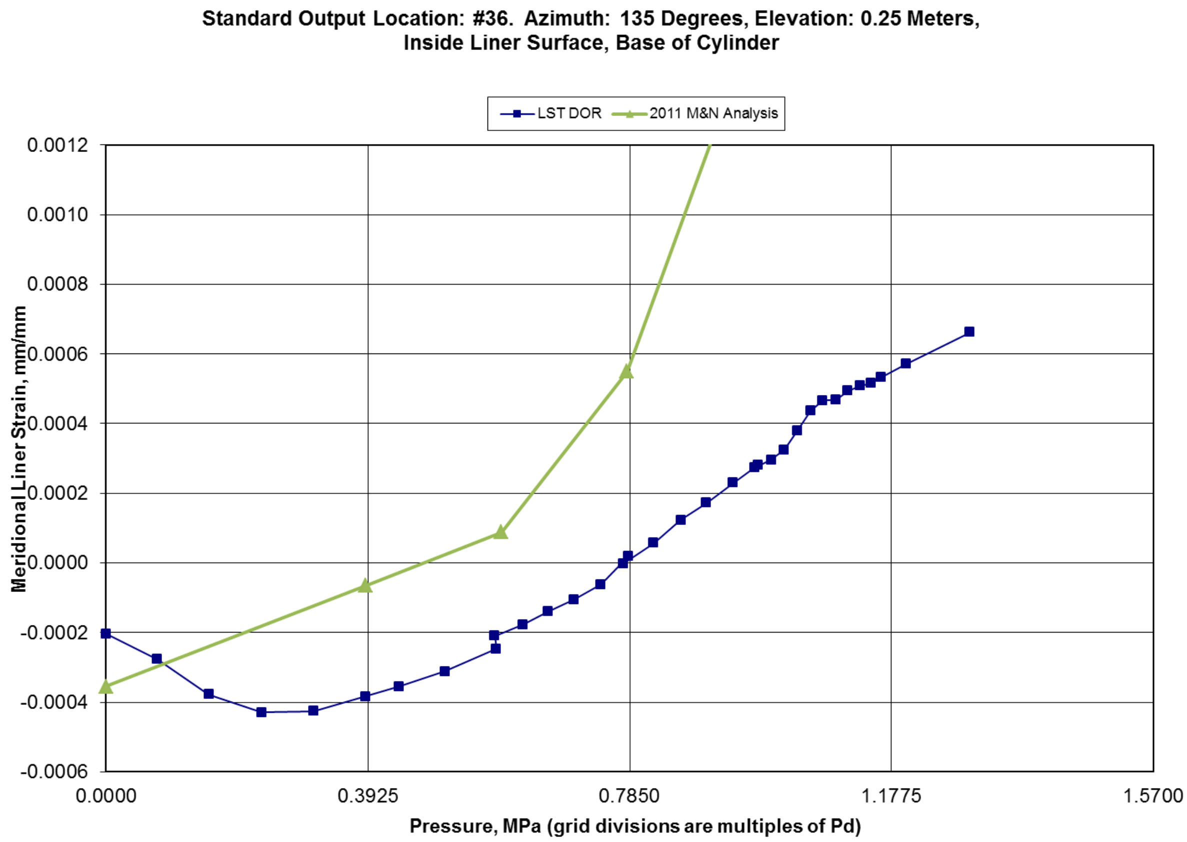
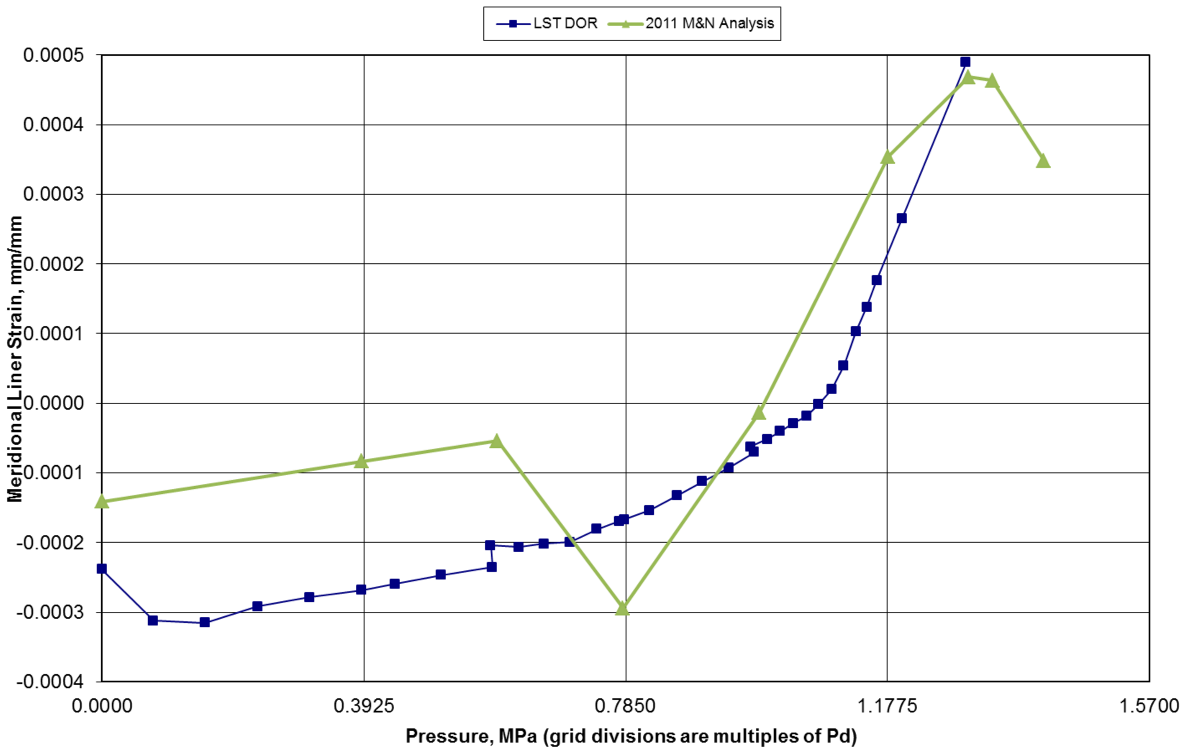
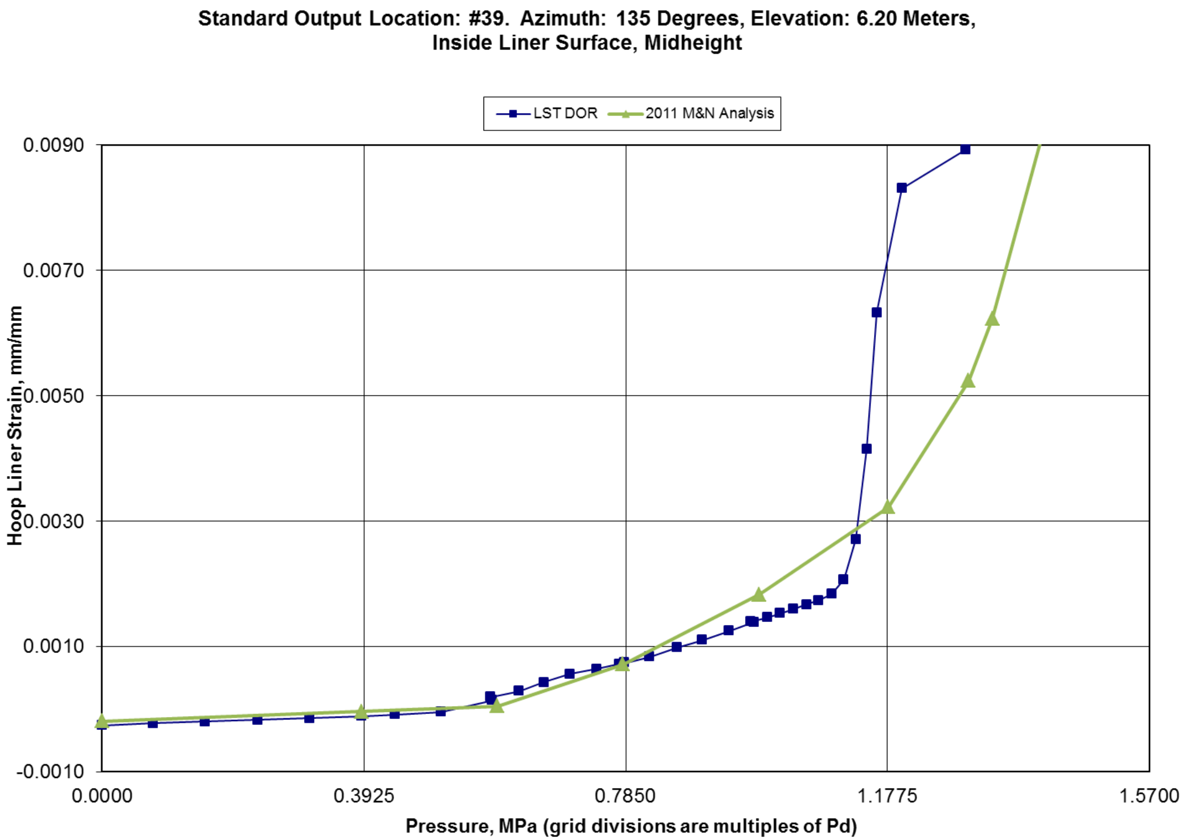


Standard Output Location: #36. Azimuth: 135 Degrees, Elevation: 0.25 Meters,
Inside Liner Surface, Base of Cylinder
LST DOR
2011 M&N Analysis
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
