AERB/NRC Workshop, Mumbai, India

Containment Capacity Analysis

Concrete Containment Nonlinear Response Analysis and Overview of Past Analysis Efforts Conducted for 1:4 Scale PCCV Test at Sandia

June 30, 2010

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Summary of NUPEC/NRC 1:4-Scale Prestressed Concrete Containment Vessel (PCCV) Model Tests and Analyses

History (from SNL Perspective)

- 1950s: Exclusion zone vs. containment
- 1973: WASH-1250 (Definition of severe accidents)
- 1975: WASH-1400 (Containment capacity)
- 1979: Three-Mile Island accident
- 1981: SNL Background Study
- 1982: NRC-sponsored program at SNL
  - 1982: 1:32-scale steel models
  - 1984: 1:8-scale steel model
  - 1987: 1:6-scale reinforced concrete model
- 1991: Joint NUPEC and NRC program at SNL
  - 1996: 1:10/1:4-scale steel model
  - 2000-2001: 1:4-scale prestressed concrete model
- 2002: Containment Capacity Studies
  - ISP 48
- 2006: Containment Integrity Research Summary

Background References

"The Safety of Nuclear Power Reactors (Light Water-Cooled) and Related Facilities," Final Draft, WASH-1250, US Atomic Energy Commission, July, 1973.

"Reactor Safety Study, An Assessment of Accident Risks in US Commercial Nuclear Power Plants," Draft WASH-1400, US Atomic Energy Commission, 1974; Final, NUREG-75/014, 1975.

Blejwas, T. E., et. al., "Background Study and Preliminary Plans for a Program on the Safety Margins of containments," NUREG/CR-2549, SAND82-0324, Sandia National Laboratories, May 1982.

Amin, M. P., P. K. Agrawal and T. J. Ahl, "An Analytical Study of the Seismic Threat to Containment Integrity", NUREG/CR-5098, SAND88-7018, Sandia National Laboratories, 1989.

Containment Integrity Research @ Sandia

- **Objective:**
  - **Evaluate methods used to predict the performance of light water reactor containment systems when subjected to loads beyond those specified in the design codes.**
  - **<u>NOT</u> to determine the pressure carrying capacity of actual containments by testing scale models.**
- **Two types of loadings are being considered:**
  - **Severe Accident Loadings (static pressurization and elevated temperature)**
  - **Earthquakes greater than the Safe Shutdown Earthquake (SSE) - analysis only**
- **An integrated program of testing models of containment structures and components (both scaled and full-size specimens) coupled with detailed pre- and posttest analyses**

Containment Integrity Research @ Sandia

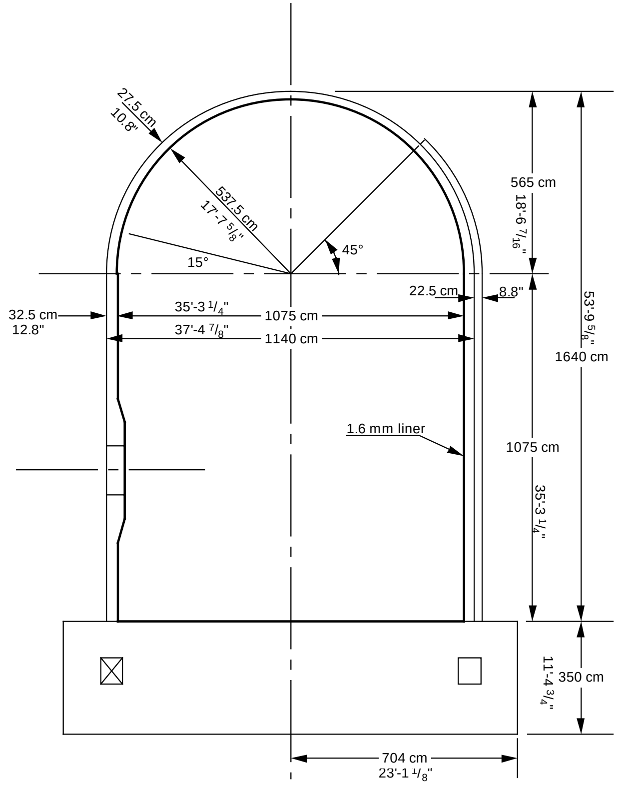
- Pneumatic pressure tests of large-scale models of representative containment structures and full scale tests of components (penetrations, etc.).
- Models of three types of containments used in current nuclear construction:
  - free-standing steel containments,
  - steel lined reinforced concrete containments and steel lined,
  - prestressed concrete containments.
- Guiding principles
  - models would incorporate representative features of the prototypes,
  - would not knowingly preclude a potential failure mode
  - and would not incorporate details which were unique to the model and not representative of the prototype.

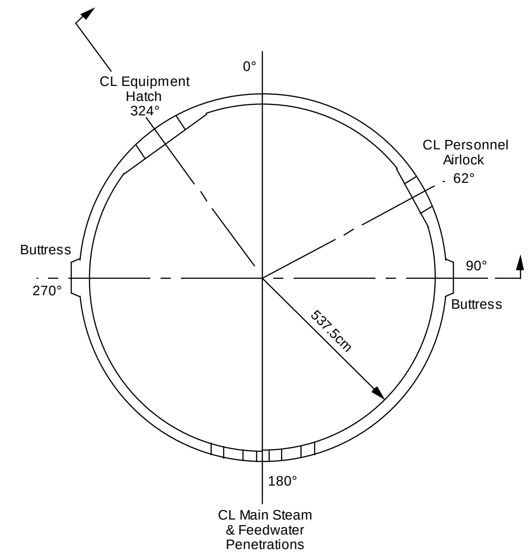
Containment Integrity Research @ Sandia

- **Scope:**
  - Scale-model Containment Overpressurization Tests
    - Steel: four 1:32-scale, one 1:8-scale, one 1:10-scale
    - Reinforced Concrete: one 1:6-scale
    - Prestressed Concrete: one 1:4-scale
  - Penetration Tests (hatches, electrical & piping penetrations, seals & gaskets)
  - Degraded Containment Analyses
  - Seismic Analyses of scale model tests
- **Related Efforts:**
  - Impact Tests (aircraft, turbine missiles)

Prestressed Concrete Containment Vessel Model

- **Model of the containment structure of Ohi Nuclear Power Station, a large, dry PWR prestressed containment vessel**
  - **Design pressure is 0.39 MPa (57 psig) :**
  - **Geometry: configuration and overall dimensions (height, radius, thickness) scaled 1:4.**





Ohi 3 & 4

Containment Technology Test Facility

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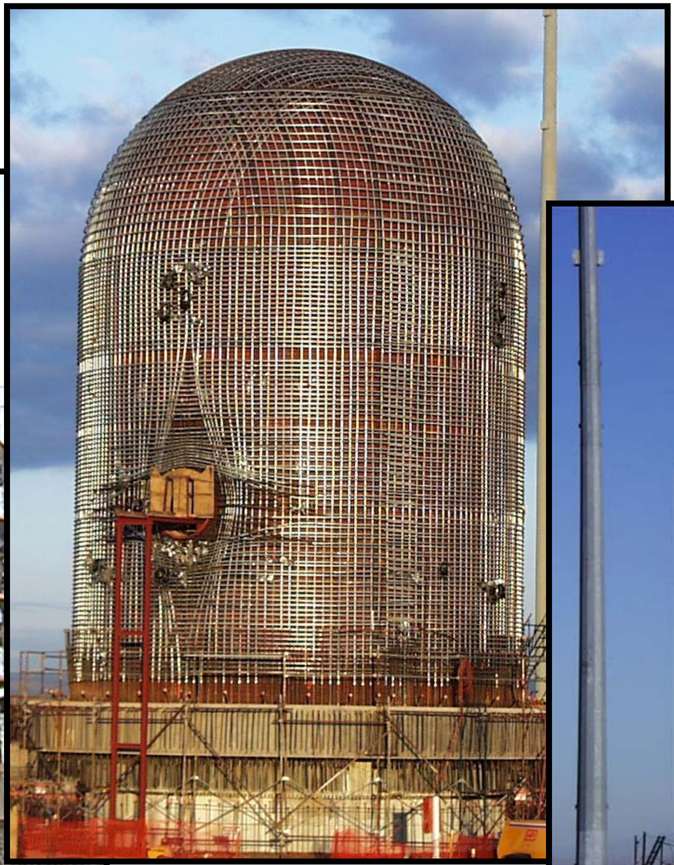
PCCV Model Construction



