Standard Problem Exercise No. 3

Model 1: Tendon Behavior Model

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Standard Problem Exercise No. 3 Summary

- SPE No. 3 examines PCCV local effects and, ultimately, developing pressure versus leakage relationships
- First phase analysis focuses on:
  - Effects of containment dilation on prestressing force
  - Slippage of prestressing and effects of force
  - Steel-concrete interface
  - Fracture mechanics behavior
  - Scatter in data of prestressed concrete properties

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Model 1: Tendon Behavior Model

- **Modeling assumptions, initial conditions, and analysis results are presented for**

  1) Pressure only analysis

  2) Pressure + temperature (saturated steam condition) analysis

Model Geometry and Initial Conditions

- Model consists of two hoop tendons, height of 225mm (8-7/8”). Boundary conditions and pressure:

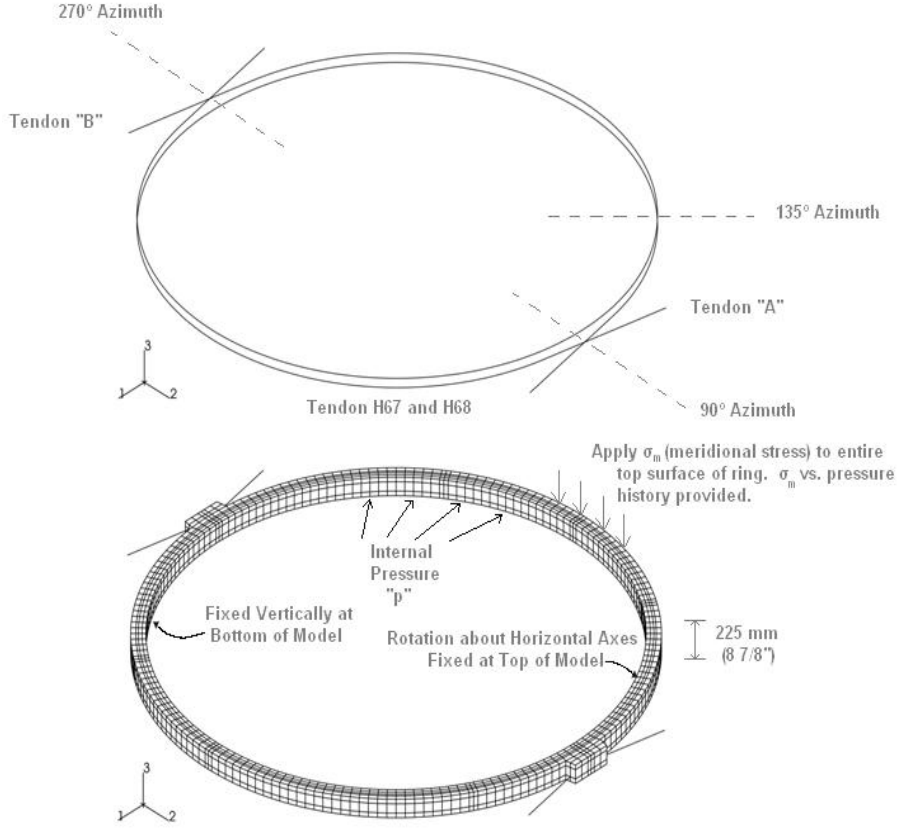

Figure 1: Model 1 - Tendon Behavior Model, Representing Tendons H53 and H54, Elev. 6.579 m (Refer to Dwg. # PCCV-QCON-04)

Model Geometry and Initial Conditions

- ABAQUS Standard FE program was used
- Model includes concrete, tendons, rebar (hoop and shear reinforcement), and liner
- Concrete modeled with 8-node 3D solid elements; Rebar modeled with embedded subelements; Tendons with 2-node truss elements; Liner with 4-node shell elements, perfectly bonded to concrete

Analytical Representation of Losses

1) **Initial conditions applied to the tendons**
2) **FE Model's representation of angular friction**

- For all participants to begin their pressure analysis from the same basis, the black line shows the prescribed starting point

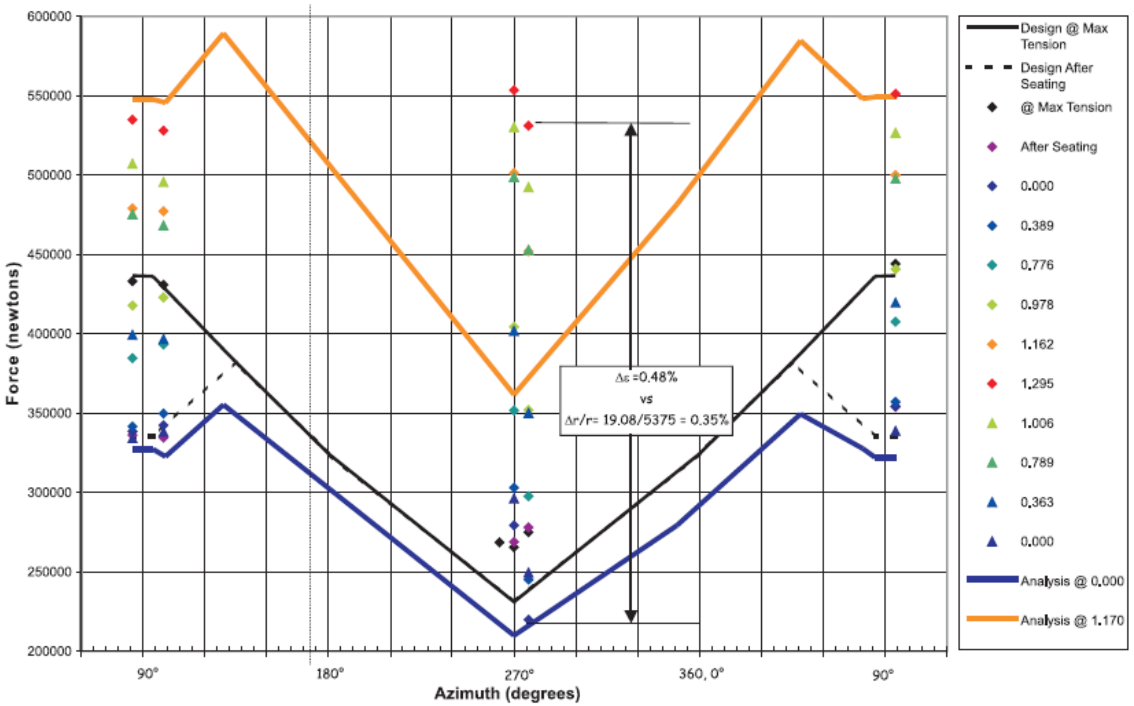

Figure 2: H53 Tendon Force Comparisons to Pretest (From NUPEC/NRC PCCV test at SNL)

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Meridional Stress vs. Internal Pressure

- Relationship between the meridional stress, σ_m and the internal pressure, p at level 6.579m is prescribed by:

σ_m from dead load, prestress, internal pressure

= 7.02 – p*8.27MPa

(p in MPA, (+) compression, (-) tension)

(Equation developed by SPE Participant, Scanscot)

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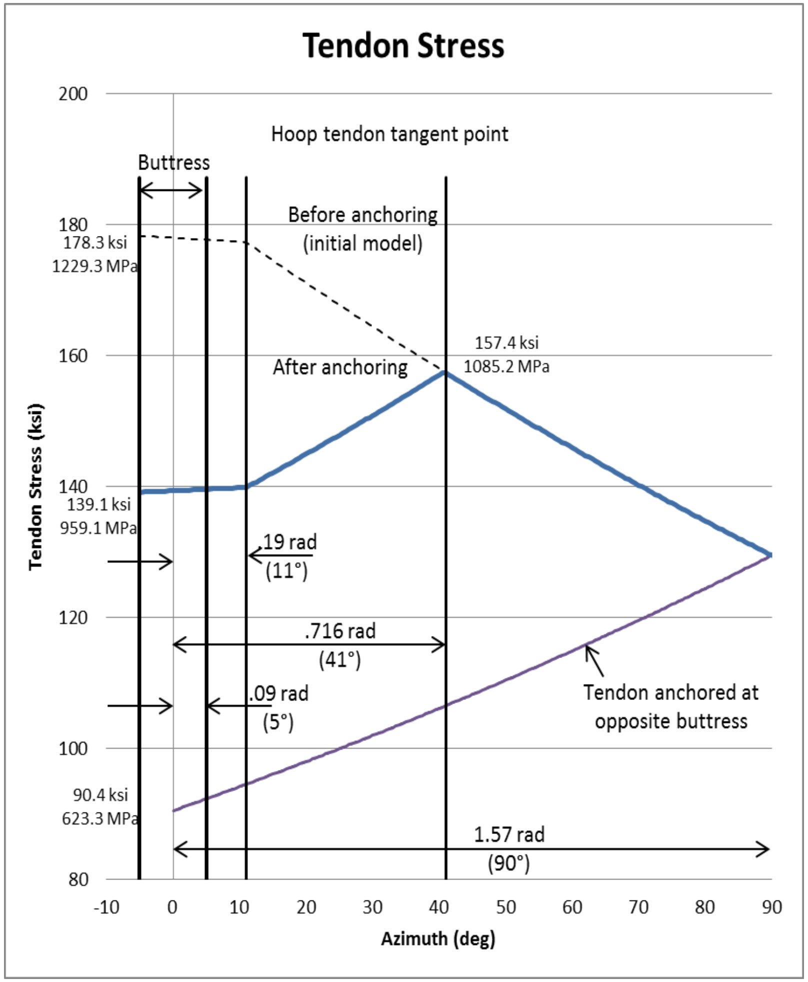
Additional Information About Tendon Friction and Seating Losses



Material Modeling

- Tendon, rebar, and concrete material stress-strain assumptions were implemented as tabulated in Appendix 1 of NUREG/CR-6810.
- Concrete simulated using ABAQUS concrete “Damaged Plasticity”, smeared-cracking in tension (where cracking occurs at element integration points) and a compressive plasticity theory.
- Steel simulated using ABAQUS Standard Plasticity where the stress-strain inputs consist of effective stress (Mises) and effective strain. Inputs taken directly from SPE Appendices.