-0.0004
-0.0006
Meridional Liner Strain, mm/mm
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)

Standard Output Location: #38. Azimuth: 135 Degrees, Elevation: 6.20 Meters, Inside Liner Surface, Midheight





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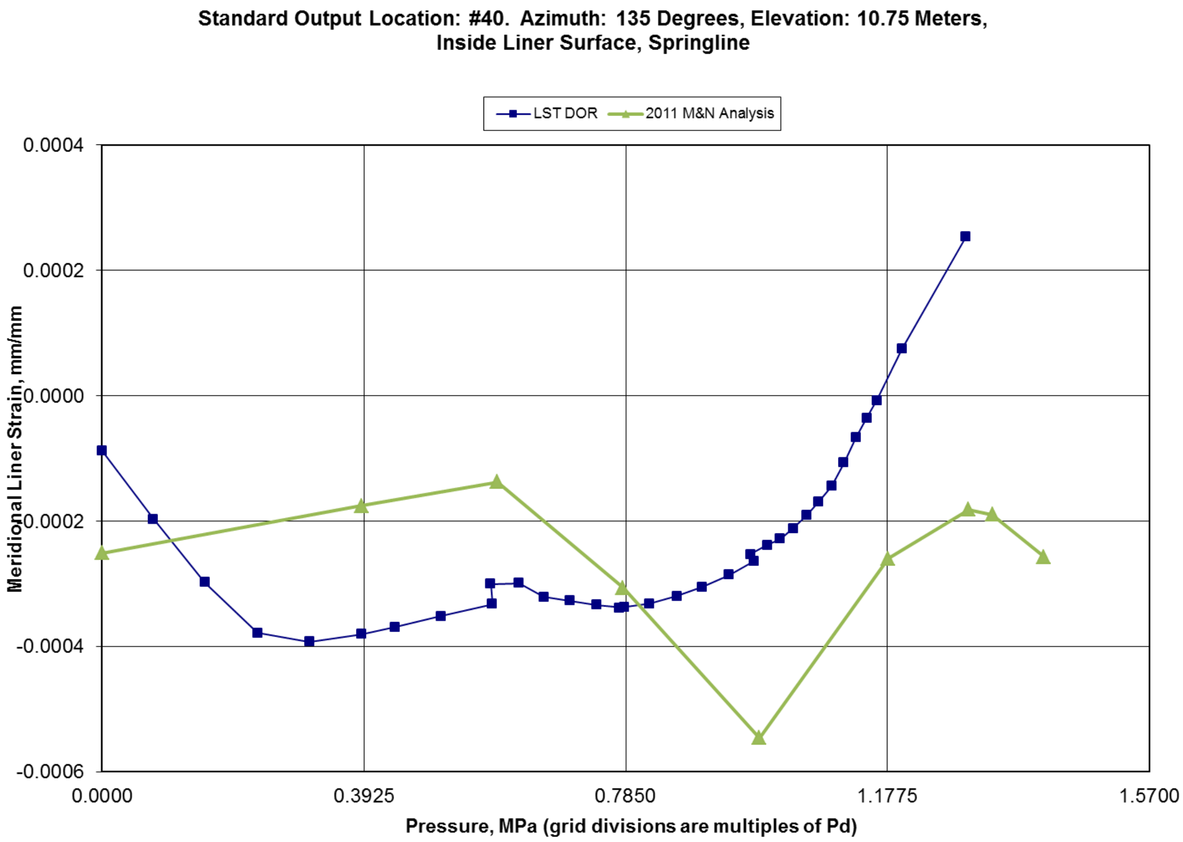