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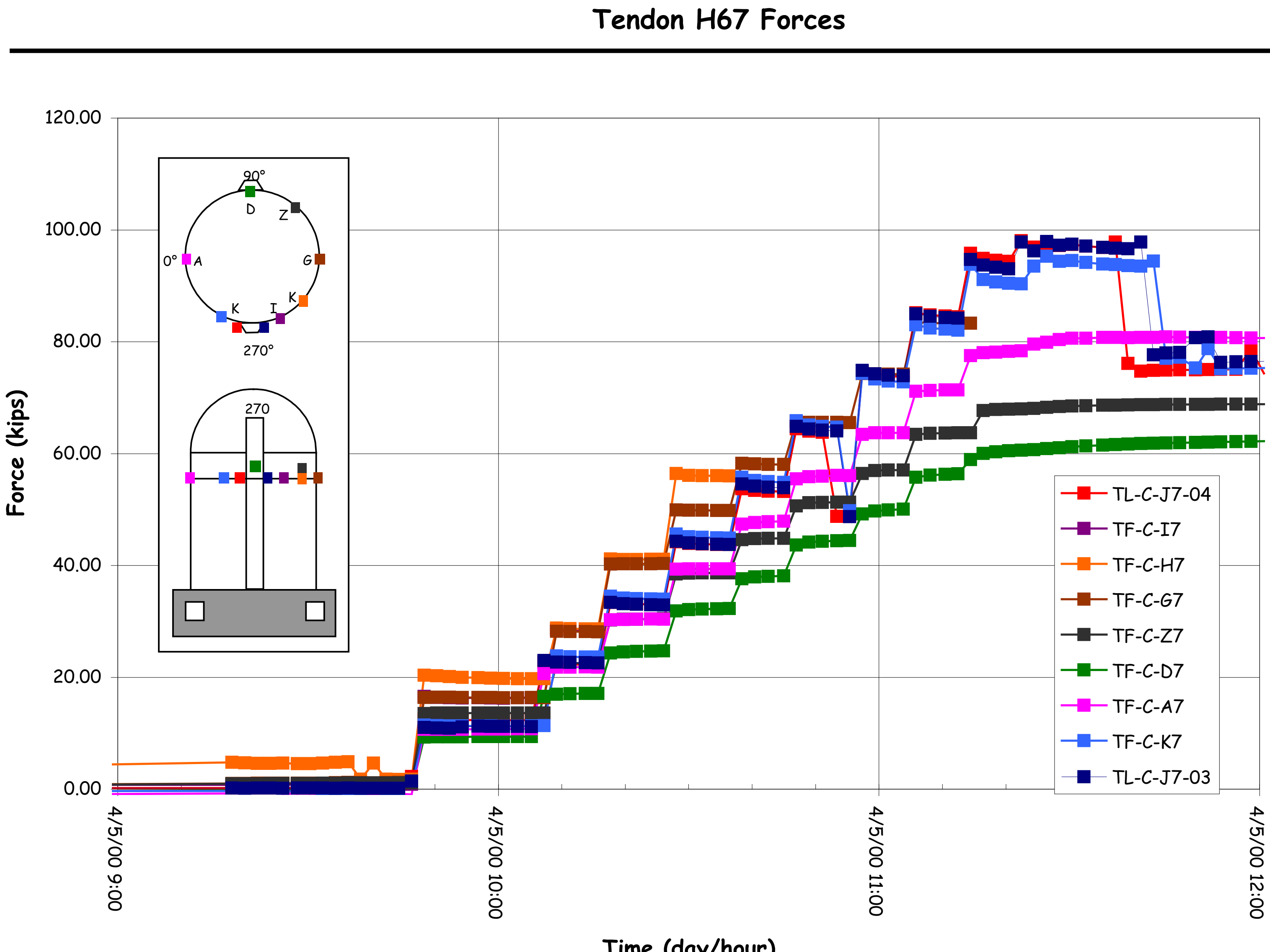
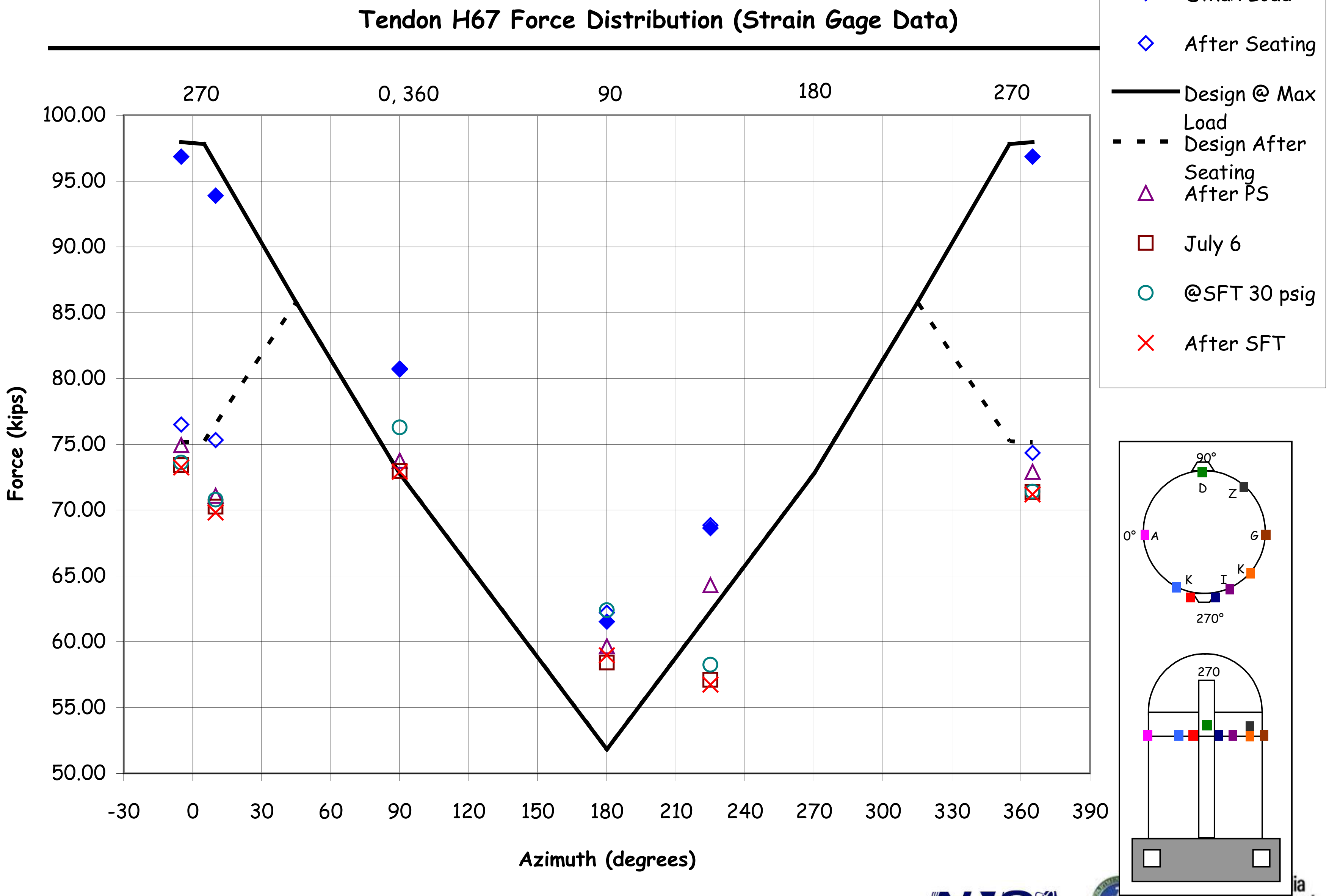
Tendon Prestressing Force Measurements



Tendon Force Measurements



Completed PCCV Model

1:4-scale PCCV Analysis Scope

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Linking Theory And Practice

- Preliminary Analyses
  - Potential Failure Modes and Locations
  - Instrumentation Planning
  - Analysis Model Development
- Pretest Analyses
  - Pretest Global & Local Response Predictions
  - Finalize Instrumentation
  - Predict Failure Pressure(s), Modes and Locations
- Posttest Analyses
  - Comparison with Test Results
  - Calibrate models
  - Study observed failure modes
  - Conclusions and Lessons Learned
- Studies on Model Artifacts and Scaling
  - Scaling Issues
  - Tendon Behavior Studies
- ISP 48
  - Formal Posttest Analysis
  - Effects of Thermal Loading in combination with Pressure

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Pretest Analysis Summary

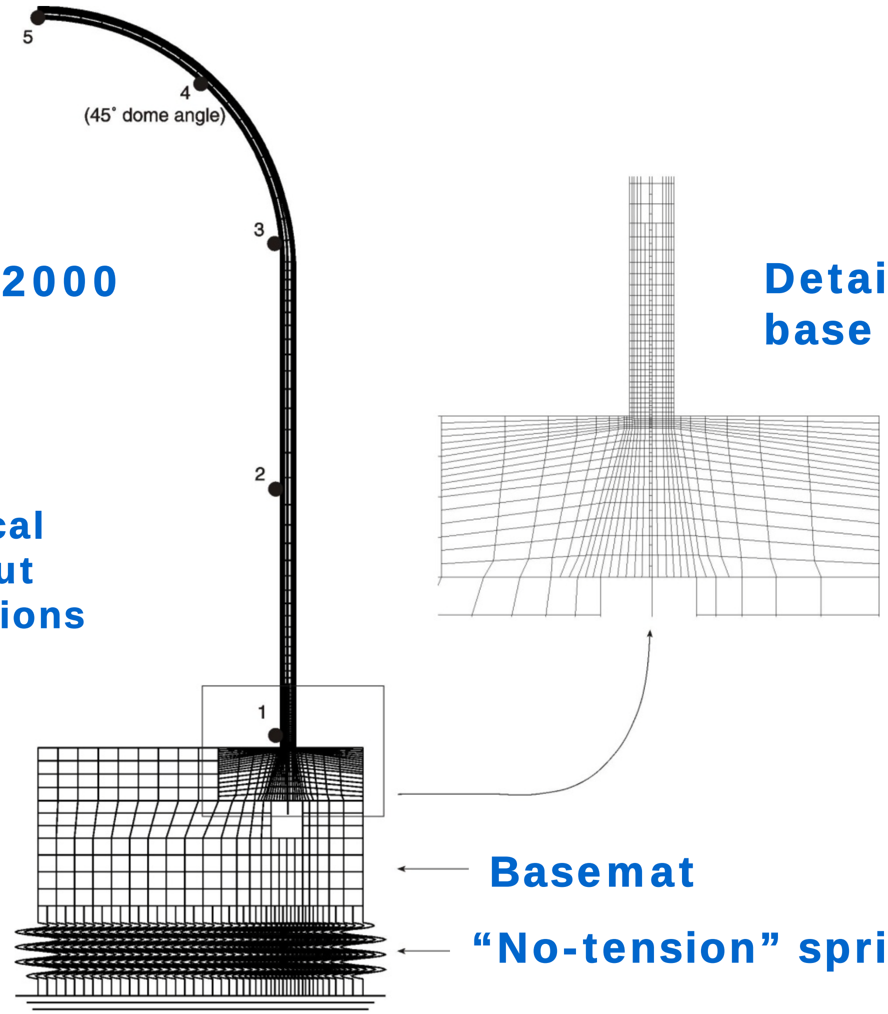
- Axisymmetric Model
  - Global axisymmetric response
  - Simulates 135° (free-field) azimuth
  - "Smeared" hoop tendon behavior
  - Highly detailed at wall-base juncture
- Three Dimensional Cylinder Mid-height (3DCM) Model
  - 3-dimensional response of cylinder
  - Detailed tendon stress and strain distribution
  - Local concrete, rebar, and liner strains near buttresses
  - Boundary conditions for local models
- E/H, A/L, M/S Local Models
  - Detailed for liner strain concentrations near penetrations

Axisymmetric Model of the PCCV

Added tendon friction ties in "2000 pretest model"