Concrete Stress-Strain Curves

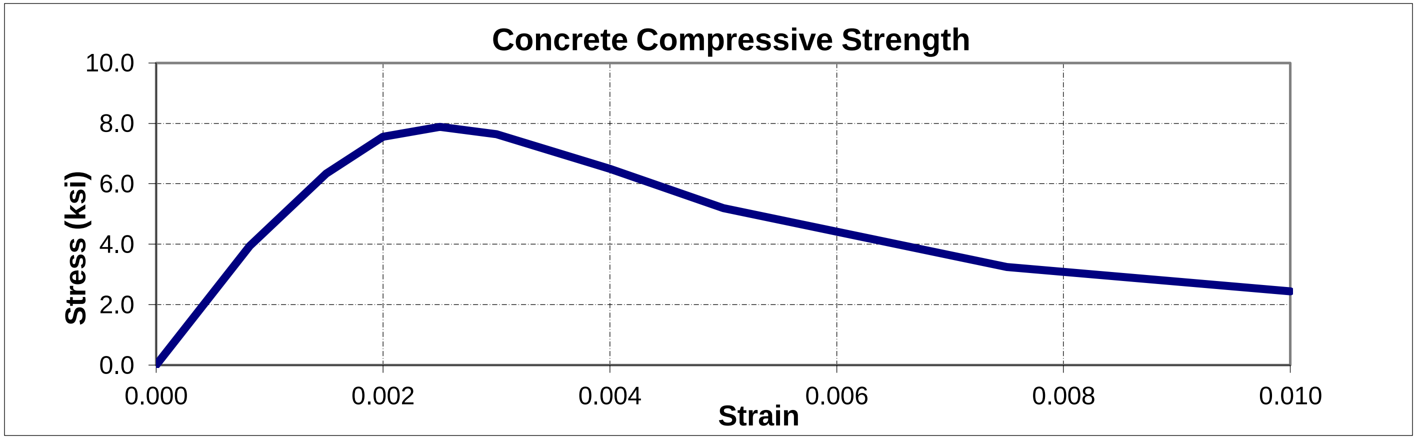


Figure 4: Concrete Compression Curve

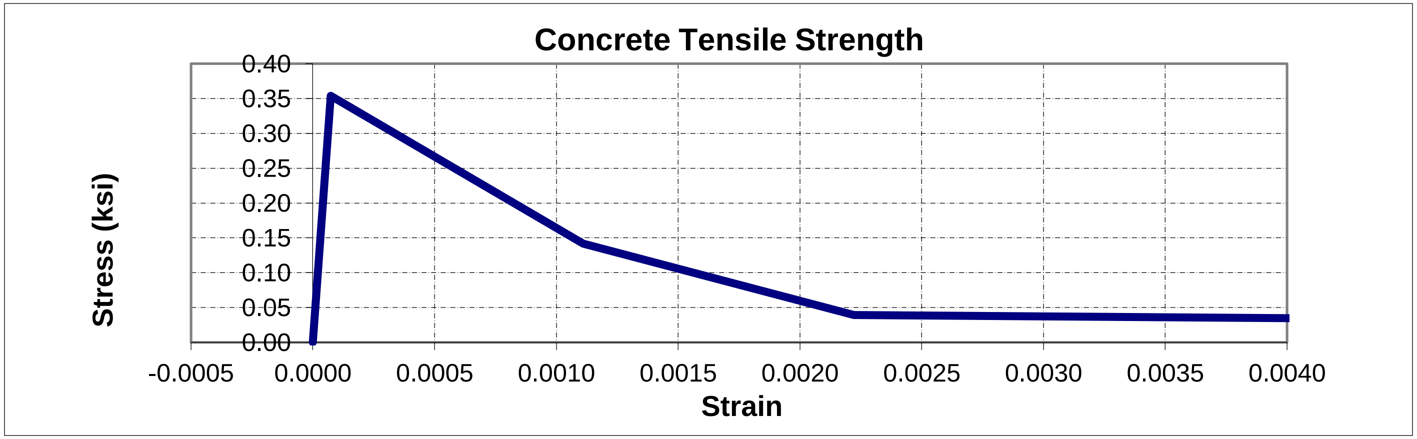


Figure 5: Concrete Tension Curve

Figure 6: Tendon Stress-Strain Curve

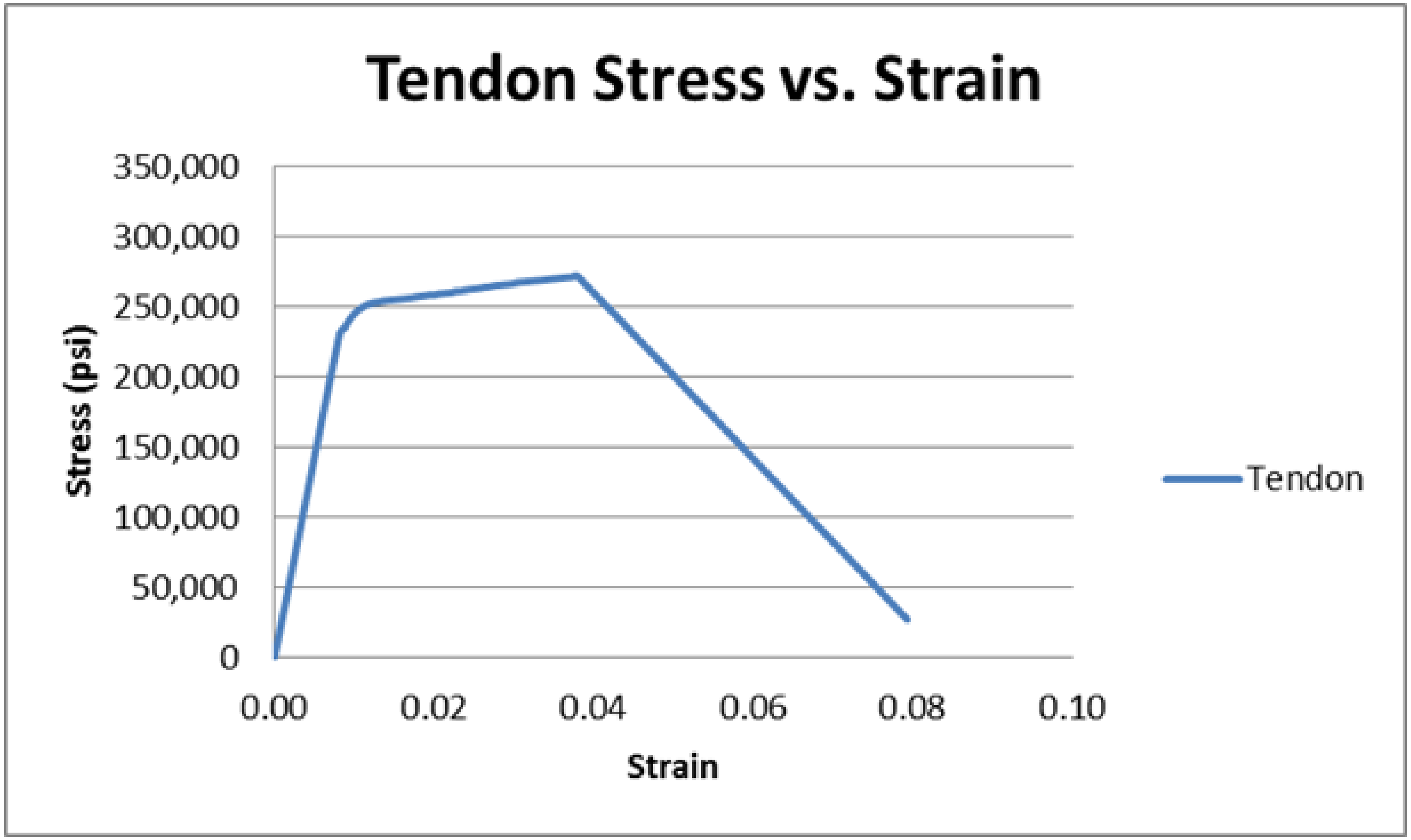


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Figure 7: Liner Stress-Strain Curve

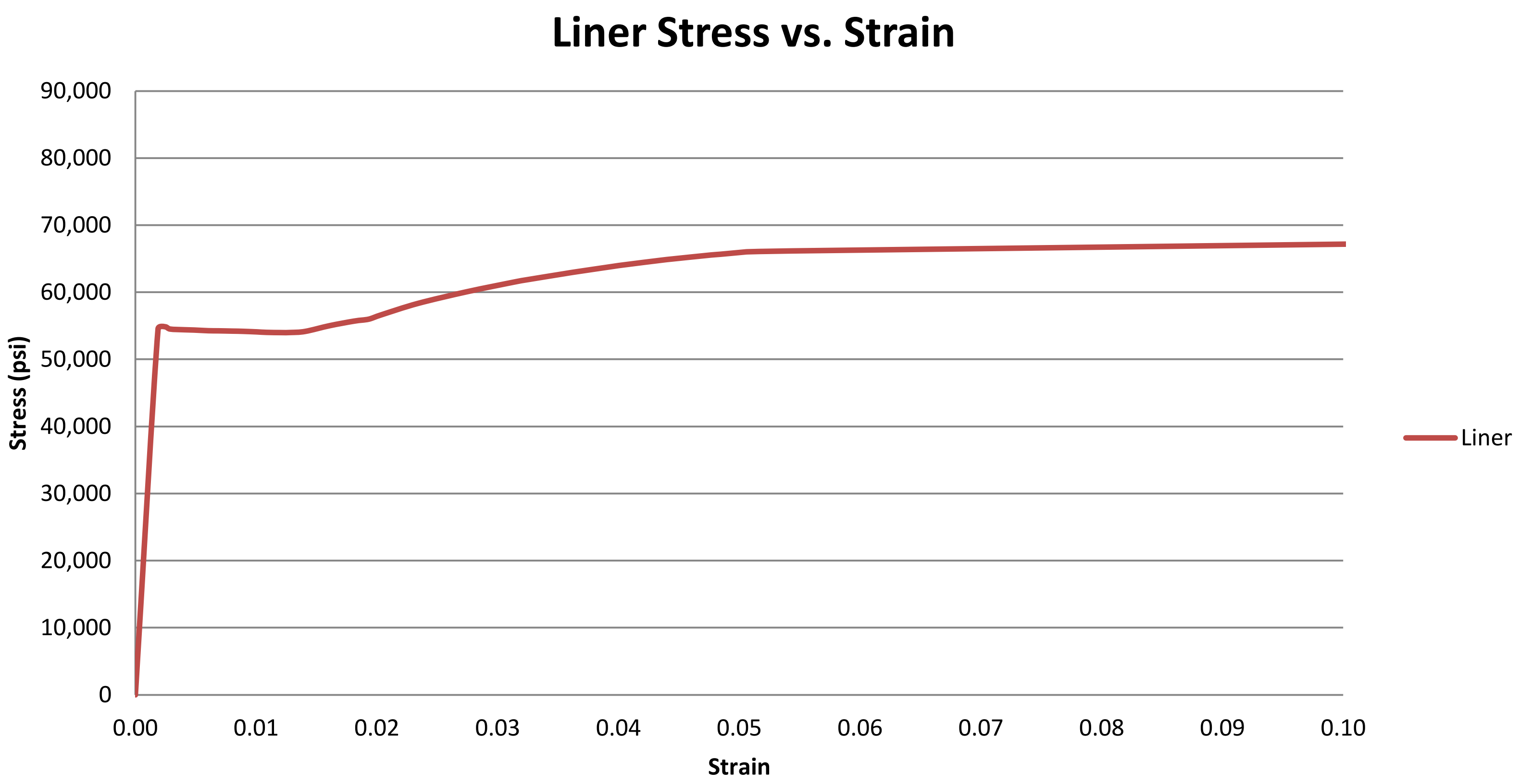

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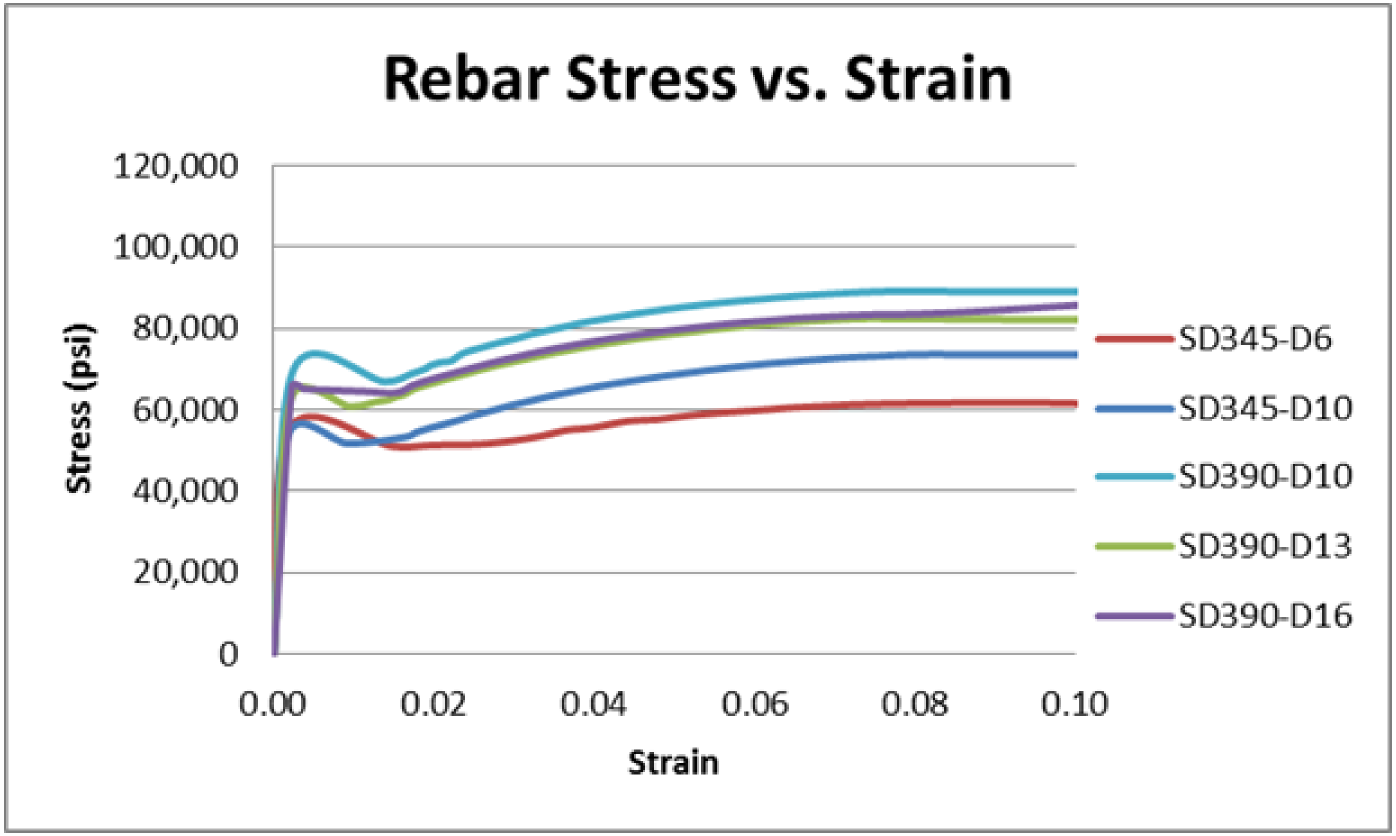
Figure 8: Rebar Stress-Strain Curve



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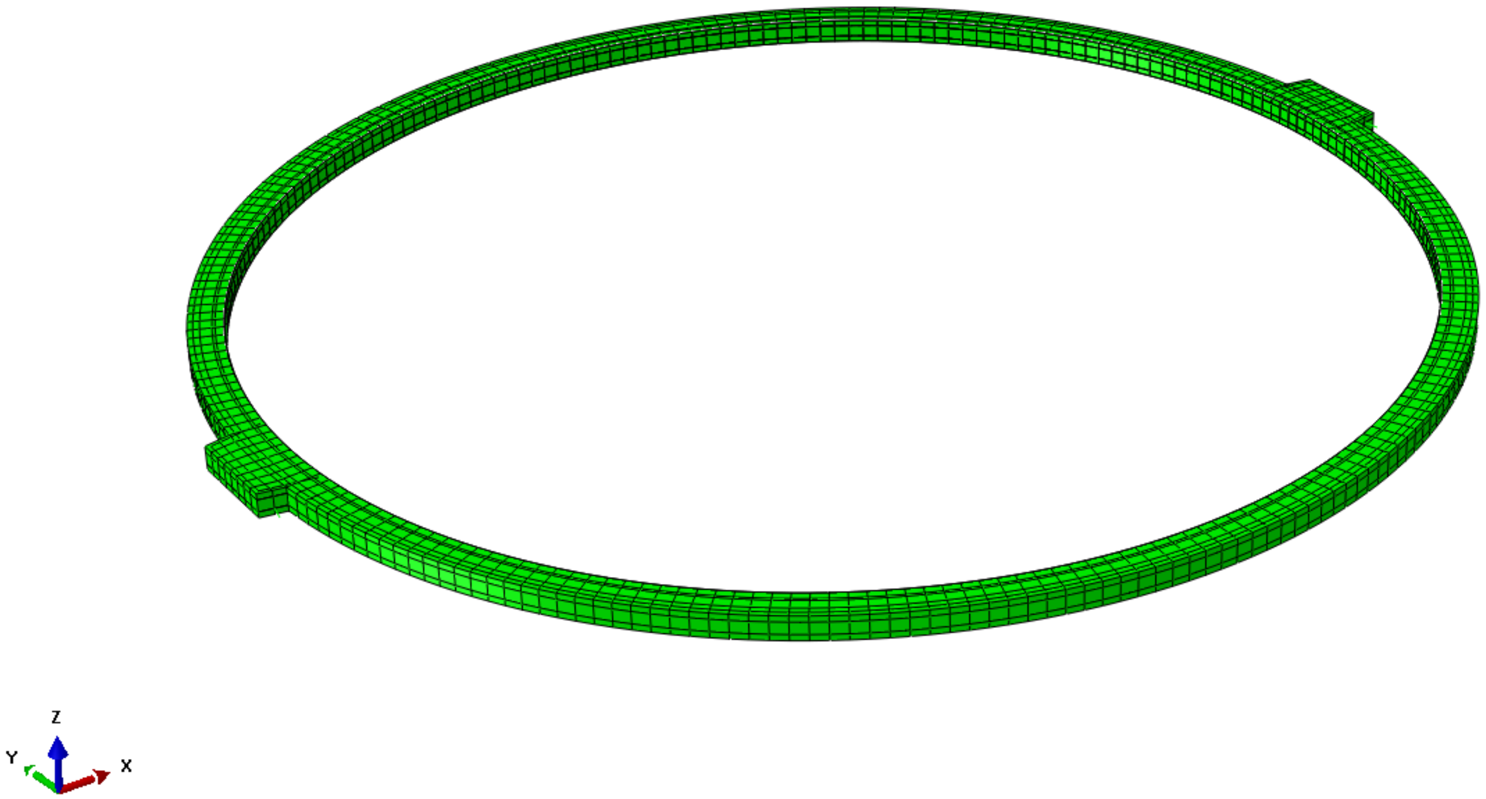
Failure Criteria