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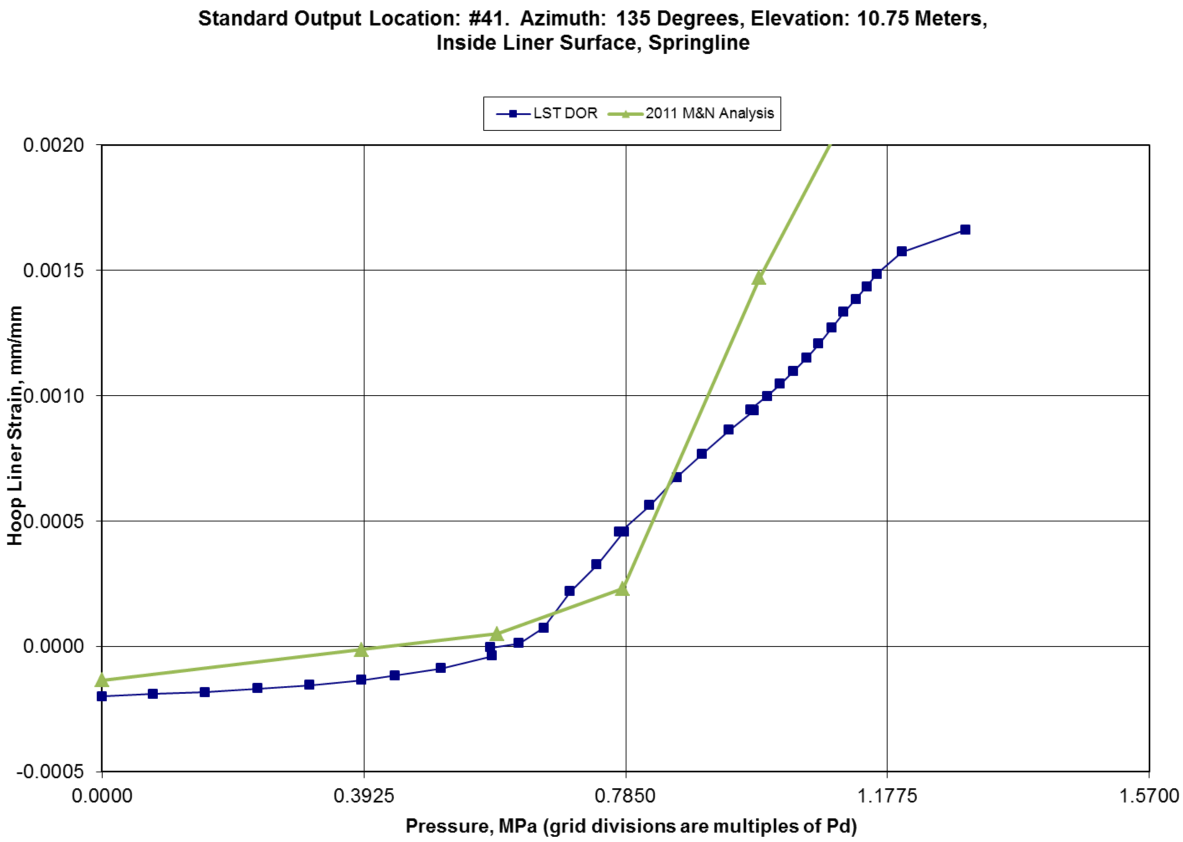
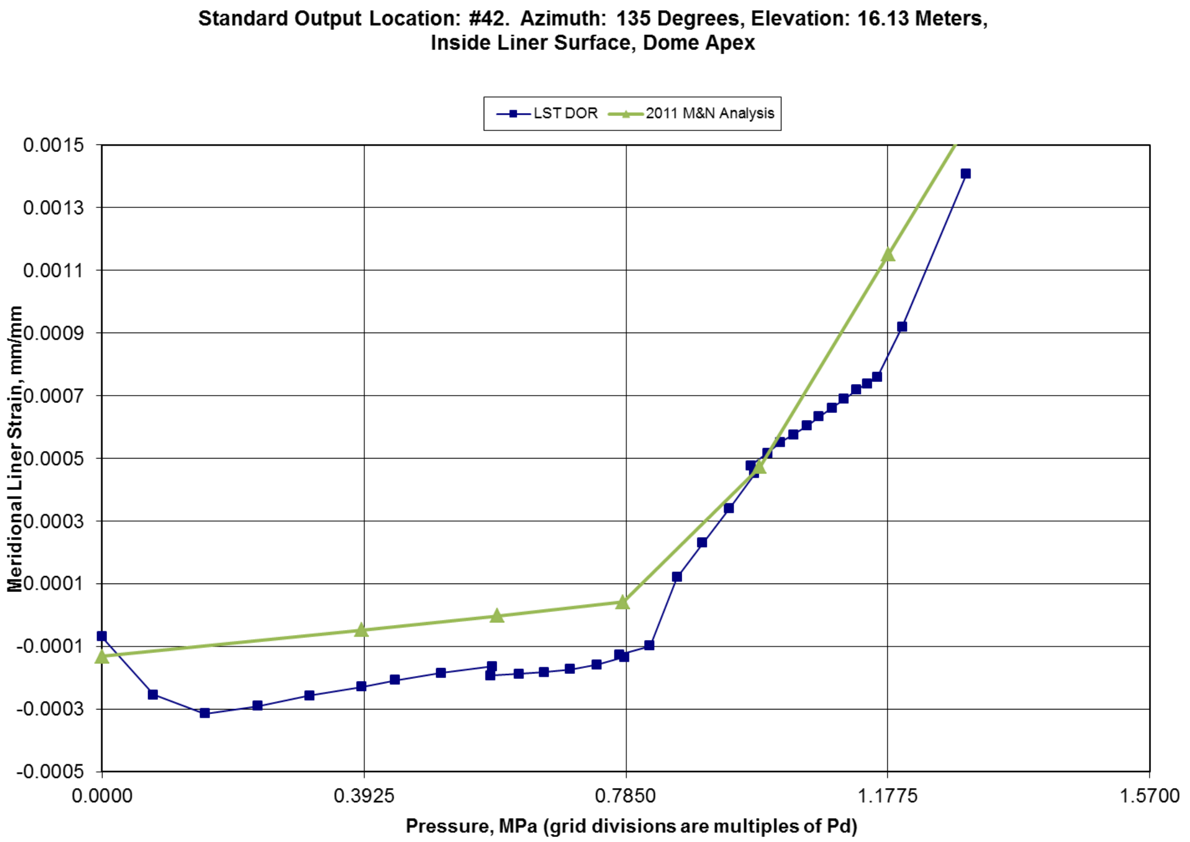


Standard Output Location: #41. Azimuth: 135 Degrees, Elevation: 10.75 Meters,
Inside Liner Surface, Springline
LST DOR