Typical output locations

Detailed wall-base model



Basemat

"No-tension" springs

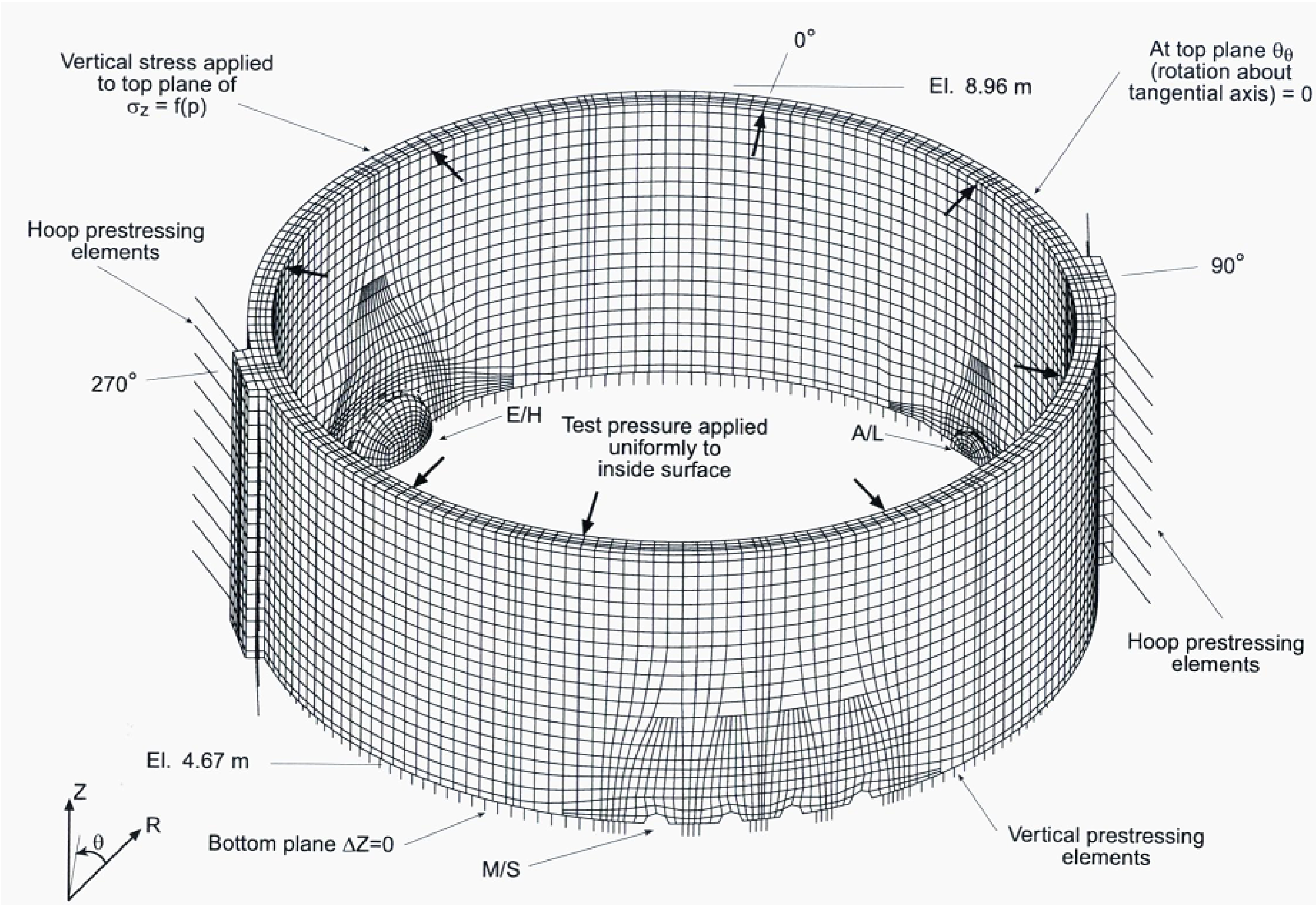
Pretest Analysis Summary, cont’d

- ANACAP-U/ABAQUS
  - Smeared crack FE method (introduced by Rashid)
  - Concrete cracking, crushing, post-cracking shear retention
  - Steel Liner, rebar, and tendon stress vs. strain
  - Development sponsored by EPRI research
  - Reasonably predicted global behavior of previous tests
  - Modeling prestressing and liner were significant new challenges

Pretest Analysis Summary, cont'd

- MODELS SHOULD BE SELECTED TO ADDRESS FAILURE MECHANISMS
  - Prestressing failure: global axisymmetric & 3DCM
  - Rebar failure: global axisymmetric, 3DCM, and local 3D models
  - Shear/bearing failure: global axisymmetric with detailed wall-base juncture modeling
  - Liner tearing: axisymmetric and 3D local models

Isometric View of 3DCM Model



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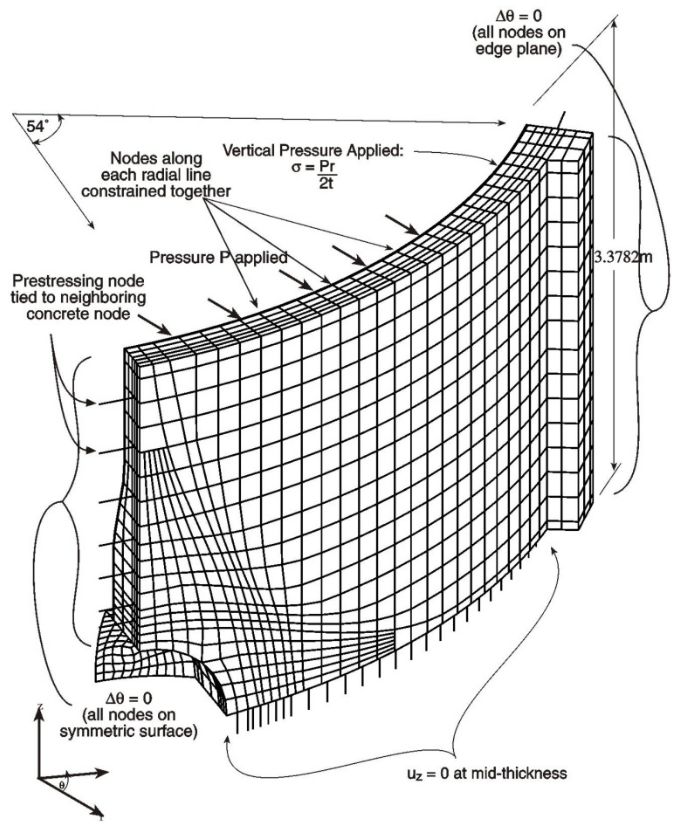
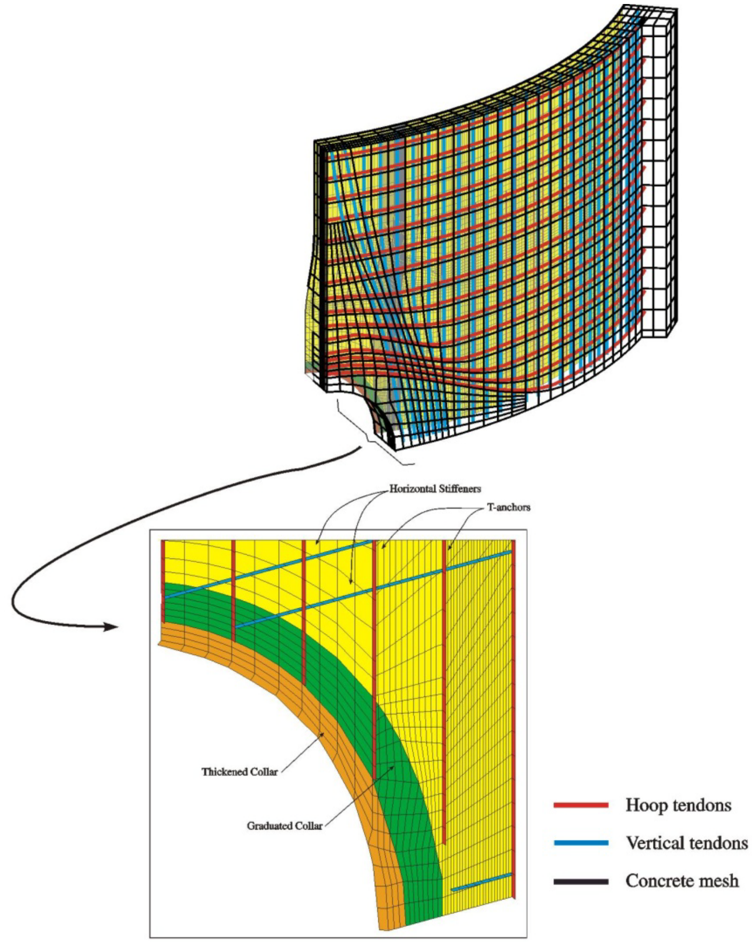
Equipment Hatch Sub-model