- Relevant failure criteria for Model 1 is TENDON failure
- Rebar is not controlling since rebar has higher ductility
- Model 1 is not focused on liner tear/leakage
- Tendon Failure criteria taken as the Tendon System Elongation (shown as strain) at Tendon rupture
- Different tests and different ways of measuring strain/elongation
- Reasonable consensus to use average of the Tendon System Tests, or 3.8%
- One study suggested using 2% as a lower-bound criteria because this is the limit-by-Specification (one tendon system test did show a premature failure at under 2% due to anchor slippage)
- Tendon rupture at 2% is still considered to be a 'possible' but not 'best-estimate' failure strain

Analysis Results
Required Output/Results for Model 1

- Description of Modeling Assumptions and Phenomenological Models
- Description of Tendon Failure Criteria Used
- Pressure Milestones. Applied Pressure When:
  - Concrete Hoop Stress (at 135° azimuth) Equals Zero
  - Concrete Hoop Cracking Occurs (at 135° azimuth)
  - Tendon A, and B Reach 1% Strain (at 135° azimuth)
  - Tendon A, and B Reach 2% Strain (at 135° azimuth)
- Deformed Shape and Tendon Stress Distribution at P=0 (prestress applied); $1xP_d$; $1.5P_d$; $2P_d$; $3P_d$; $3.3P_d$; $3.4P_d$; Ultimate Pressure
- Description of Observations About Tendon Force as a Function of Containment Dilation and Tendon Slippage

Model-1 ABAQUS Model



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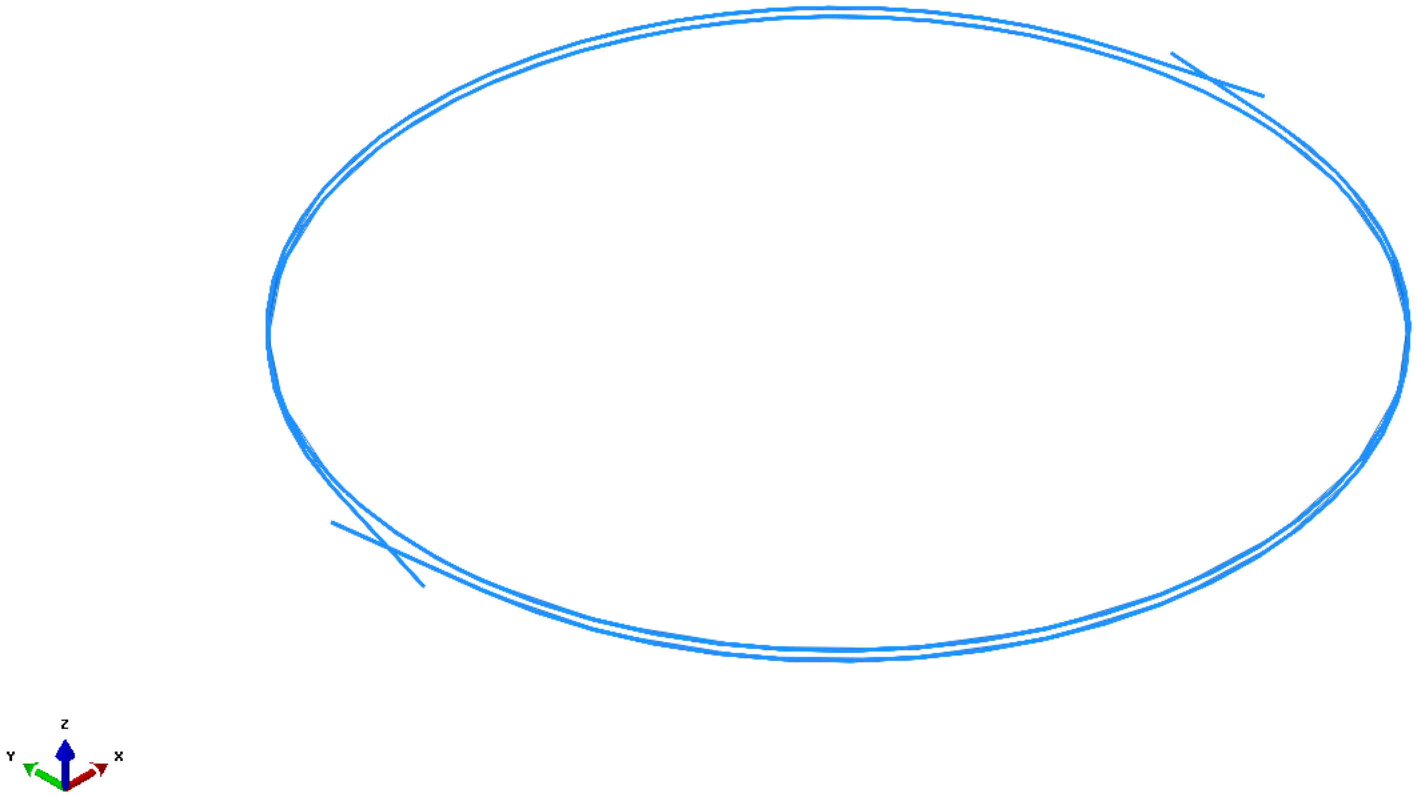
Tendon Layout



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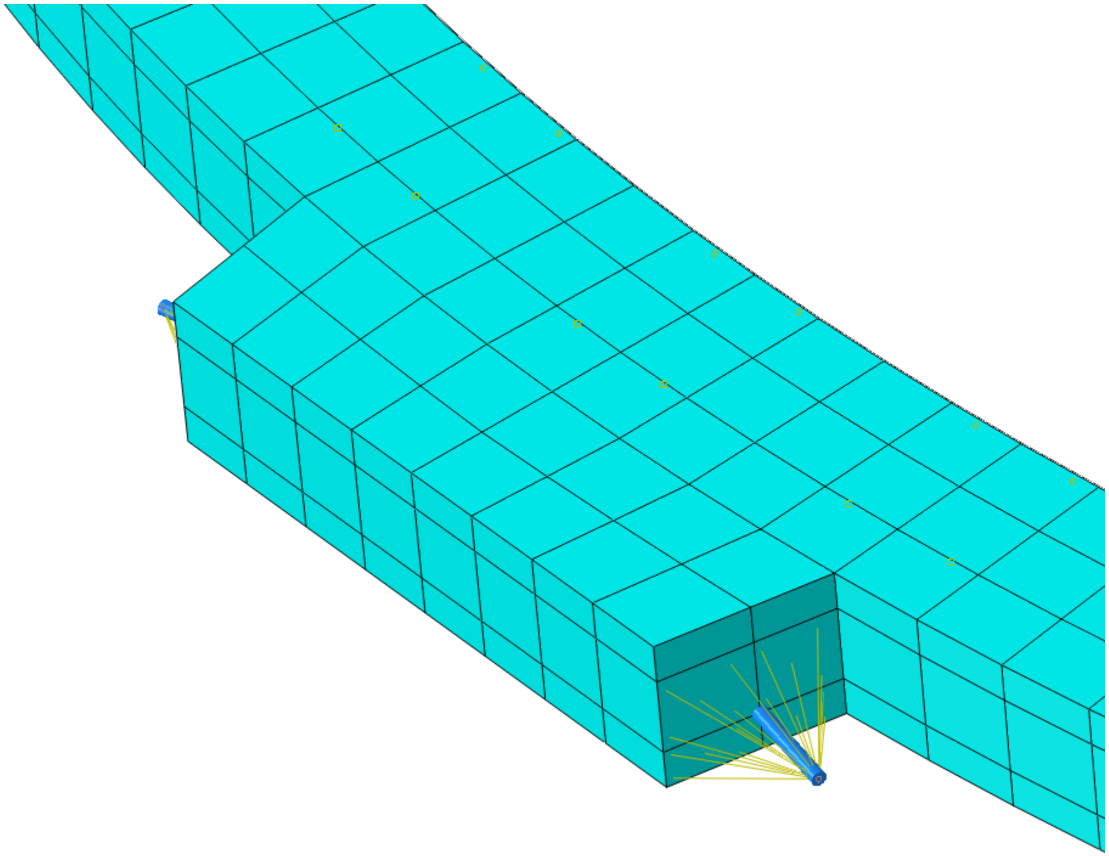
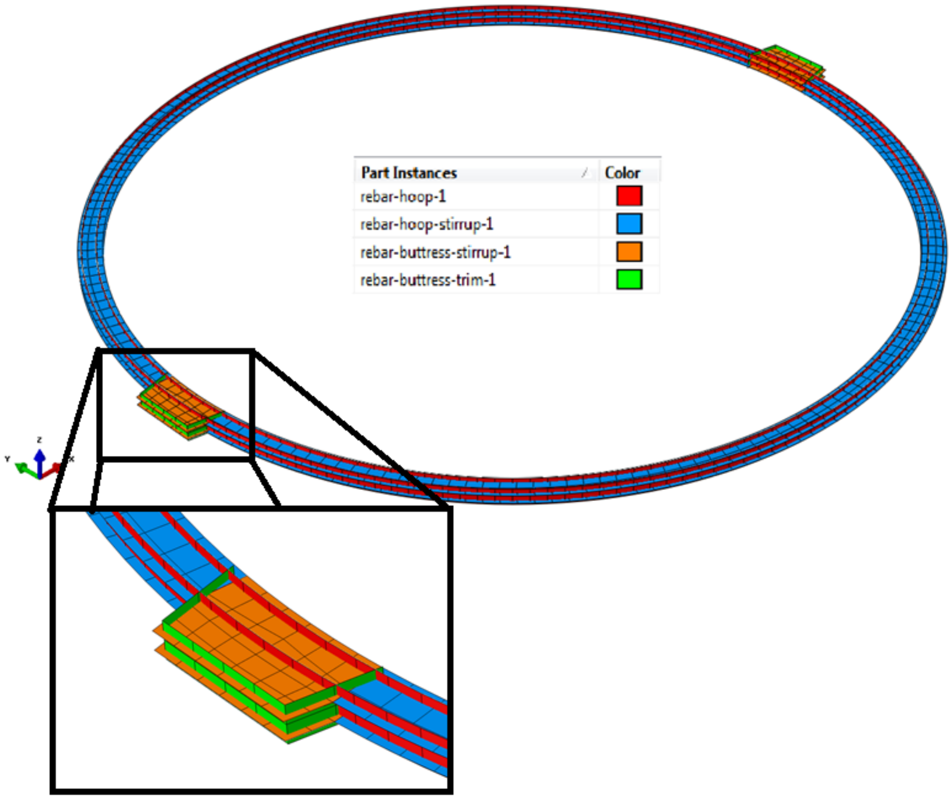
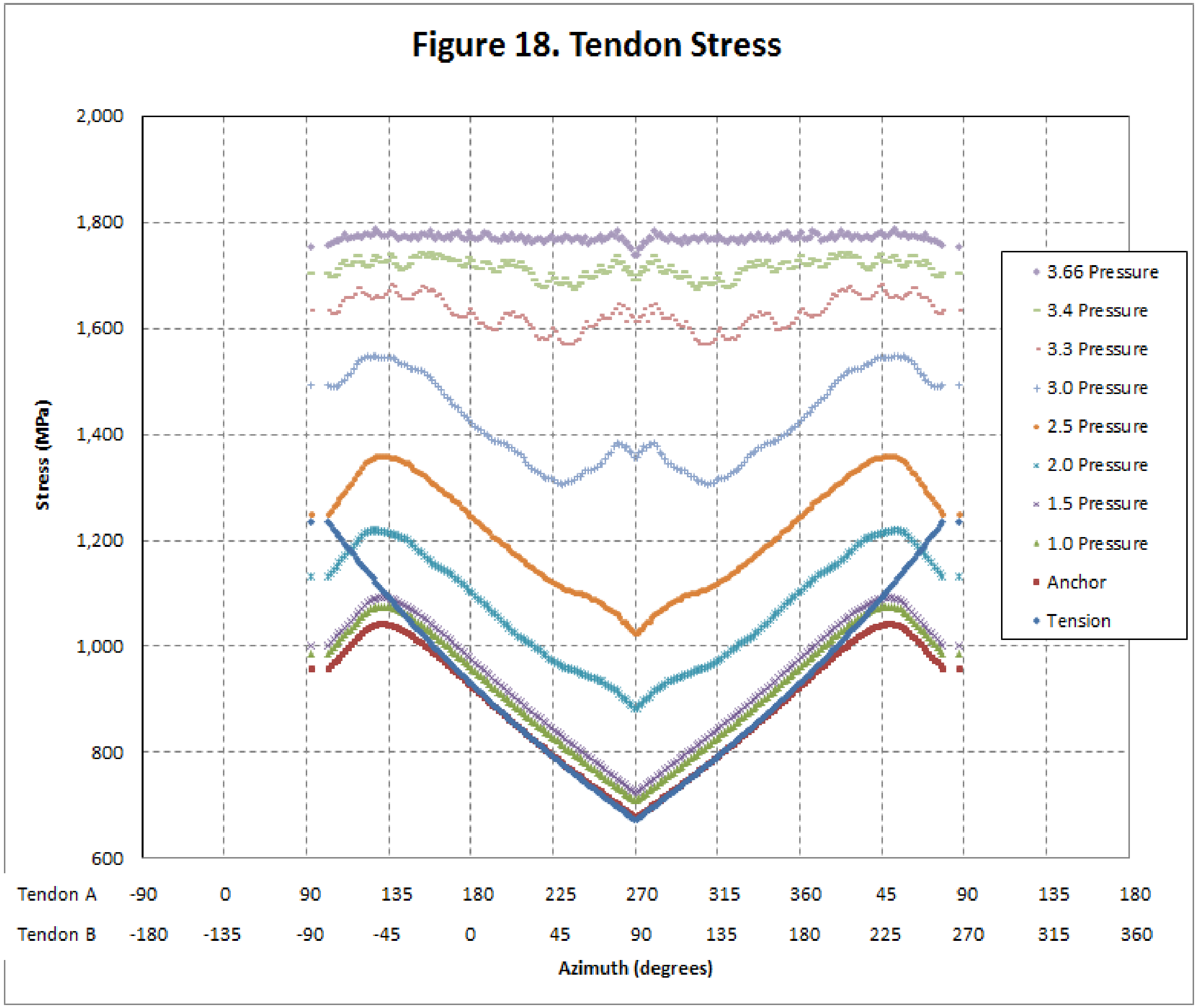
Anchorage of Tendon to Concrete