2011 M&N Analysis
Hoop Liner Strain, mm/mm
0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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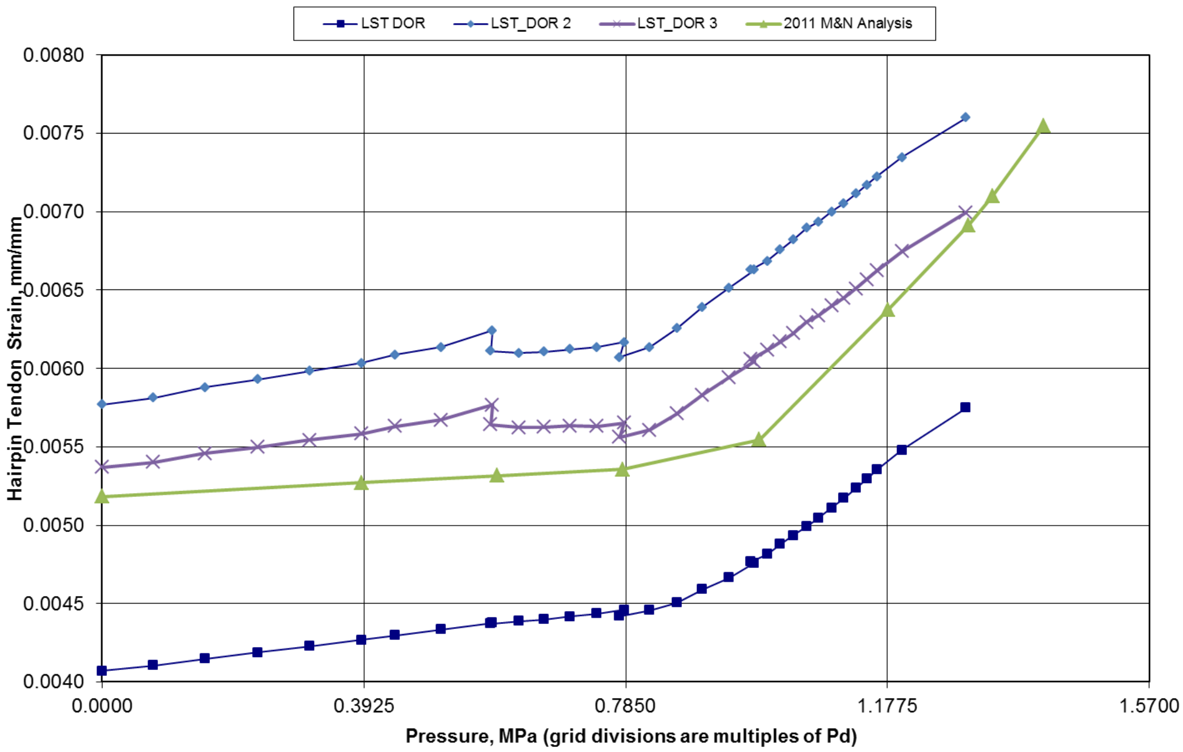
Standard Output Location: #48. Azimuth: 180 Degrees, Elevation: 15.6 Meters, Tendon V37, Tendon Apex