Boundary Conditions and Geometry
for 3D Equipment Hatch Model



Finite Element Mesh Including
Tendons, Liner, Anchors, and Stiffeners

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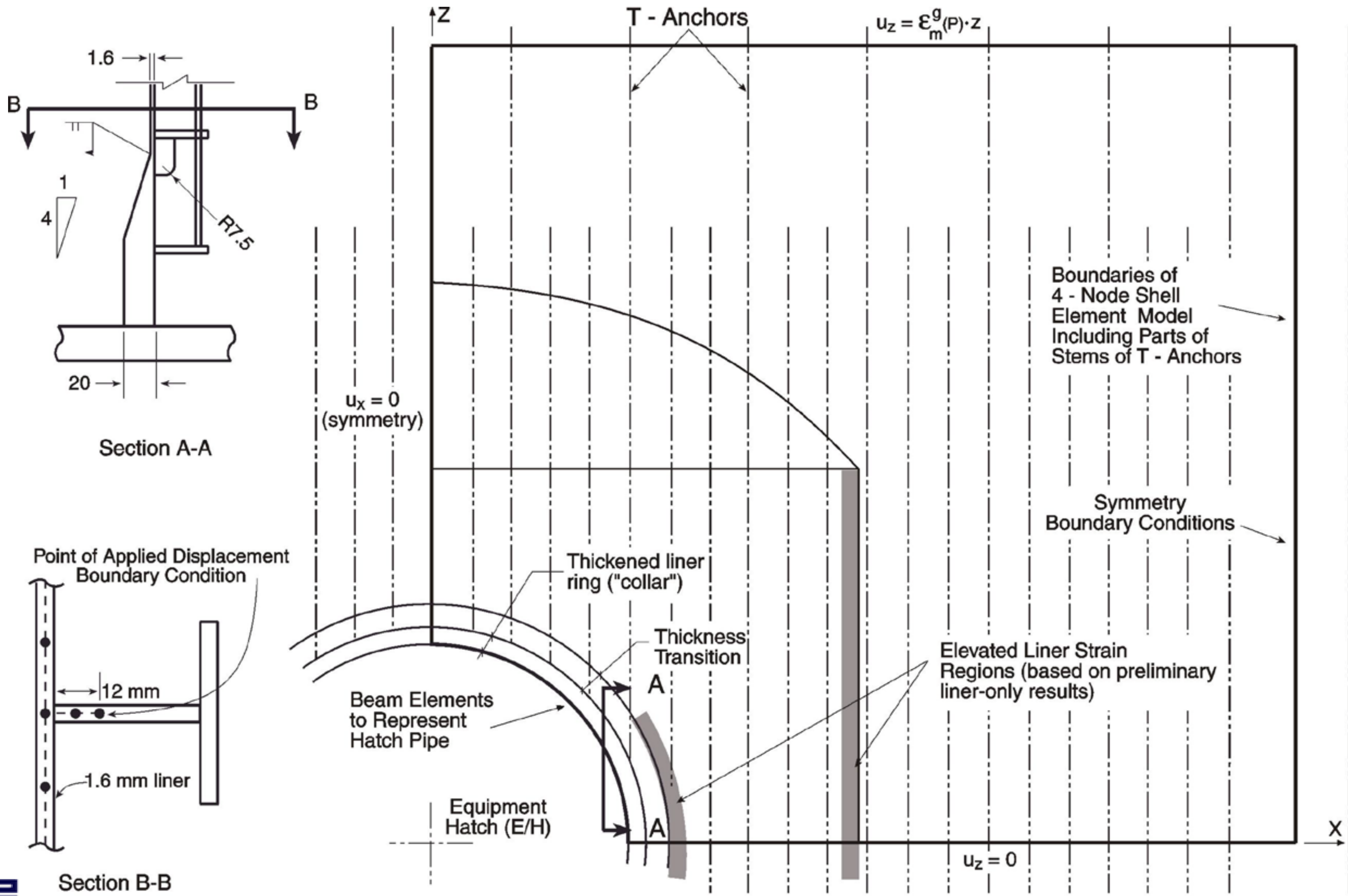
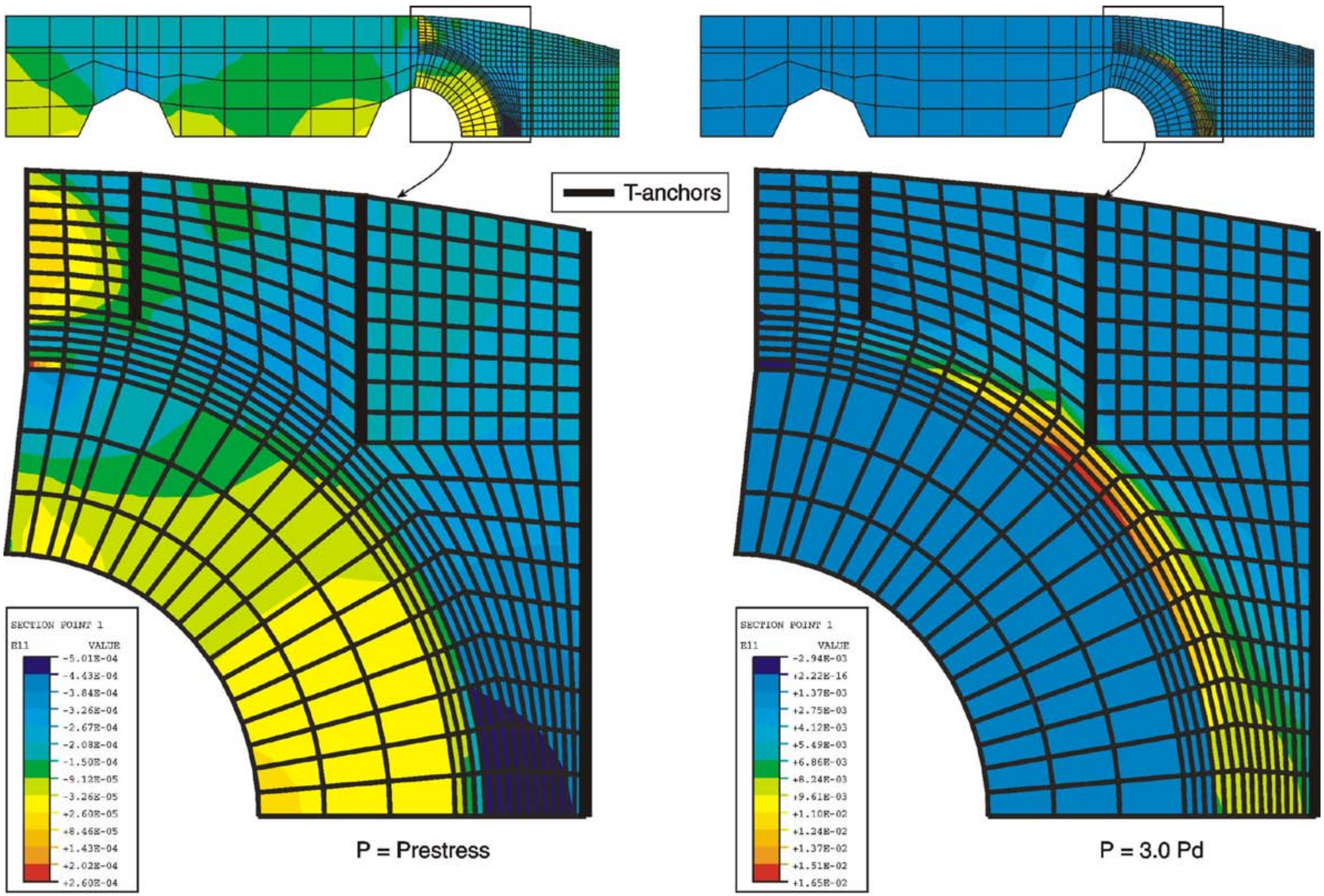
Equipment Hatch Liner Submodel



Liner Strain Concentrations predicted in M/S Penetration Model



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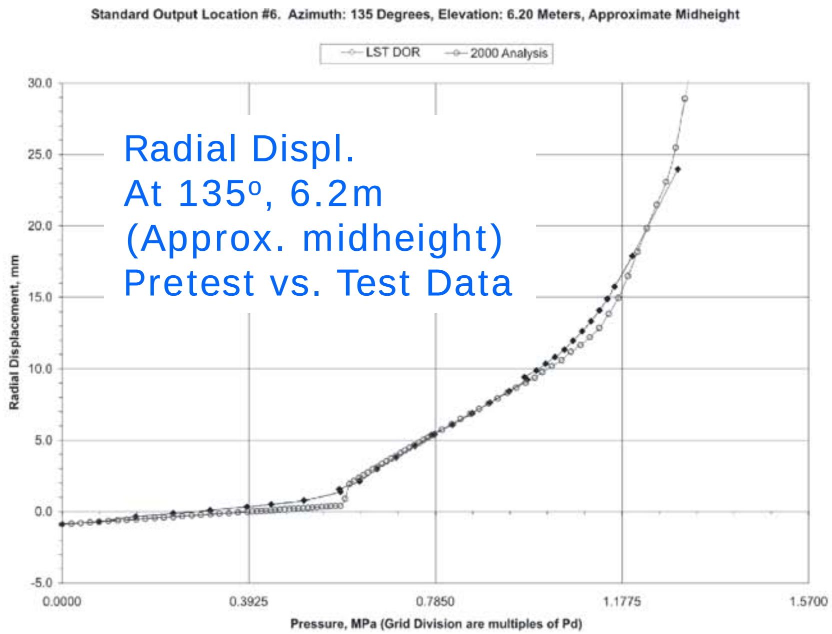
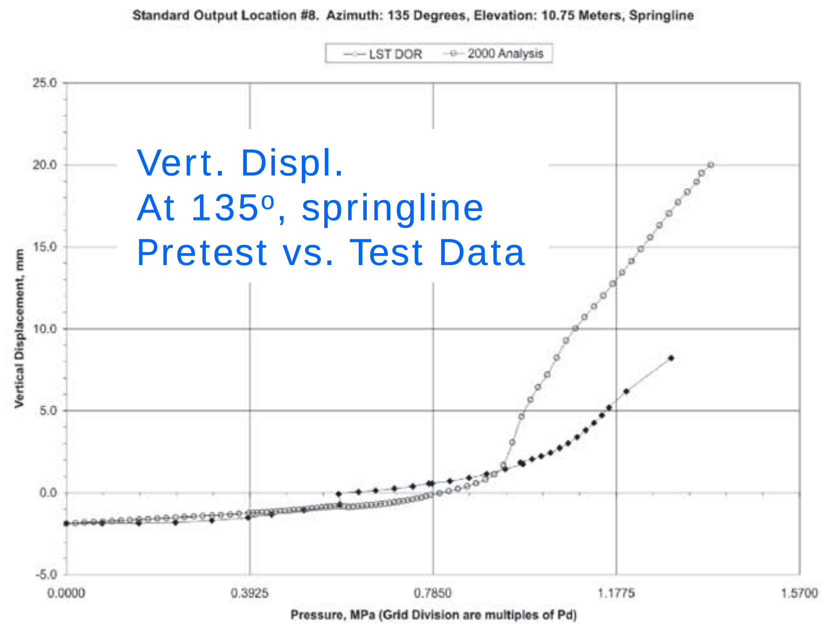
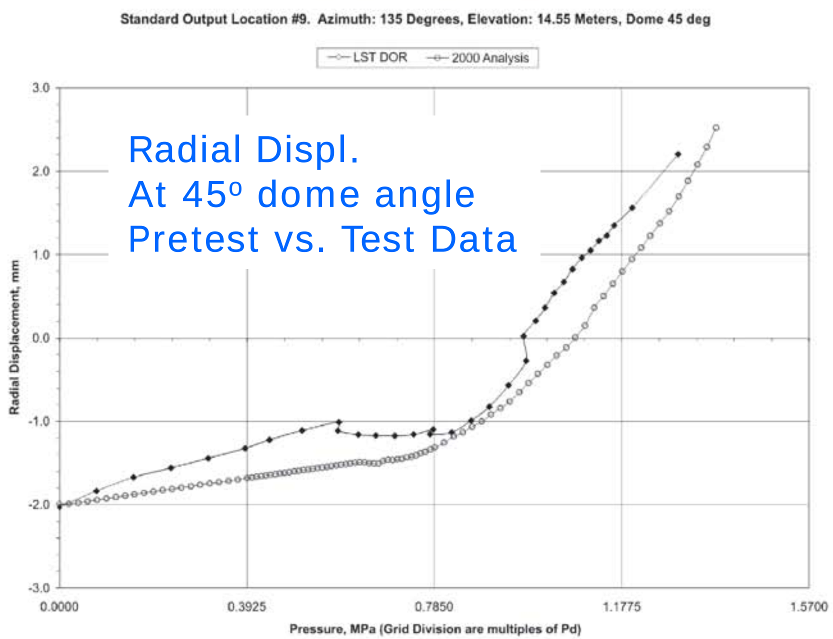
PRETEST ANALYSIS OVERVIEW, CONT'D