Rebar Layers Embedded in Concrete



Tendon Stress



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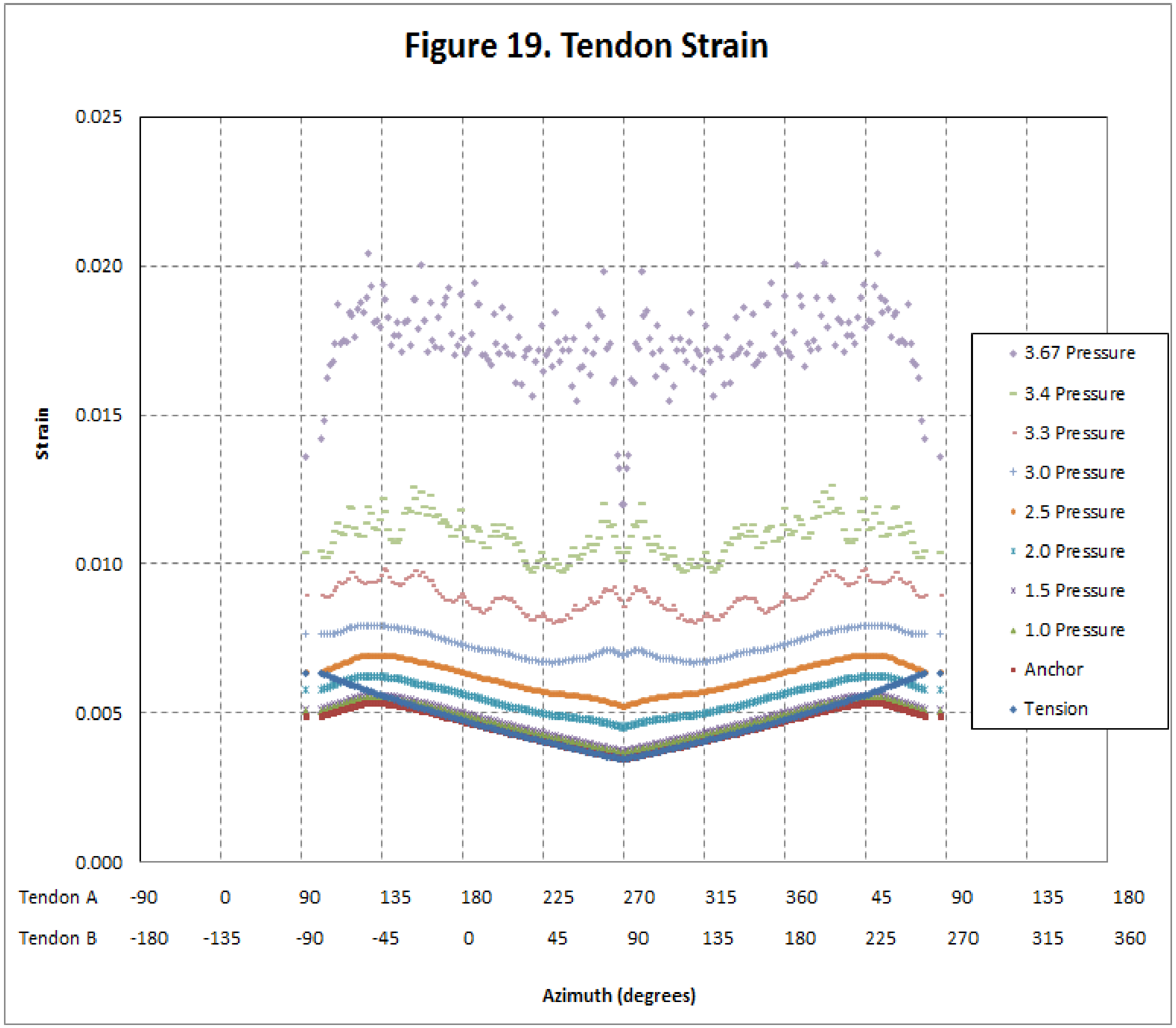
Tendon Strain



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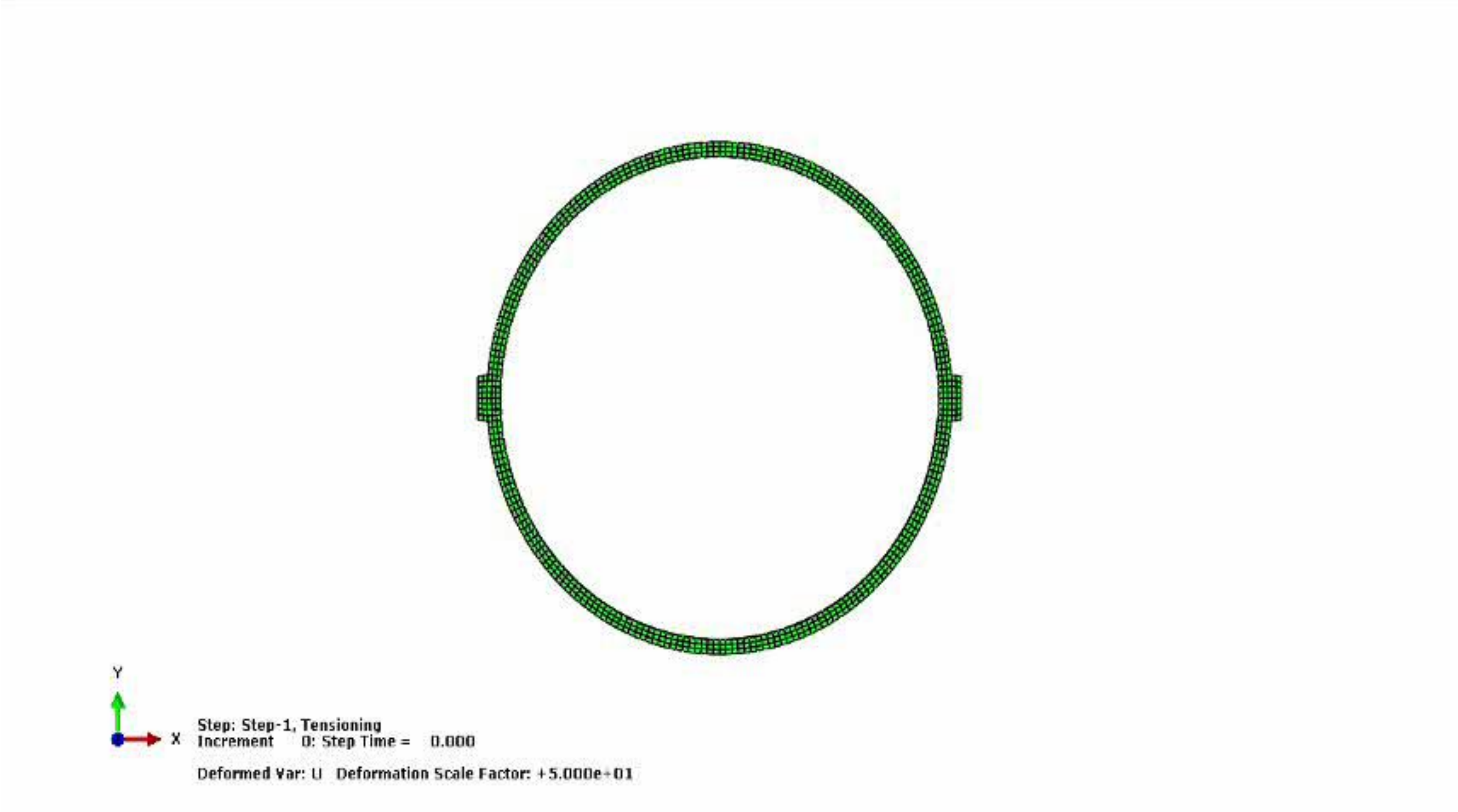
Results by Pressure Milestones
Pressure Only Case

Milestone	Pressure (MPa)	x Pd
Concrete Hoop Stress (at 135° azimuth) Equals Zero	0.562	1.433
Concrete Hoop Cracking Occurs (at 135° azimuth)	0.707	1.801
Tendon A Reaches 1% Strain (at 135° azimuth)	1.299	3.310
Tendon B Reaches 1% Strain (at 135° azimuth)	1.328	3.383
Tendon A Reaches 2% Strain (at 135° azimuth)	1.442	3.673
Tendon B Reaches 2% Strain (at 135° azimuth)	1.449	3.691

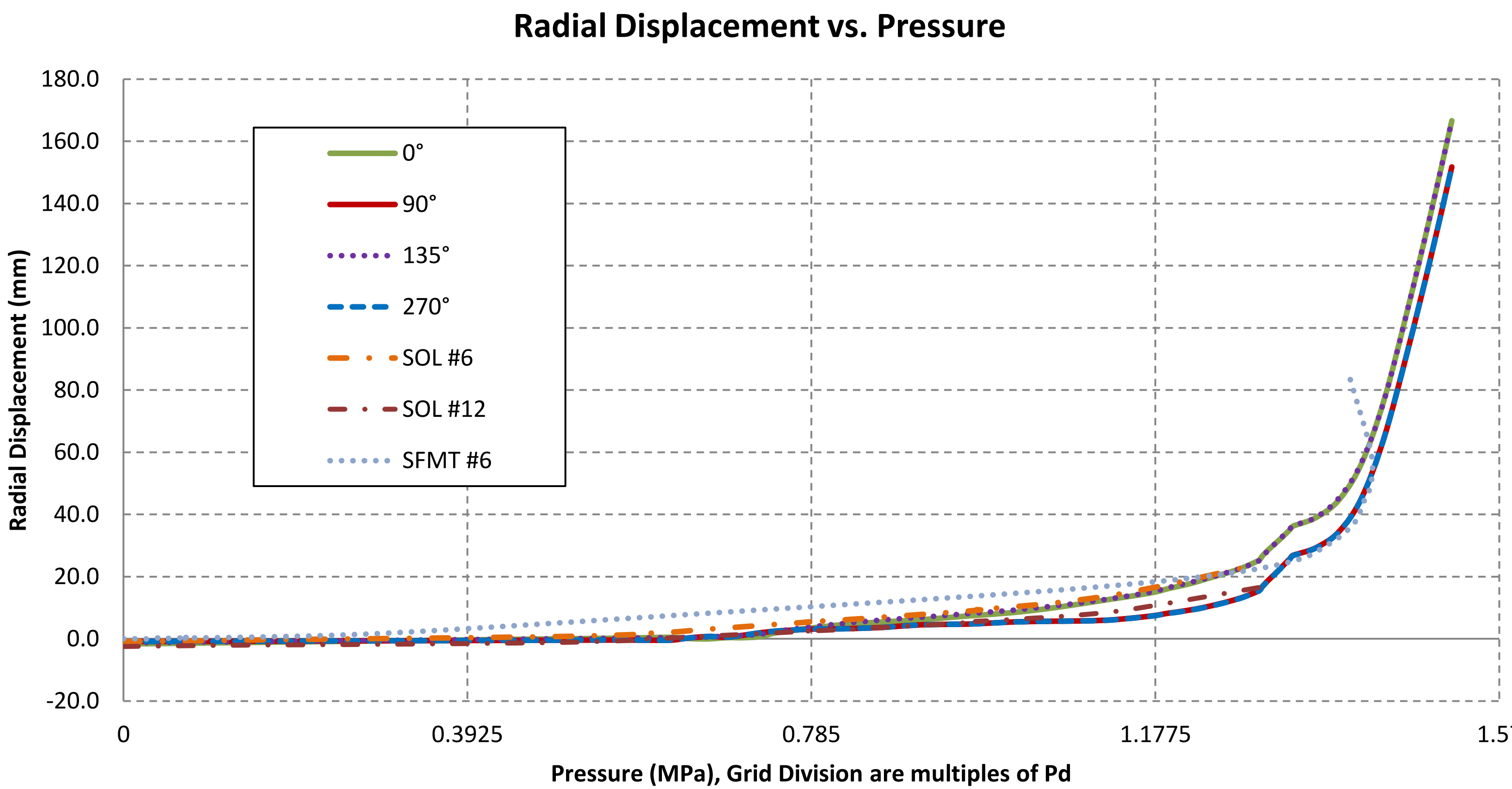
Conclusions from Model 1

- Tendon peak strains tend to be located at near where strain is maximum after prestress anchor set, i.e., azimuth 130-degrees
- But the "peak" moves around as the tendons yield, reposition and slip relative to the concrete
- Circumferential slip of tendons relative to the concrete is about 2 millimeters
- Using the contact surface method, such data as shown are conveniently available