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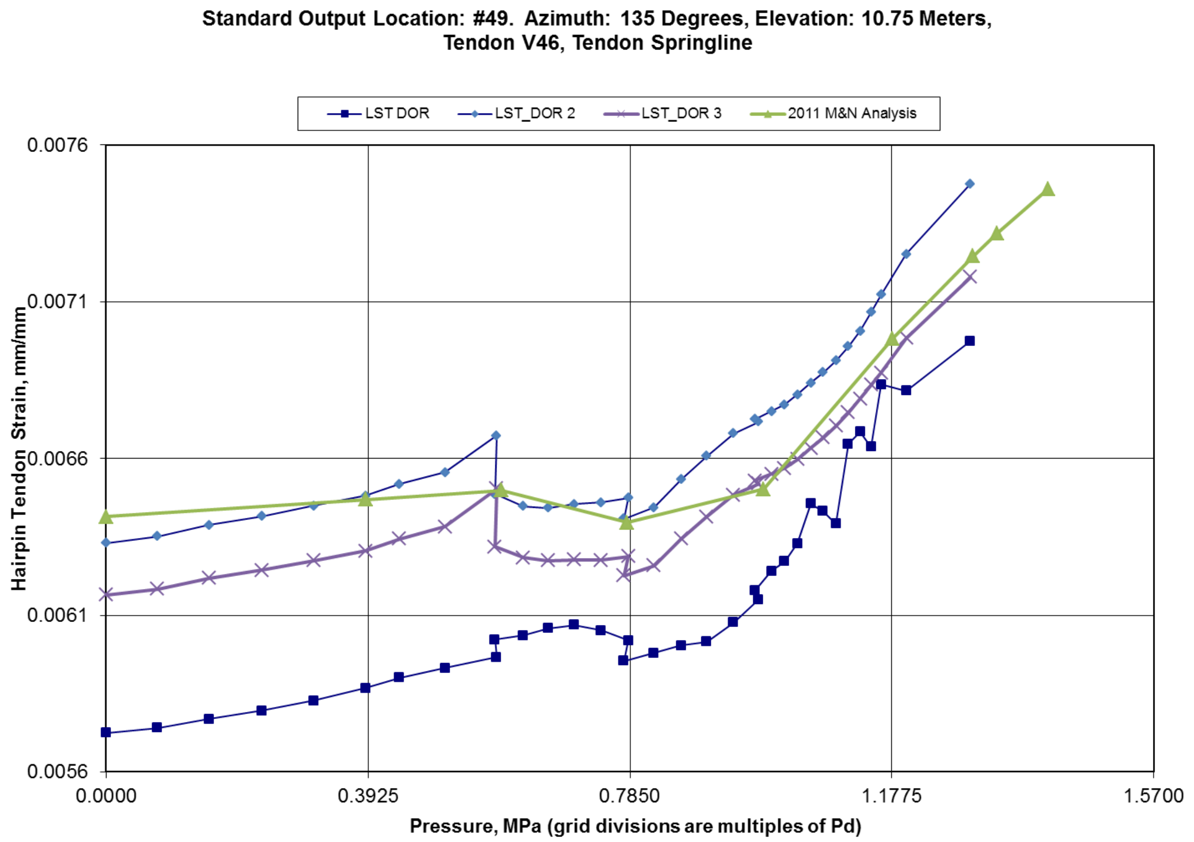

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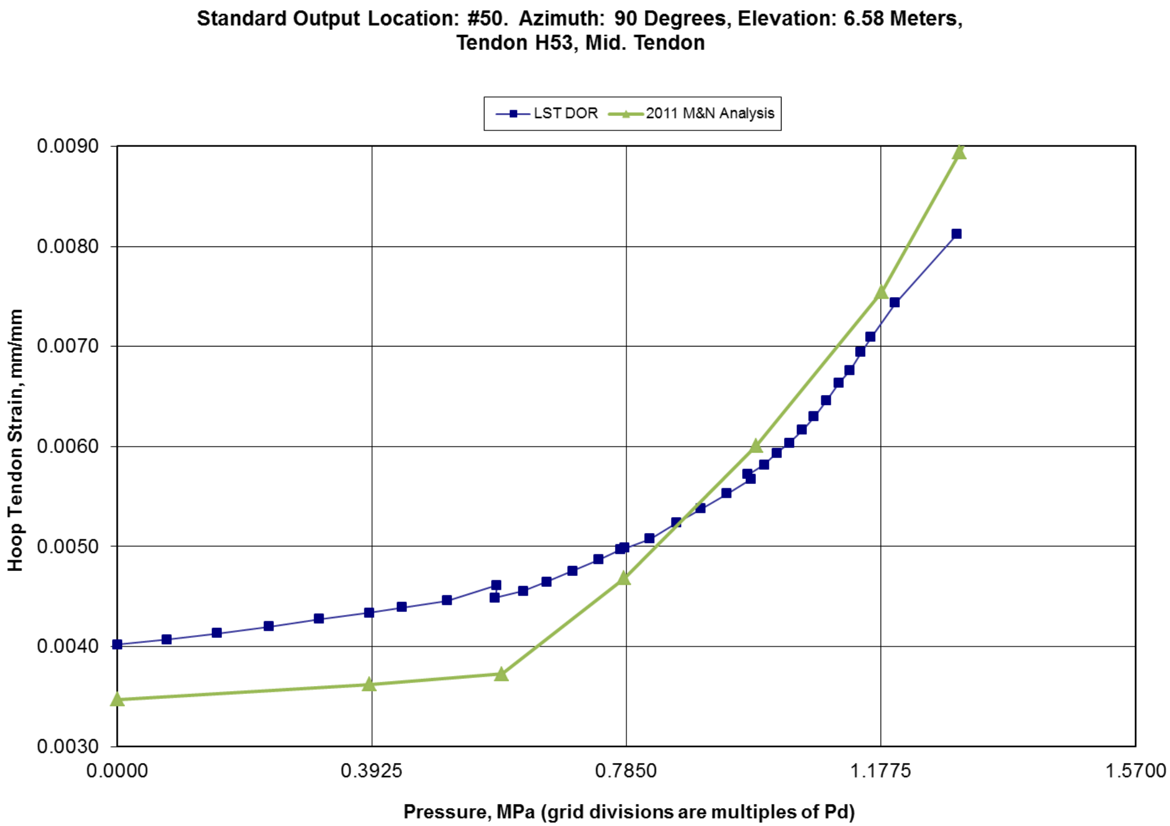

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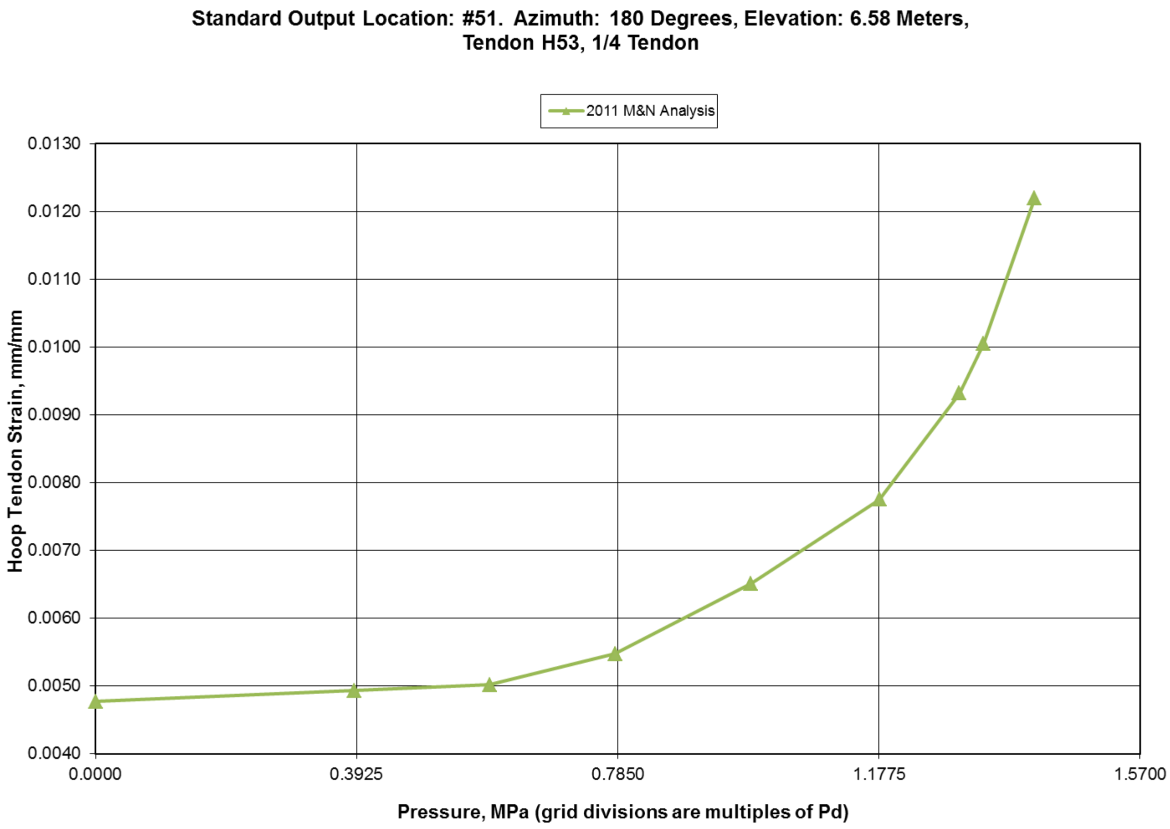