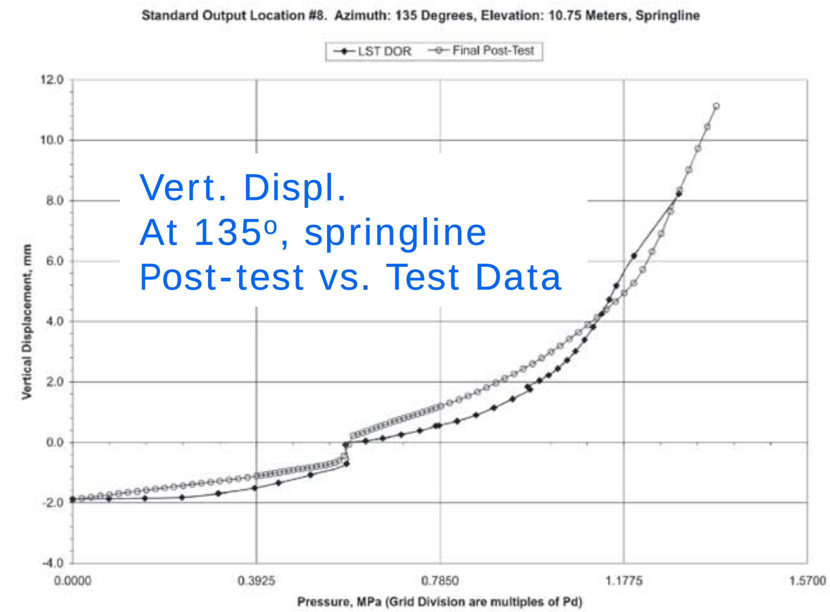
- **2 GLOBAL PRETEST ANALYSES**
  - **1999**
    - **Published in Round Robin Analysis Report**
    - **Used preliminary mat'l props. for concrete**
    - **No vertical tendon friction in cylinder**
    - **Somewhat higher tendon prestress**
  - **2000**
    - **Performed just before LST**
    - **Revised concrete properties**
    - **Vertical tendon friction in cylinder**
    - **Lower prestress (~6%) to account for creep**

- **RESULTS…**



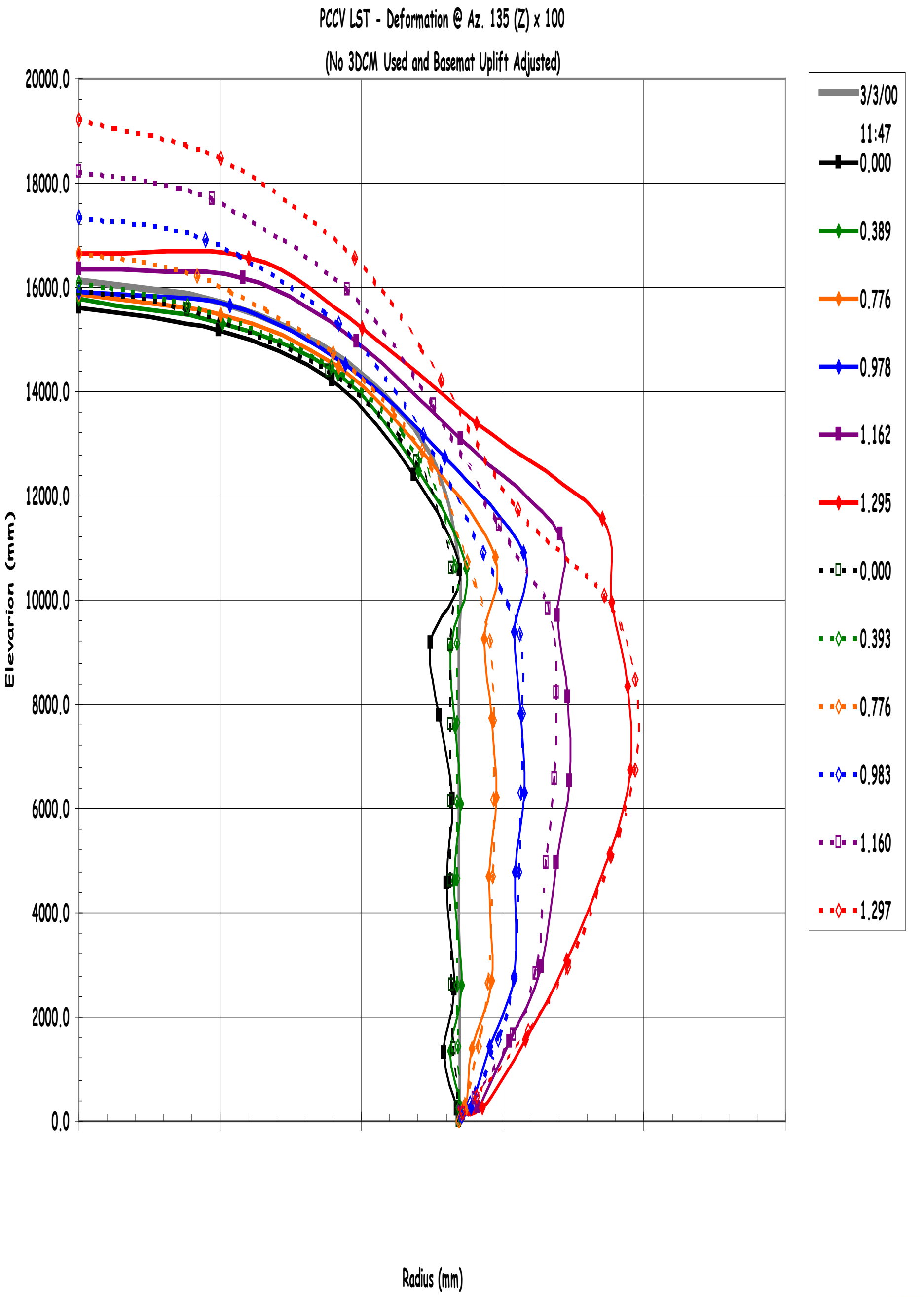






Comparisons of Pretest and Post-test Axisymm. Analysis to Test Data

Radial & Vertical Displ. Mapping Comparison



Test Data

Pre-test Analysis

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Pretest Analysis Summary, cont'd

- **FINAL "FAILURE" LOCATION PREDICTIONS – Potential Liner Failure Locations quoted from Pretest Analysis Report:**

1. **Horizontal Stiffener Splices Straddling Vertical Liner Seams: These occur at dozens of locations and can be a straight connection or at an angle/re-entrant corner. The sudden gap in the hoop stiffener at the "rat-hole" needed for welding electrode access tends to cause a strain riser near the liner seam weld zone, which is already somewhat less ductile than virgin liner material.**

2. **Horizontal Stiffener Termination on the 1.6 mm Liner Near Thickened Insert Plate. "Double" concentration caused by hoop stiffener termination in a zone already subject to strain concentration due to adjacent material thickness change. These locations further exacerbated by presence of weld to insert plate and weld of stiffener to 1.6 mm liner.**

3. **Vertical T-Anchor Termination on the 1.6 mm Liner Near Thickened Insert Plate. Similar to # 2, except the vertical T-anchor is a stronger embedment (due to T-flange) than the hoop stiffener. But T-anchor does not carry hoop stress, which is additional strain concentration in #2.**

4. **Severe Acute Angle Weld Splices. These occur at the confluence of normal splicing of liner segments with the edge of a penetration, such as is shown for mainsteam penetrations or as occurs at corners of the embossed regions of the E/H and A/L.**

5. **Wall-Base Juncture Liner Connection Detail. Proximity to vertical T-anchor termination and to rigid basemat embedment cause strain concentration. The liner is not spliced here, so it retains its full ductility.**