Animation of the Deformed Shapes at the Required Pressure Milestones



Results of Radial Displacement vs. Pressure at Different Azimuths



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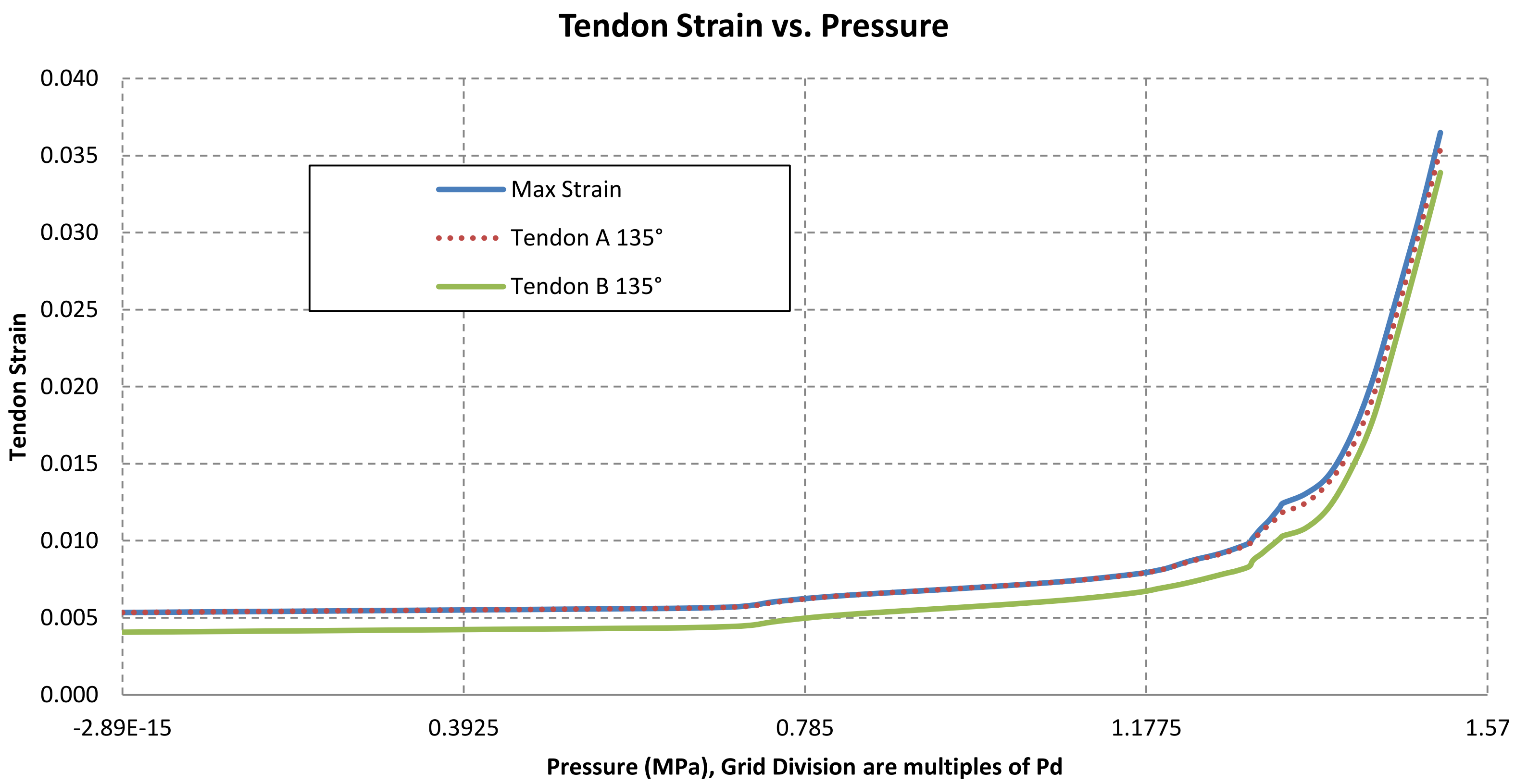
Tendon Strains and Stresses vs. Pressure



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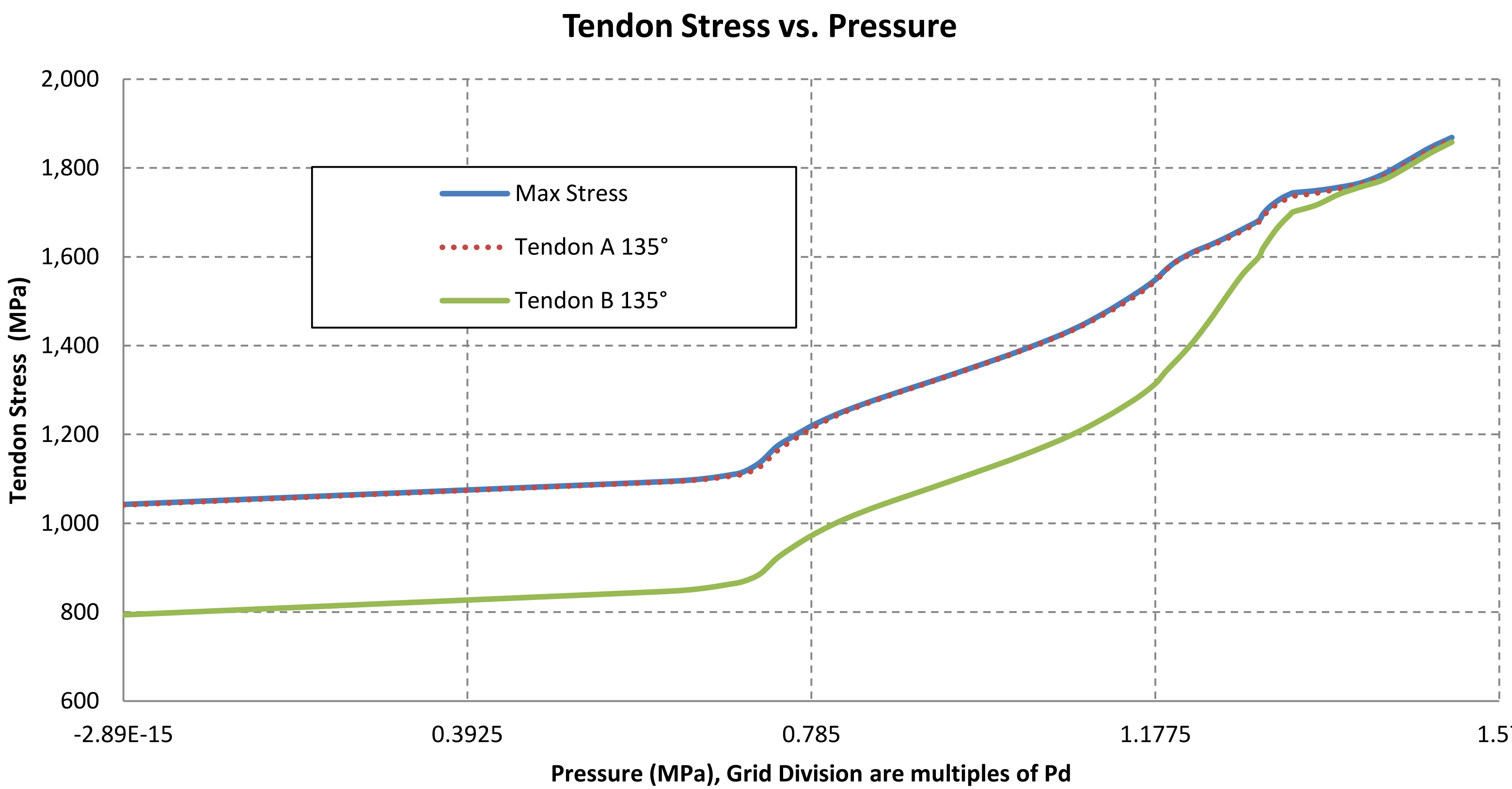
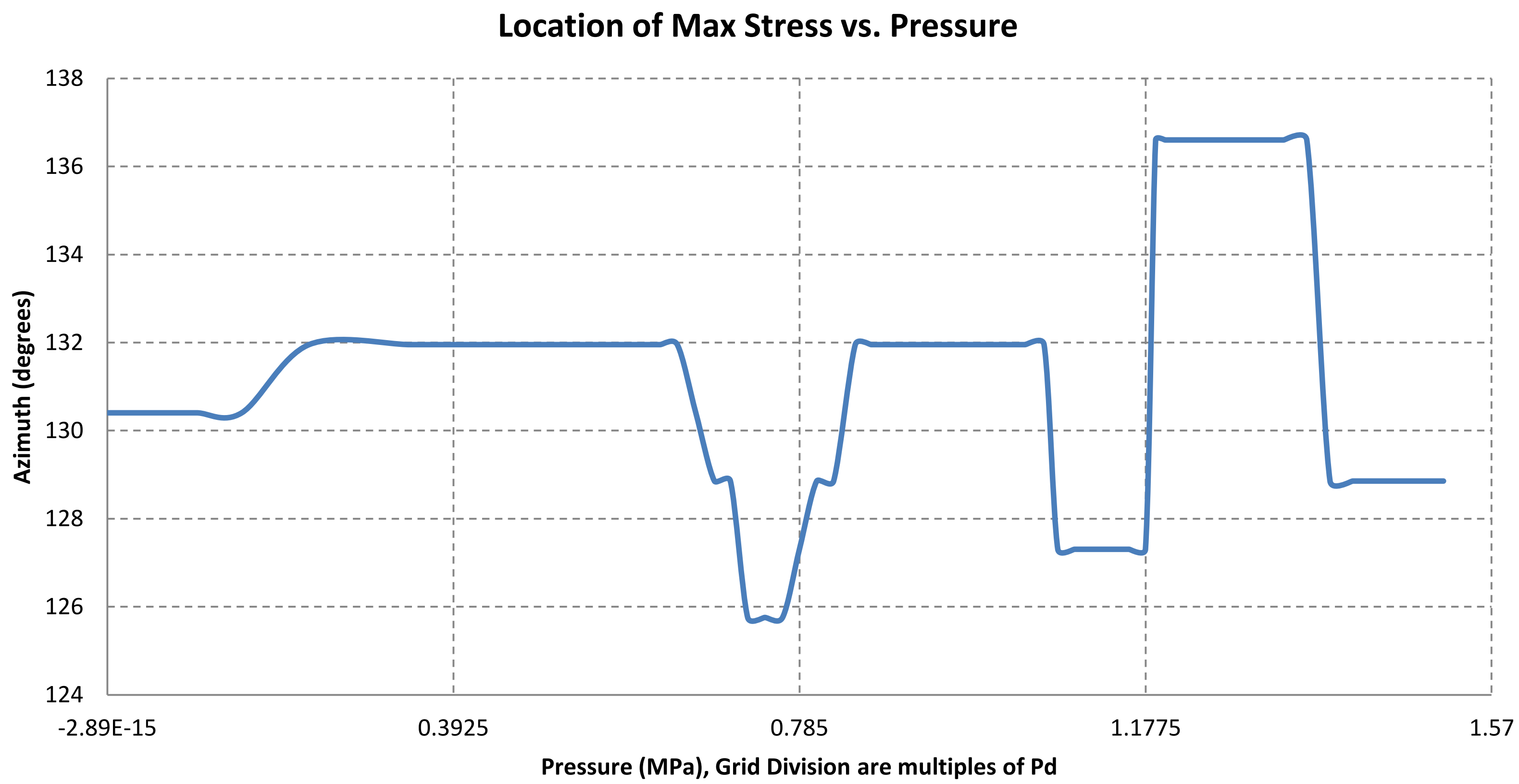
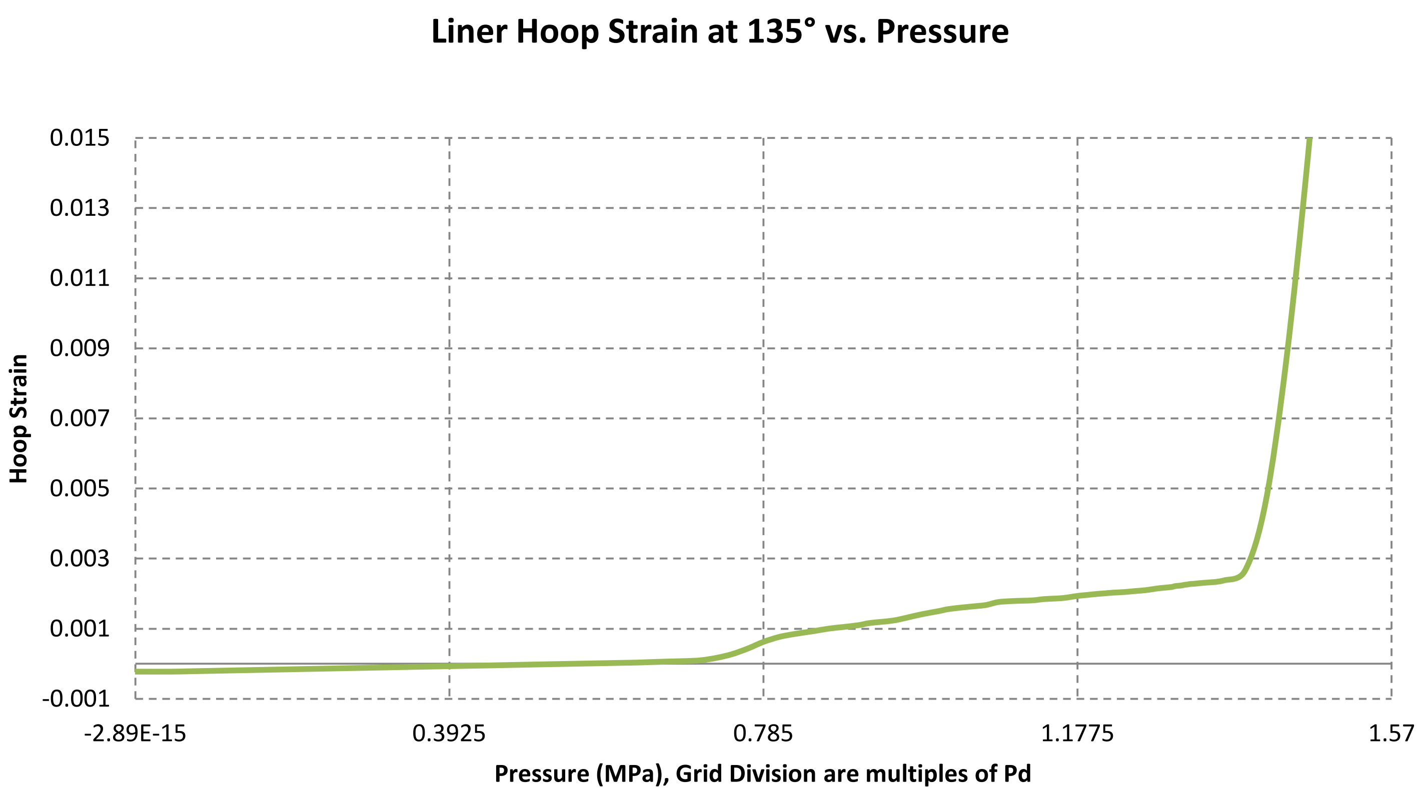
Tendon Strains and Stresses vs. Pressure