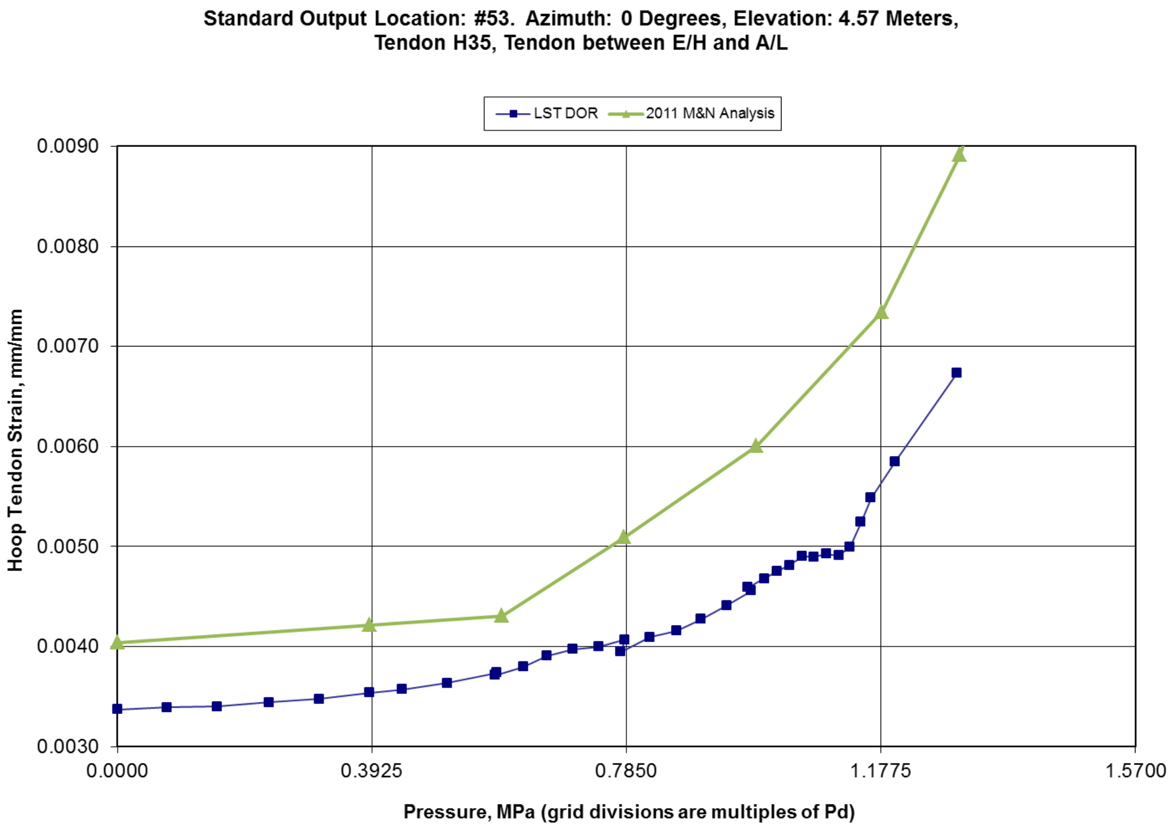
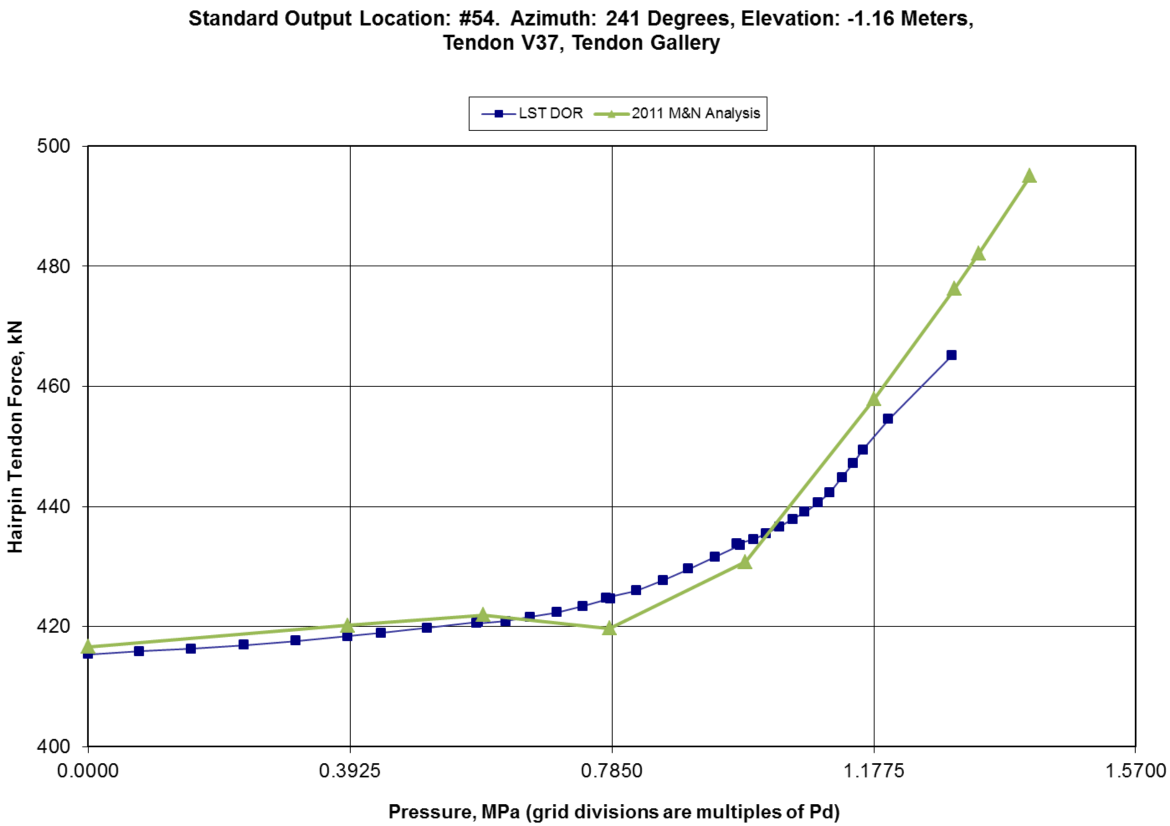

Standard Output Location: #51. Azimuth: 180 Degrees, Elevation: 6.58 Meters, Tendon H53, 1/4 Tendon
2011 M&N Analysis
Hoop Tendon Strain, mm/mm
0.0130
0.0120
0.0110
0.0100
0.0090
0.0080
0.0070
0.0060
0.0050
0.0040