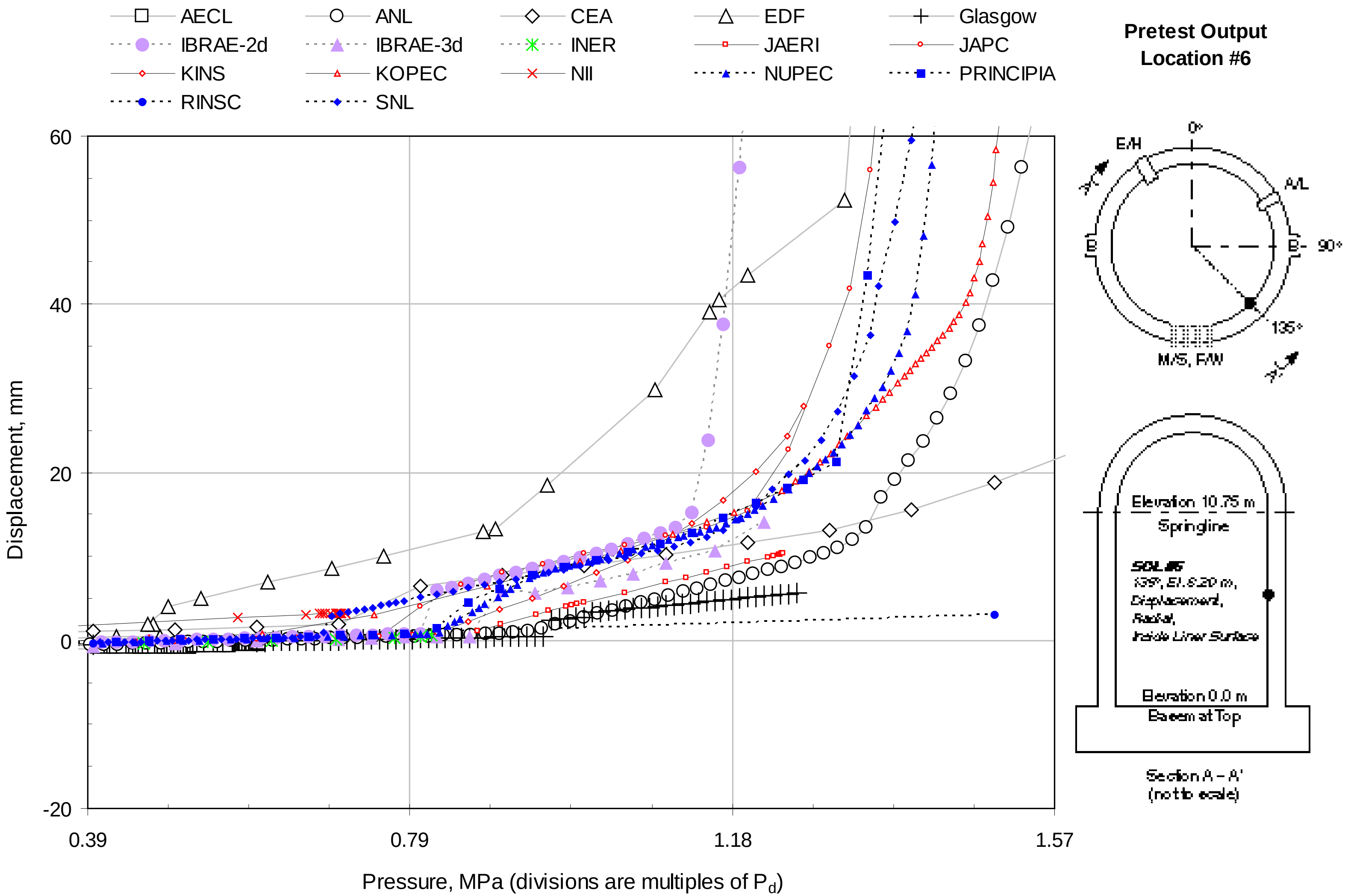
PCCV Pretest Round Robin Participants

- Argonne National Laboratory (ANL) (U.S.)
- Atomic Energy of Canada Limited (AECL) (Canada)
- Commisariat A L'Energie Atomique/Saclay/DRN (France)
- Electricite de France (EDF) (France)
- Institute of Nuclear Energy Research (INER) (Repub. of China)*
- Institut de Protection et de Sûreté Nucléaire (IPSN) (France)
- Japan Atomic Energy Research Institute (JAERI) (Japan)*
- Japan Atomic Power Company / PWR Utility Research Group (Japan)
- Korea Institute of Nuclear Safety (KINS) (Repub. of Korea)
- Korea Power Engineering Company (KOPEC)
- Nuclear Installations Inspectorate (U.K.)
- Nuclear Power Engineering Corporation (NUPEC) (Japan)
- Nuclear Safety Institute (IBRAE) (Russia)*
- PRINCIPIA-EQE SA (Spain)
- Research and Development Institute of Power Engineering (Russia)
- Sandia National Laboratories (SNL)/ANATECH (U.S.)
- University of Glasgow (U.K.)

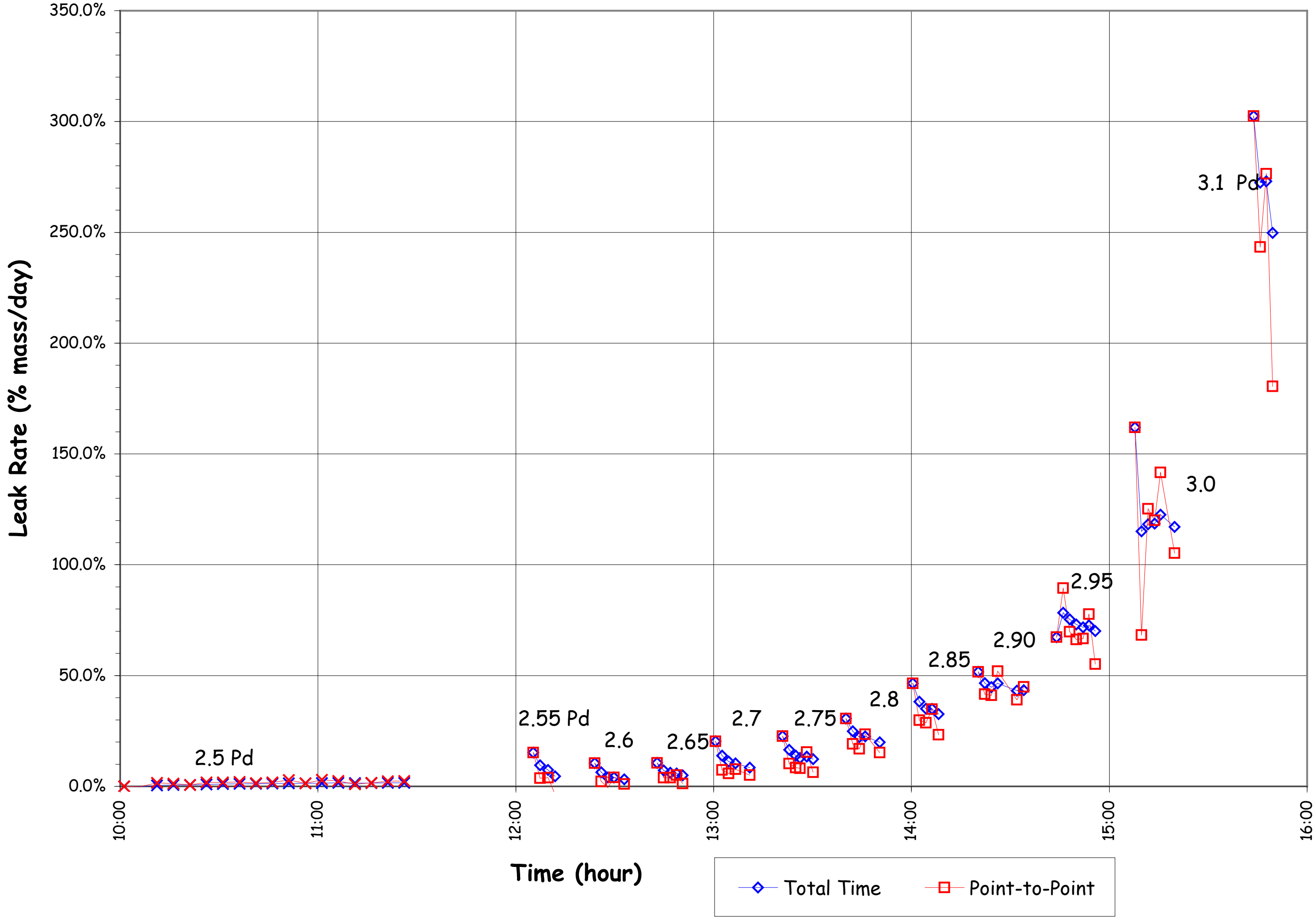
Summary of Pretest Round Robin Predictions

Participant	Cracking		Liner Yield	Hoop Tendon Stress		Pressure @ Failure	Free Field Hoop Strain	Mode
	Hoop	Meridonal		Yield	2%			
ANL	0.68	0.64	1.00	1.23	1.53	1.51 1.62	1.69% 3.31%	local liner tear (Elev. 6.4 m) mid-height hoop tendon failure at Elev. 6.4 m
AECL (3D) **(Axi)**	0.97 0.87	0.85 0.78	— 1.06	— —	— —	0.94 1.24		complete cracking axisymmetric yield
CEA	0.70	0.50				1.60 1.70		numerically unstable
EDF	0.47	0.86		1.30	1.38	1.95		
INER	0.69					0.81		
JAERI	0.92	0.74	1.20				1.24%	buckling at dome portion or local fracture by bending in cylinder portion
JAPC	0.60	0.65	0.96	1.15	1.37	1.45 1.55		Rupture of structural elements (tendon, rebar or liner) placed in the hoop direction at a wall height of about El. 7m.
KINS	0.39	0.62			1.33	1.25 1.44		tendon rupture
KOPEC (2D) **(3D)**	0.64 0.61		1.01 0.94	1.03 1.41	1.36	1.30 1.51		 tendon @ 3.55%
HSE/NNC	0.57	0.57		1.60	1.75	1.98	3%	Liner tear with extensive concrete cracking at buttress region.
NUPEC	0.82	0.59	1.02		1.49	1.49 1.57	 3%	 Tendon rupture
IBRAE	0.70	0.78	1.15	1.01	1.21	1.26		Tendon Rupture
Principia	0.56	0.92		1.30		1.30		tendon yielding
RINSC		1.00				1.50		hoop failure of vessel
ANATECH (SNL)	0.59	0.57			1.27	1.18 1.25 1.40 1.42	 2%	local liner strain (lower bound) 16% liner strain @ E/H-best guess tendon rupture 2% global strain (upper bound)
U. Glasgow	0.95		1.00 1.10					