Tendon Strains and Stresses vs. Pressure



Liner Strains vs. Pressure



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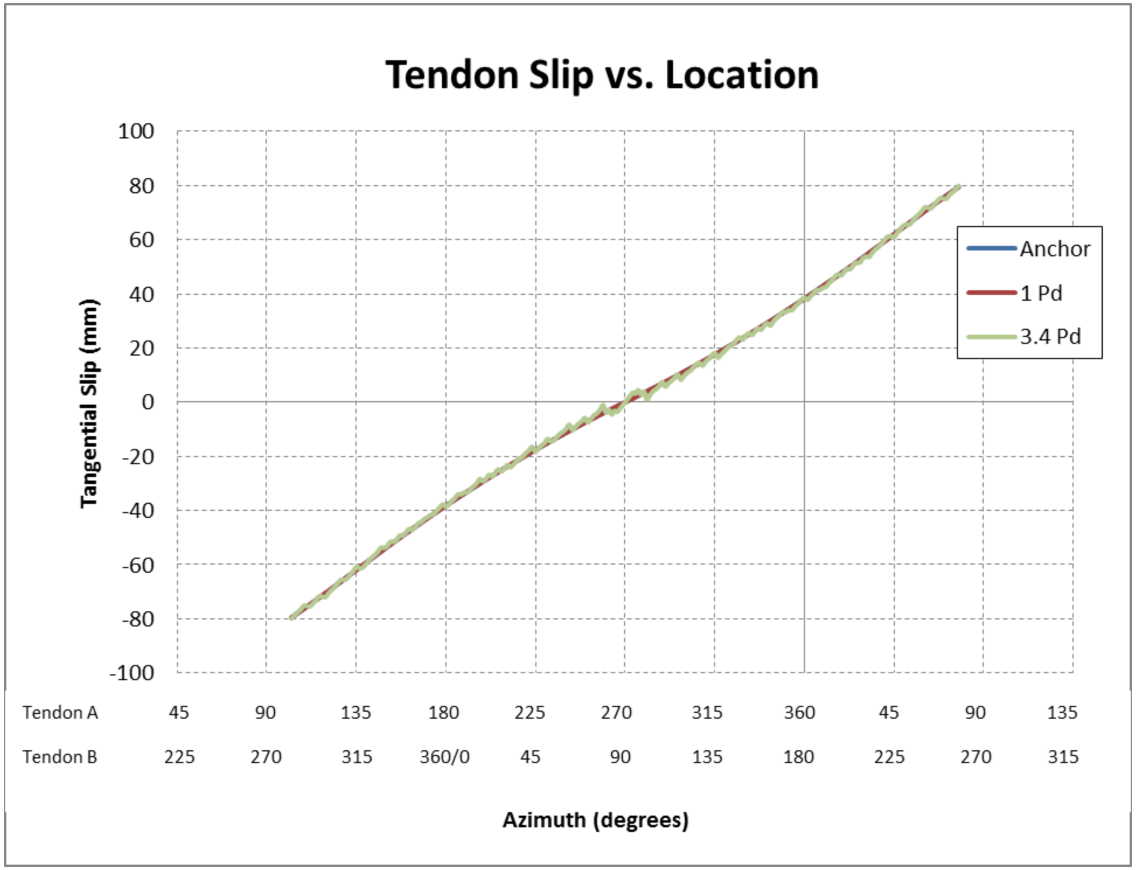
Circumferential Slip of Tendons Relative to the Concrete



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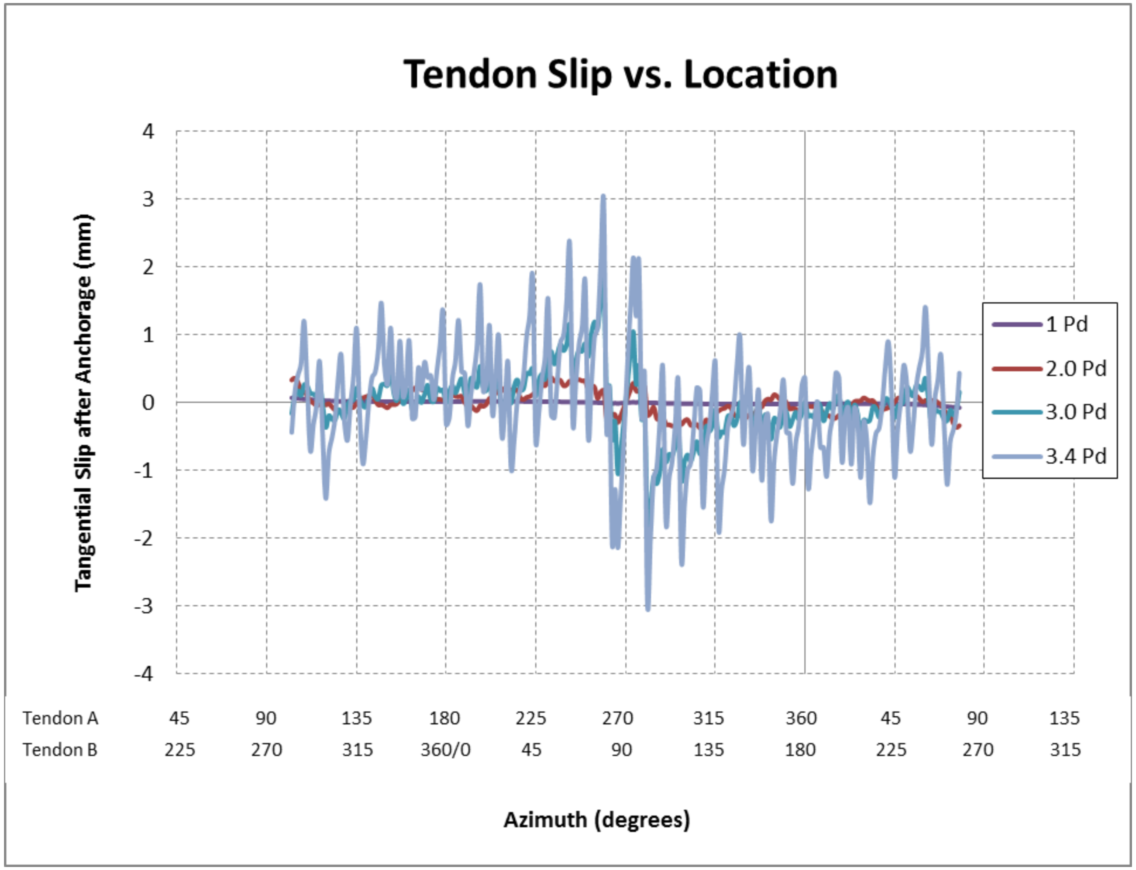

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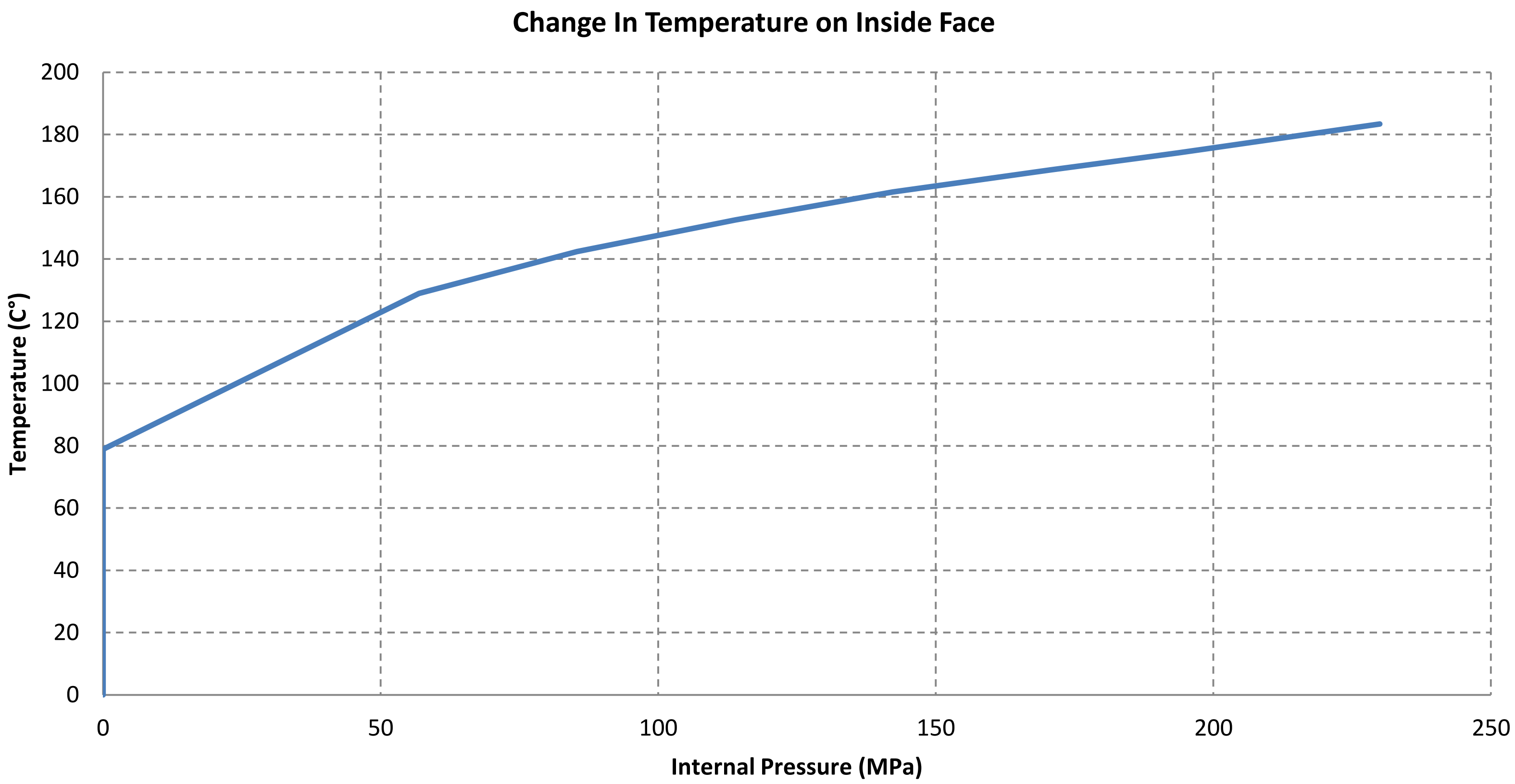
Pressure + Temperature Case

- Used ‘Saturated Steam’ condition for a PCCV
- Pressure-temperature relationship applied to the inside face
- Used temperature distribution from ISP-48 thermal analysis (through the thickness of the wall mid-height)
- Temperature triggers degradation of material properties
- Temperatures are not high enough to affect the steel, but they are high enough to affect concrete
- The three layers of concrete elements through the thickness of Model 1 were assigned slightly degraded properties
- After prestressing and anchor set, an additional equilibrium step is added where temperature is raised to 80° C, and then the temperature and pressure are increased together

Pressure-Temperature Relationship Applied to the Inside Face



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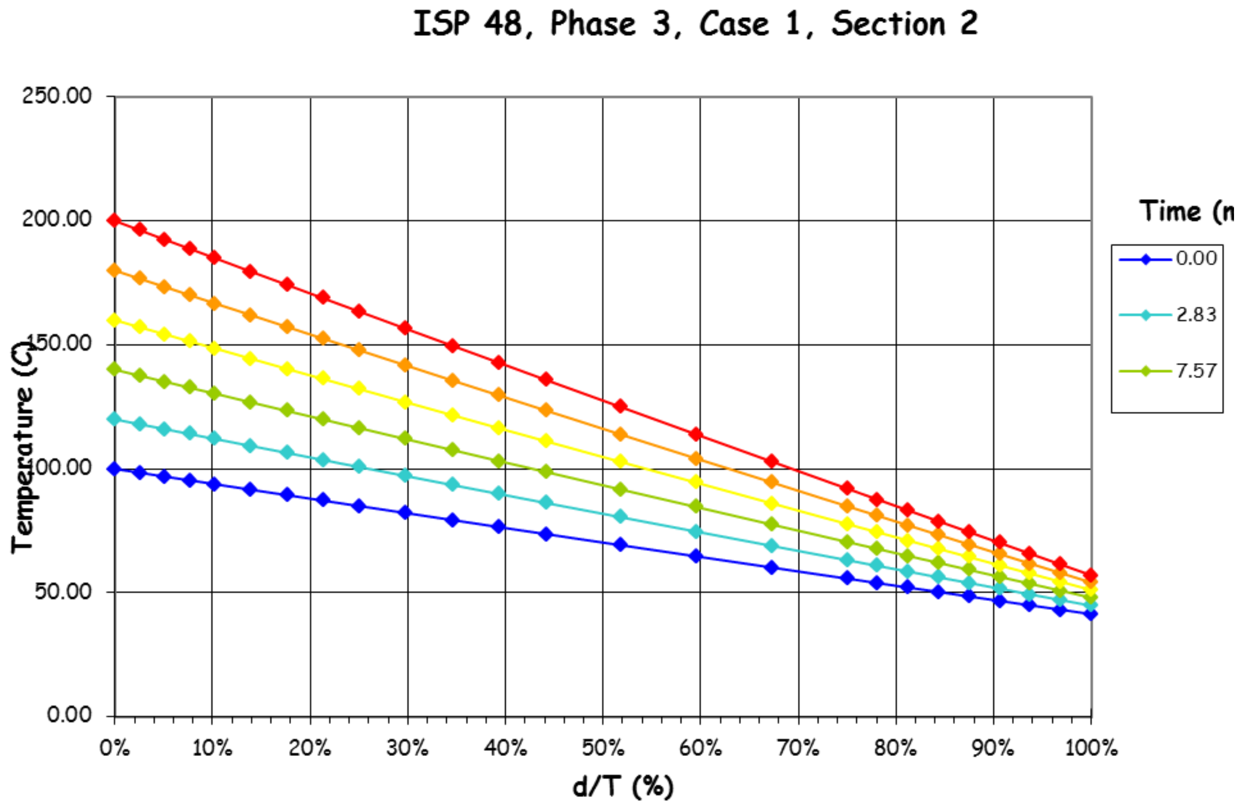
Temperature Variation Through Vessel Wall (Ambient Temp = 21.1 ° C