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)


Standard Output Location: #53. Azimuth: 0 Degrees, Elevation: 4.57 Meters,
Tendon H35, Tendon between E/H and A/L
LST DOR
2011 M&N Analysis
0.0090
0.0080
0.0070
0.0060
0.0050
0.0040
0.0030
Hoop Tendon Strain, mm/mm
0.0000
0.3925
0.7850
1.1775
1.5700
Pressure, MPa (grid divisions are multiples of Pd)



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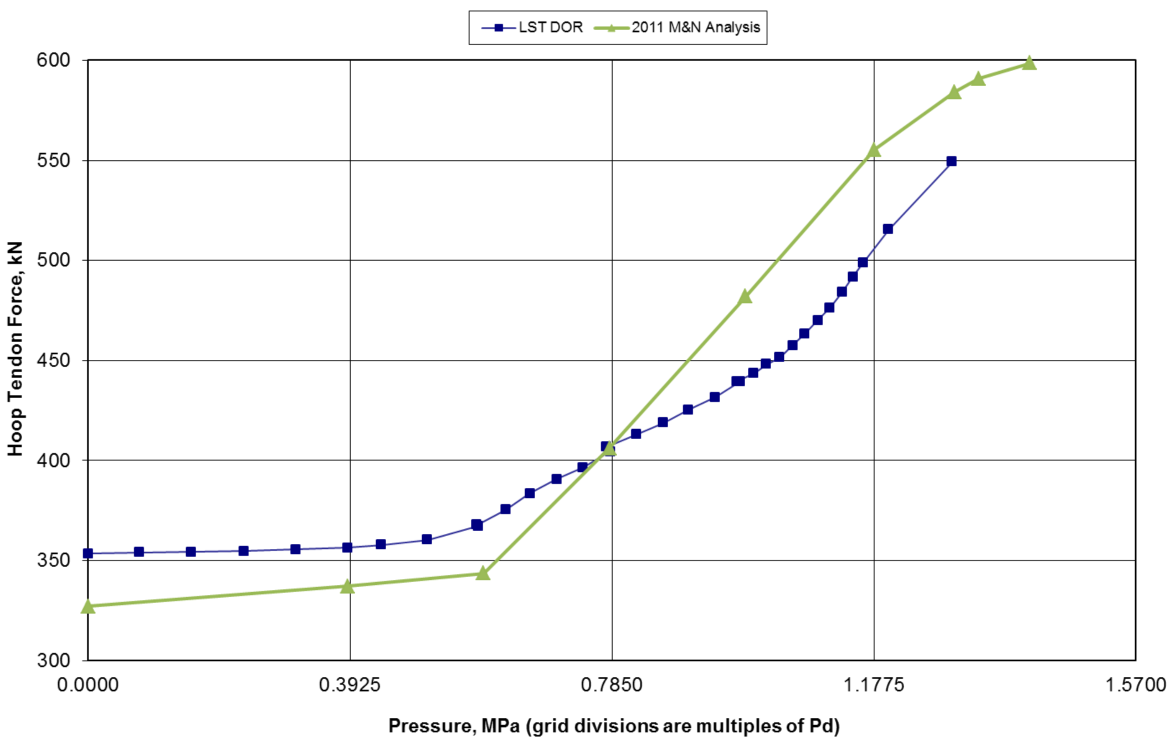
Standard Output Location: #55. Azimuth: 275 Degrees, Elevation: 6.58 Meters, Tendon H53, at Buttress



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