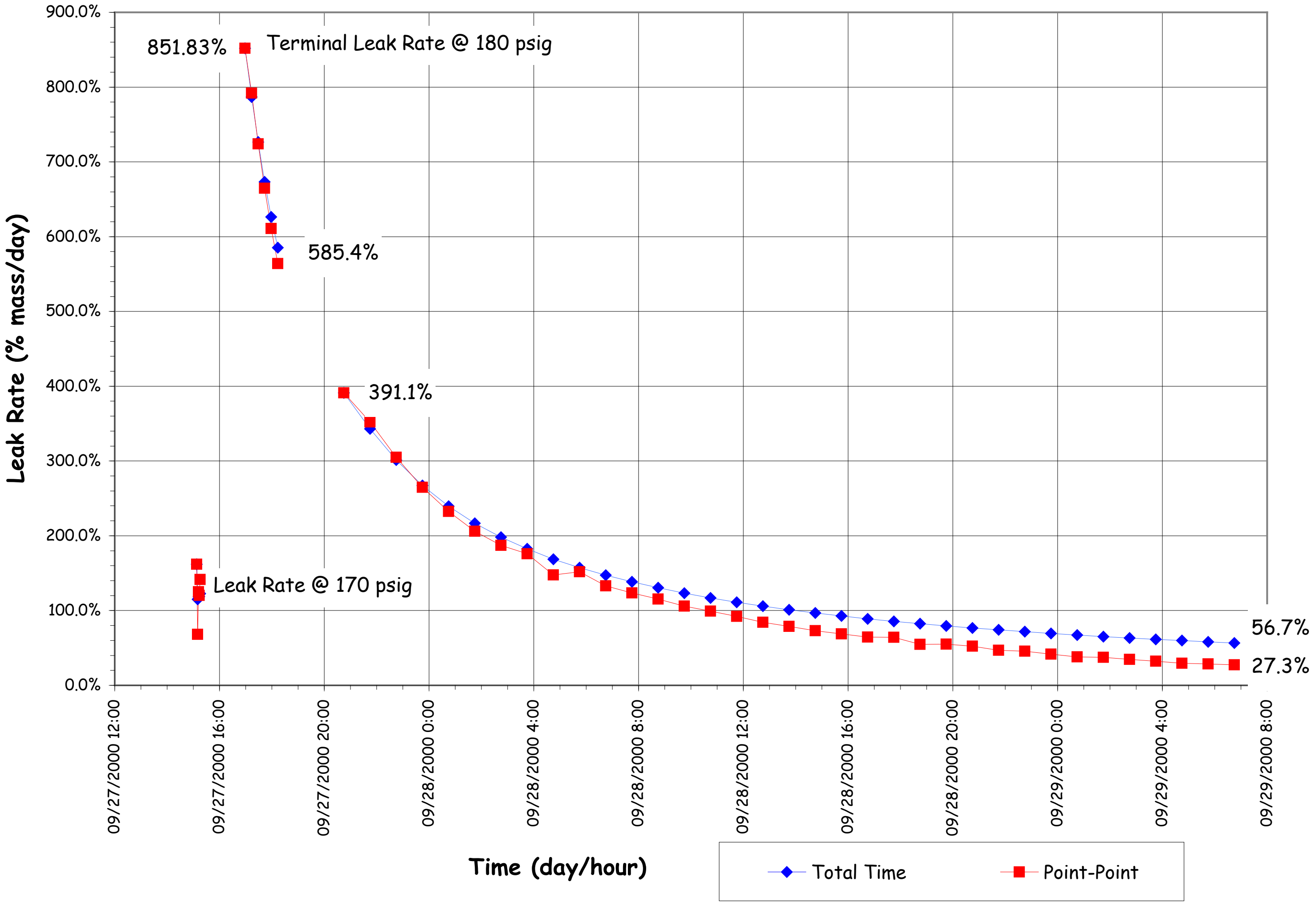
Pretest Round Robin Predictions
Radial Displacement at Cylinder Mid-height



PCCV LST - Estimated Leak Rates (2.5-3.1 Pd)



PCCV LST - Calculated Leak Rate



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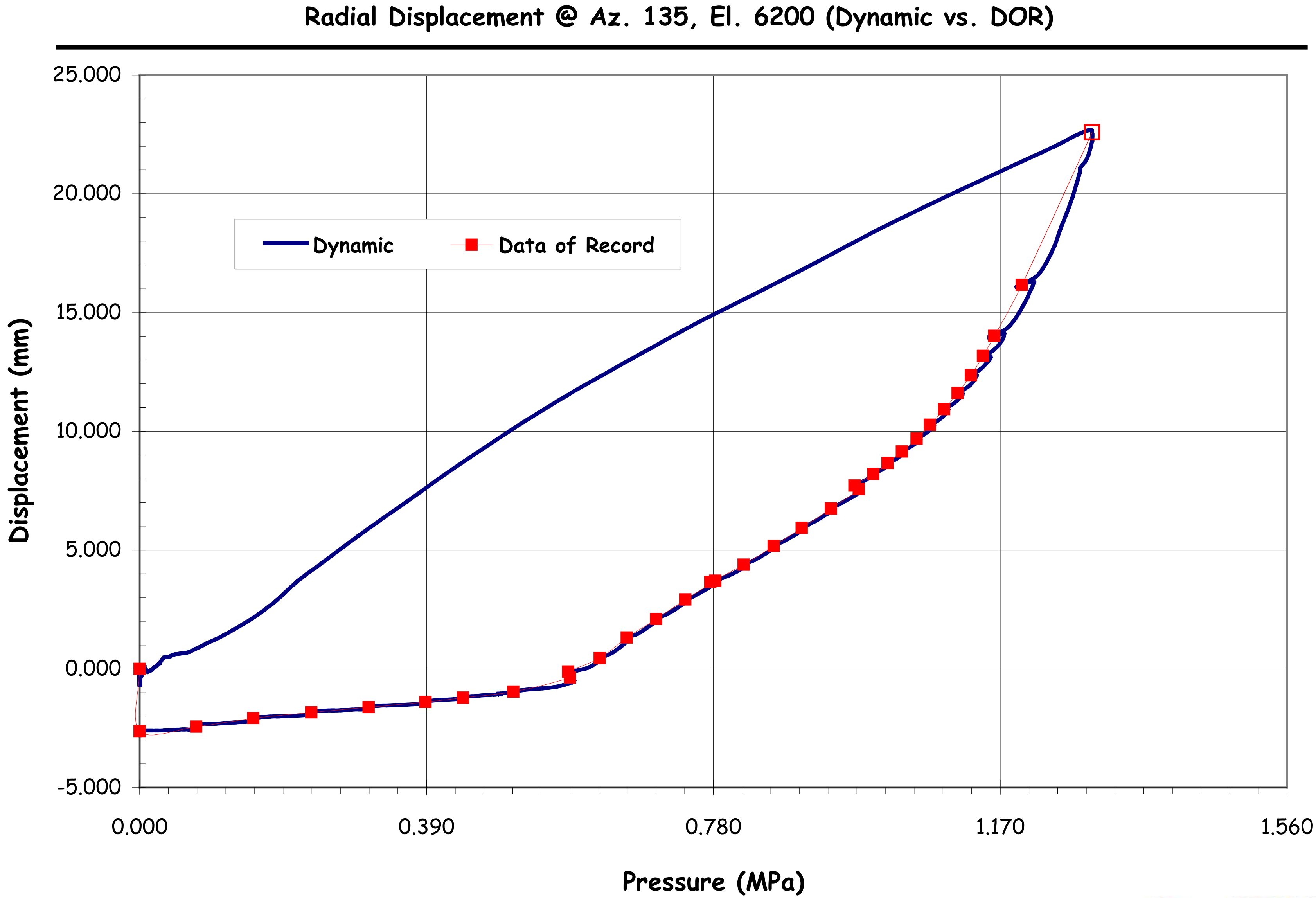
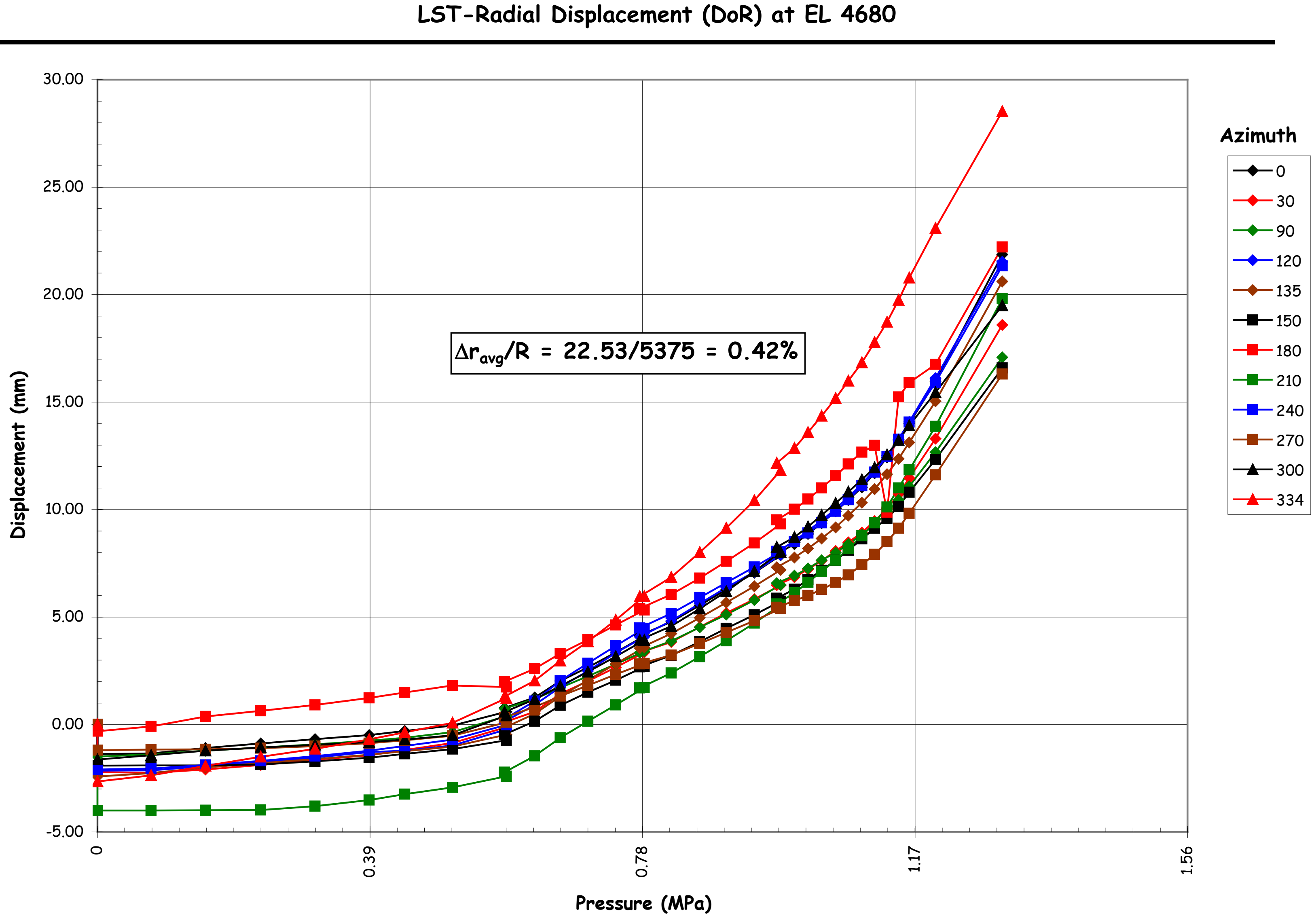
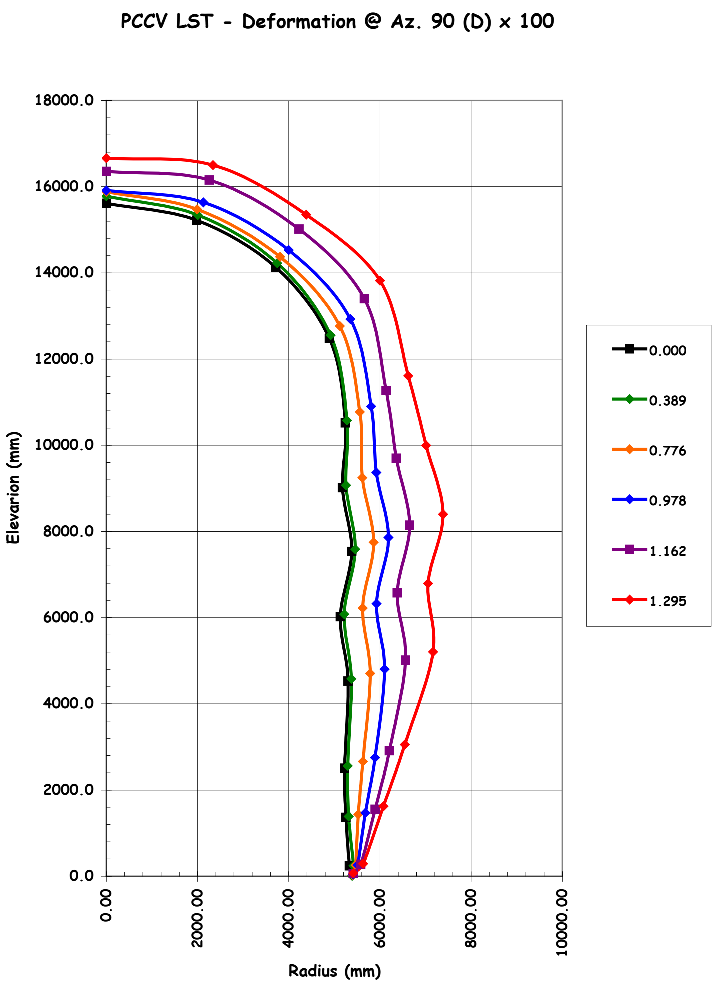
Radial Displacement @ Cylinder Mid-height