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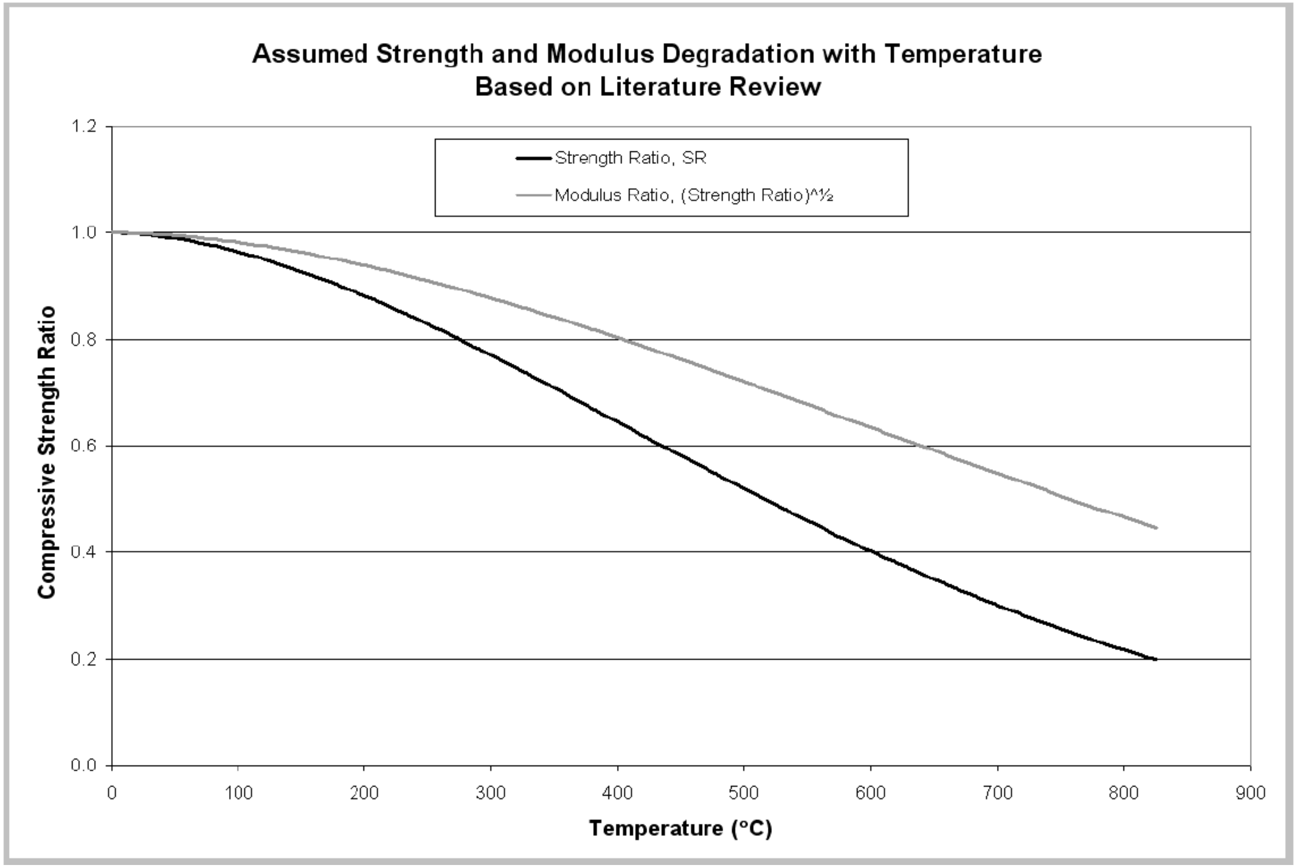
Concrete Degradation with Change in Temperature



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Results by Pressure Milestones
Pressure + Temperature Case

Milestone	Pressure (MPa)	x Pd
Concrete Hoop Stress (at 135° azimuth) Equals Zero	0.488	1.243
Concrete Hoop Cracking Occurs (at 135° azimuth)	0.705	1.797
Tendon A Reaches 1% Strain (at 135° azimuth)	1.237	3.150
Tendon B Reaches 1% Strain (at 135° azimuth)	1.296	3.301
Tendon A Reaches 2% Strain (at 135° azimuth)	1.402	3.571
Tendon B Reaches 2% Strain (at 135° azimuth)	1.415	3.606

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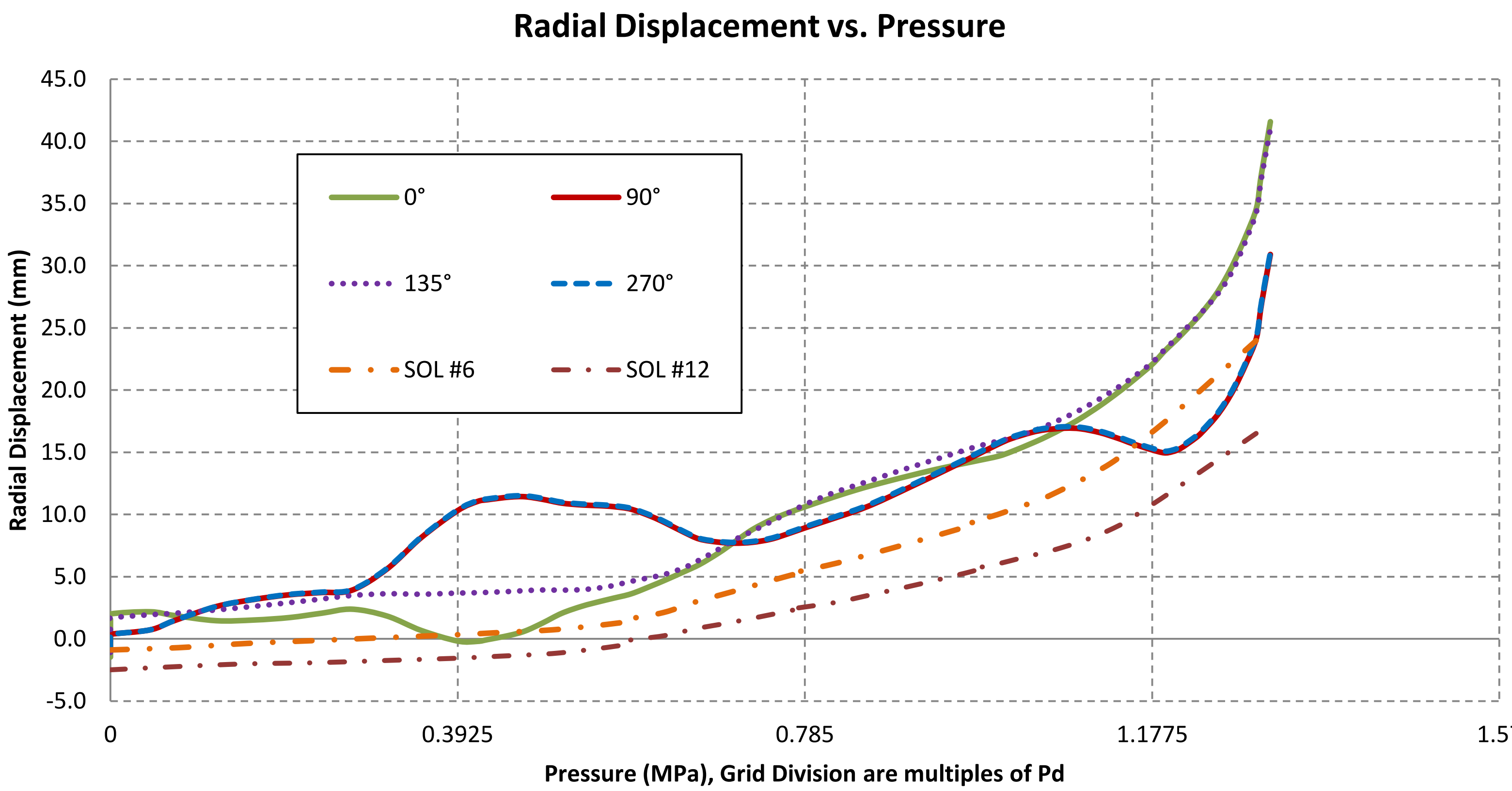
Temperature Case



Conclusions from Pressure + Temperature Case

- No significantly different conclusions in terms of ultimate limit state for PCCV for pressure + temperature
- Interesting phenomenon between $1P_d$ and $2P_d$
  - During this range, ovalized shape of "ring" changes from "dimpled" at buttresses, to ovalized outward at the buttresses. At larger pressures, shape of ring returns to similar pattern as for pressure only analysis.
- Another difference, the tendon-slippage relative to the concrete reaches 3.2mm, which is larger than the 1.8mm observed for pressure only analysis

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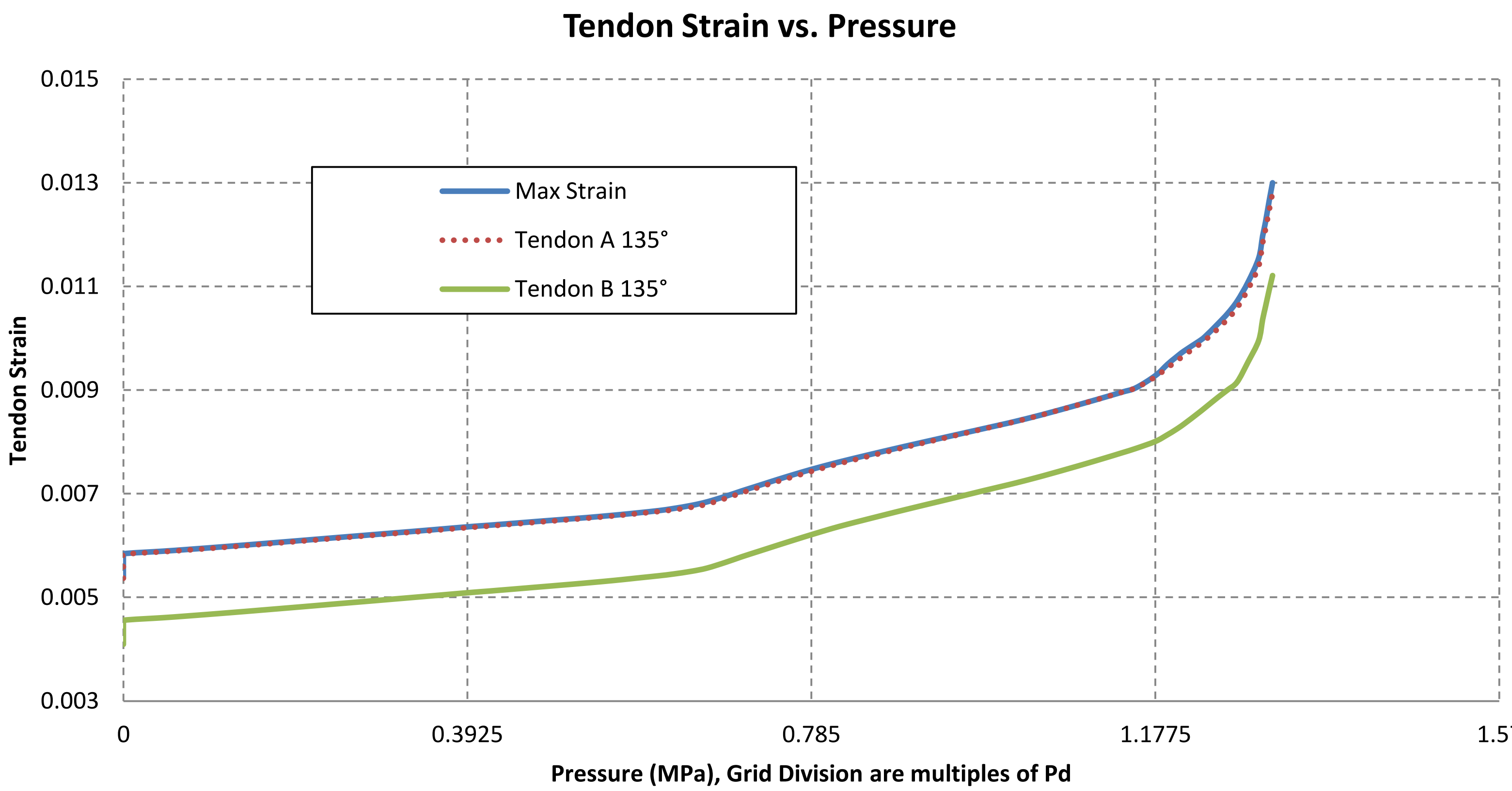
Temperature Case



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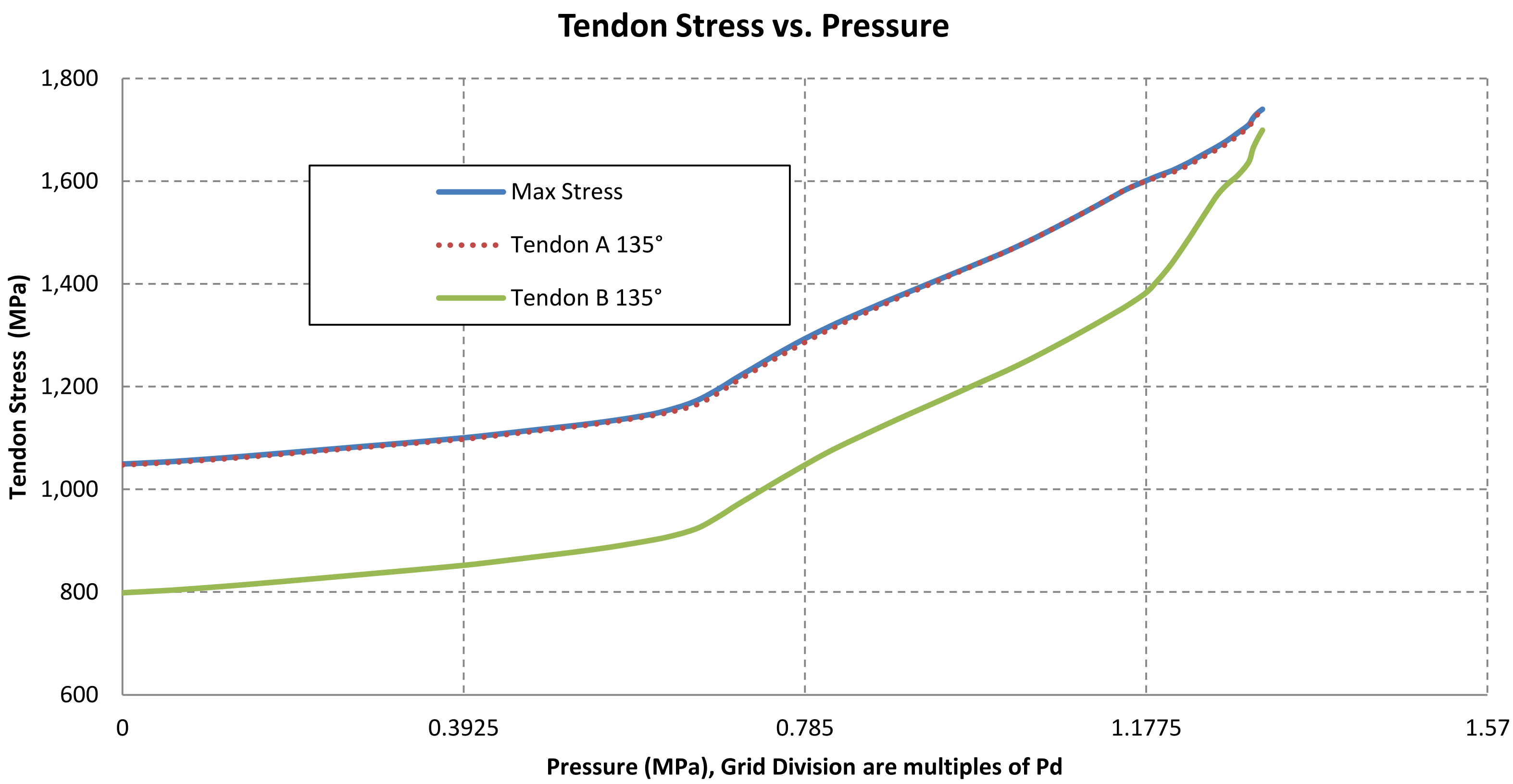

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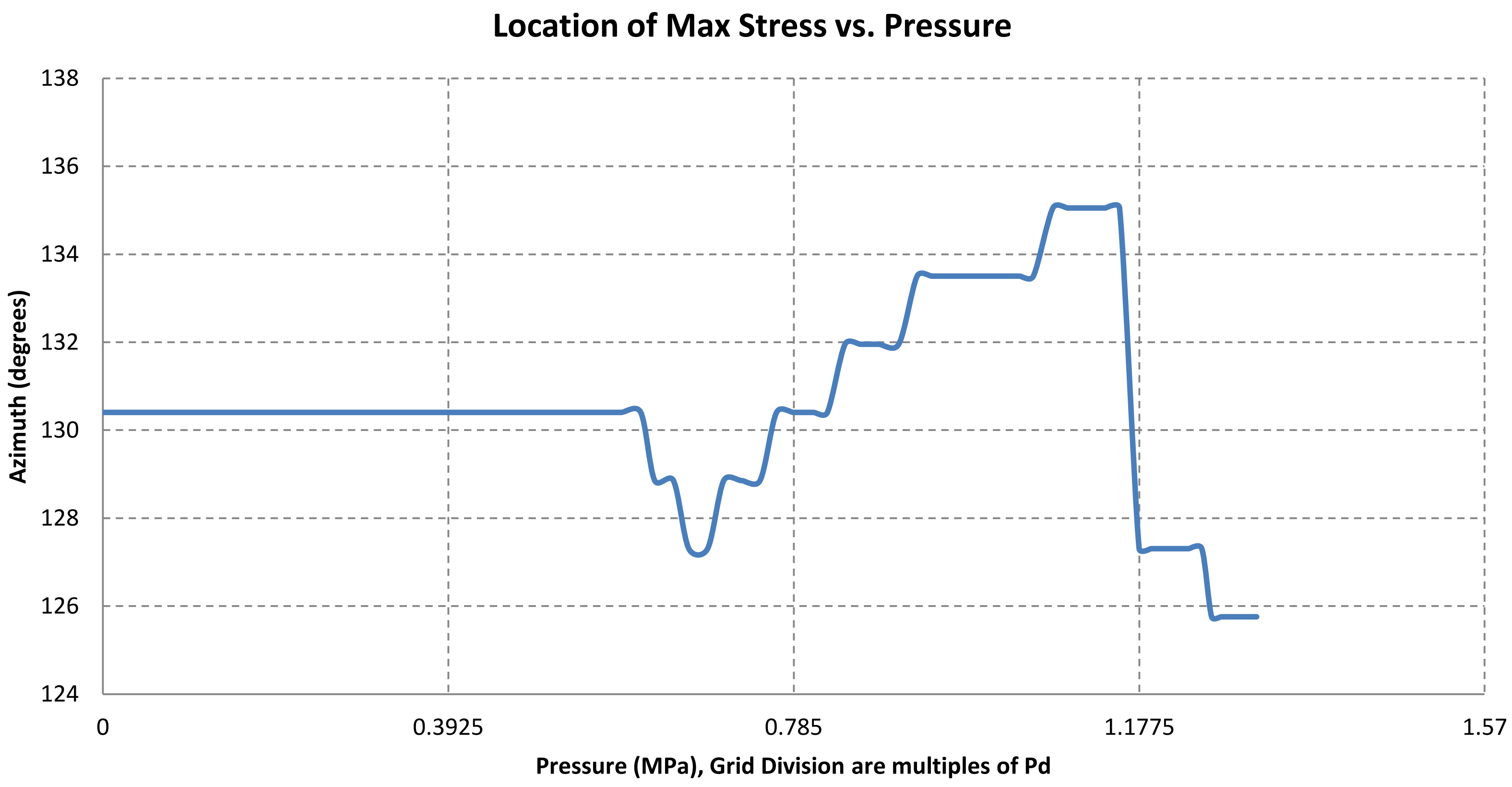

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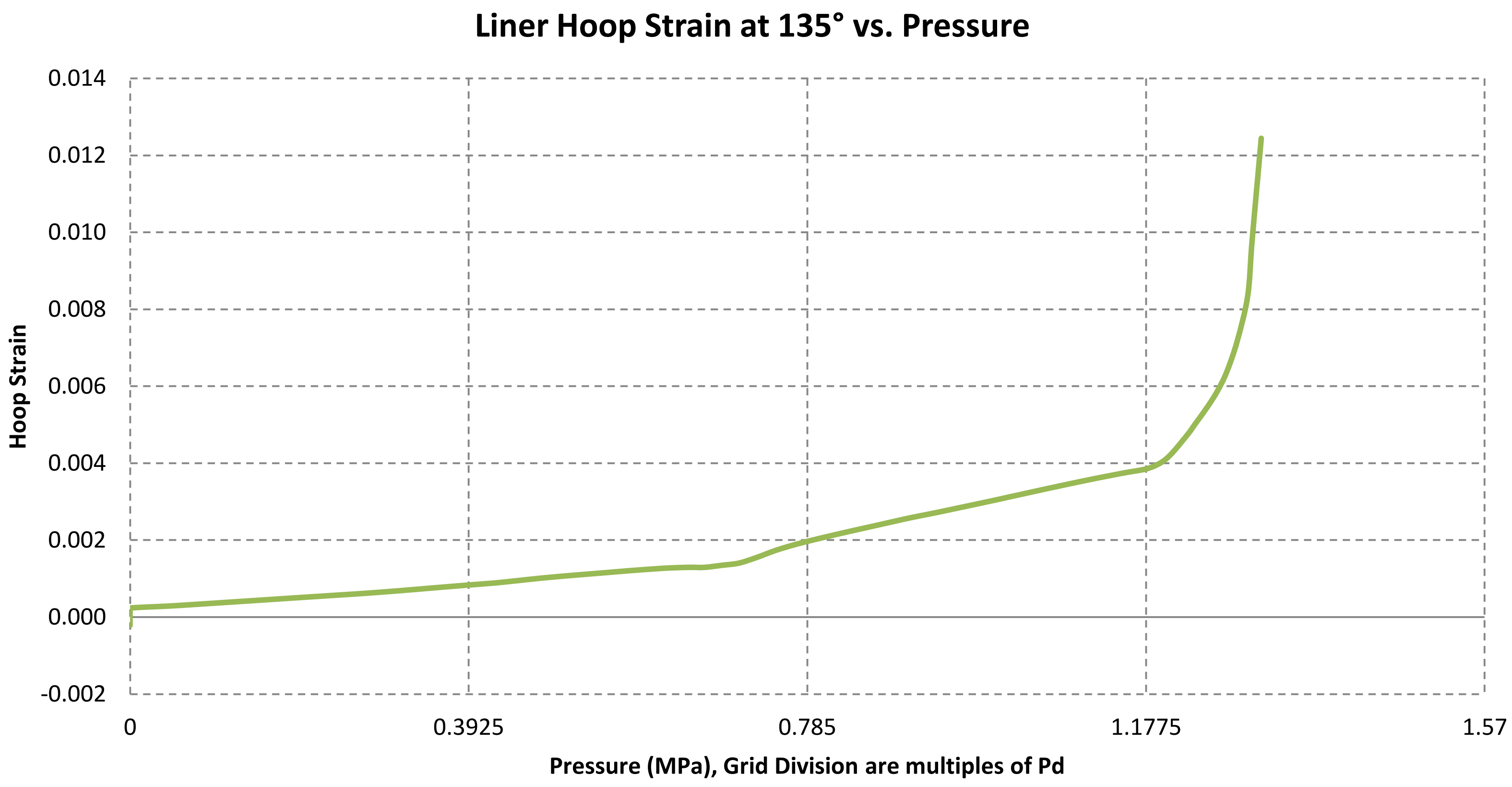
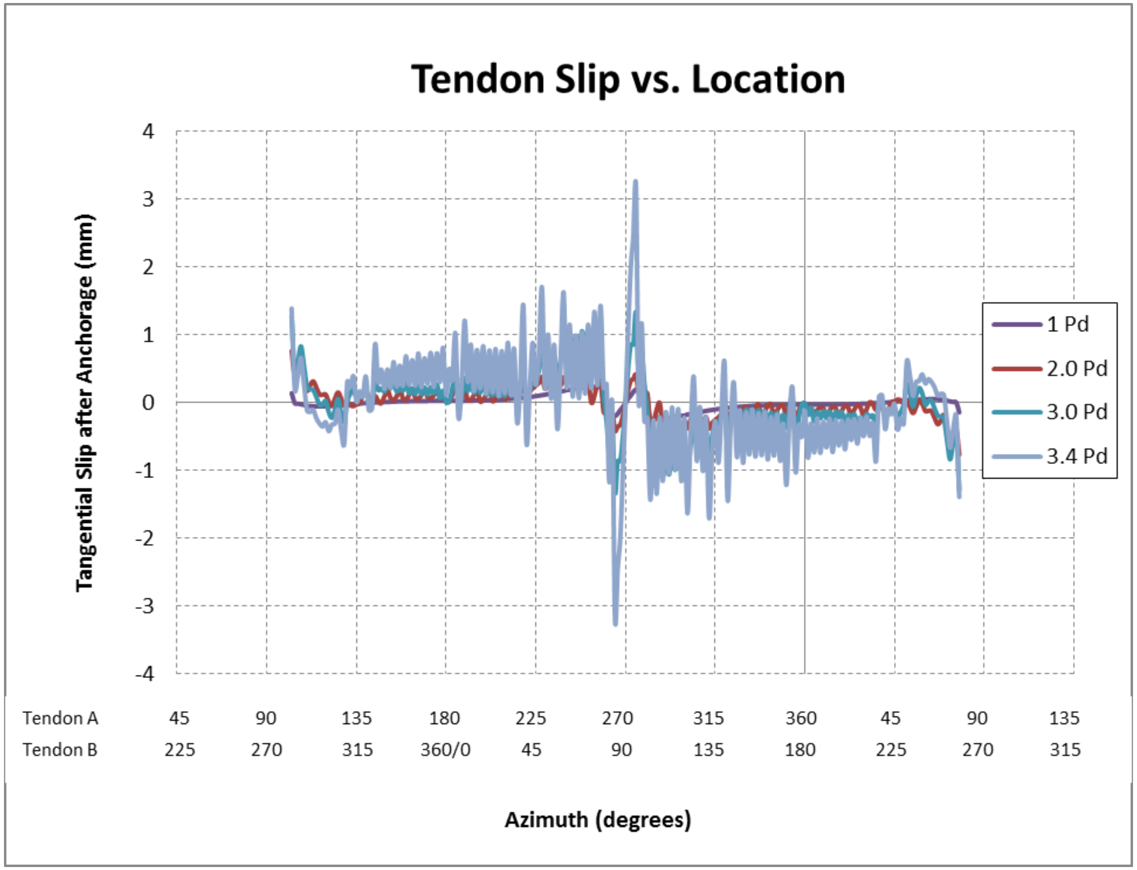


Temperature Case



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Animation of the Deformed Shapes
Temperature Case