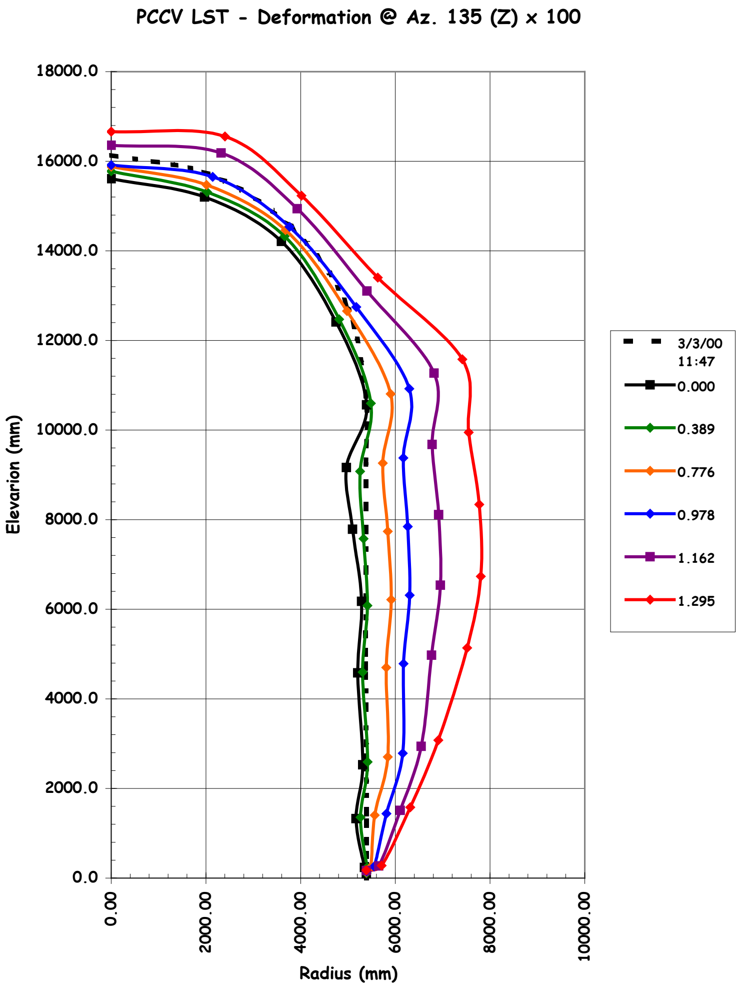


Radial Displacement @ Cylinder Mid-height

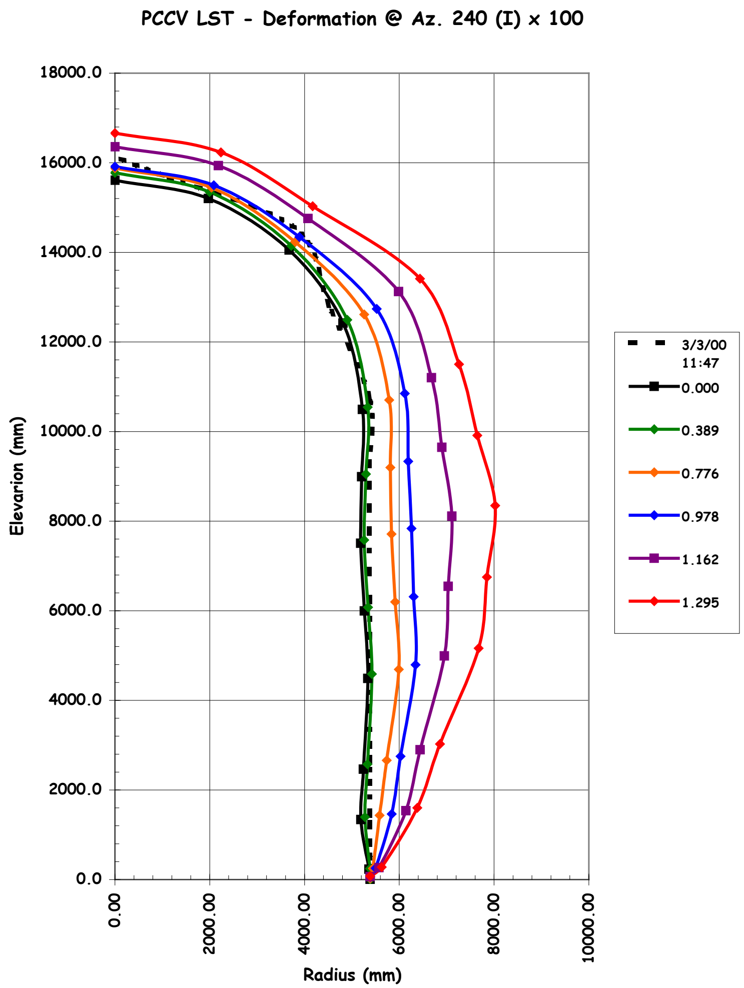


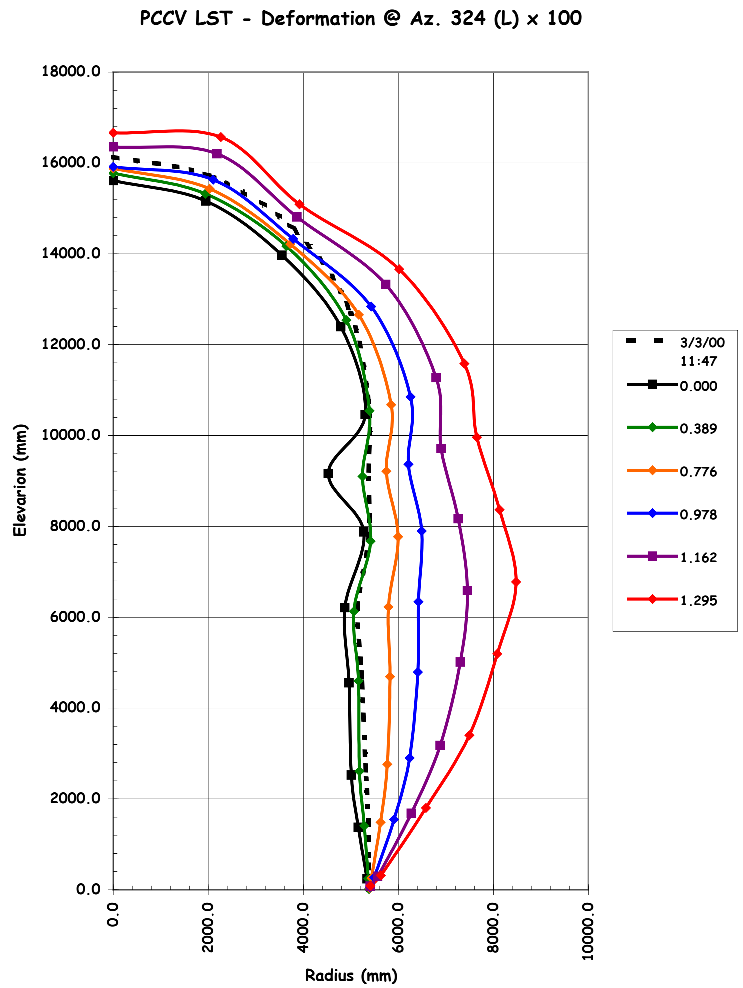
Displacement Profiles



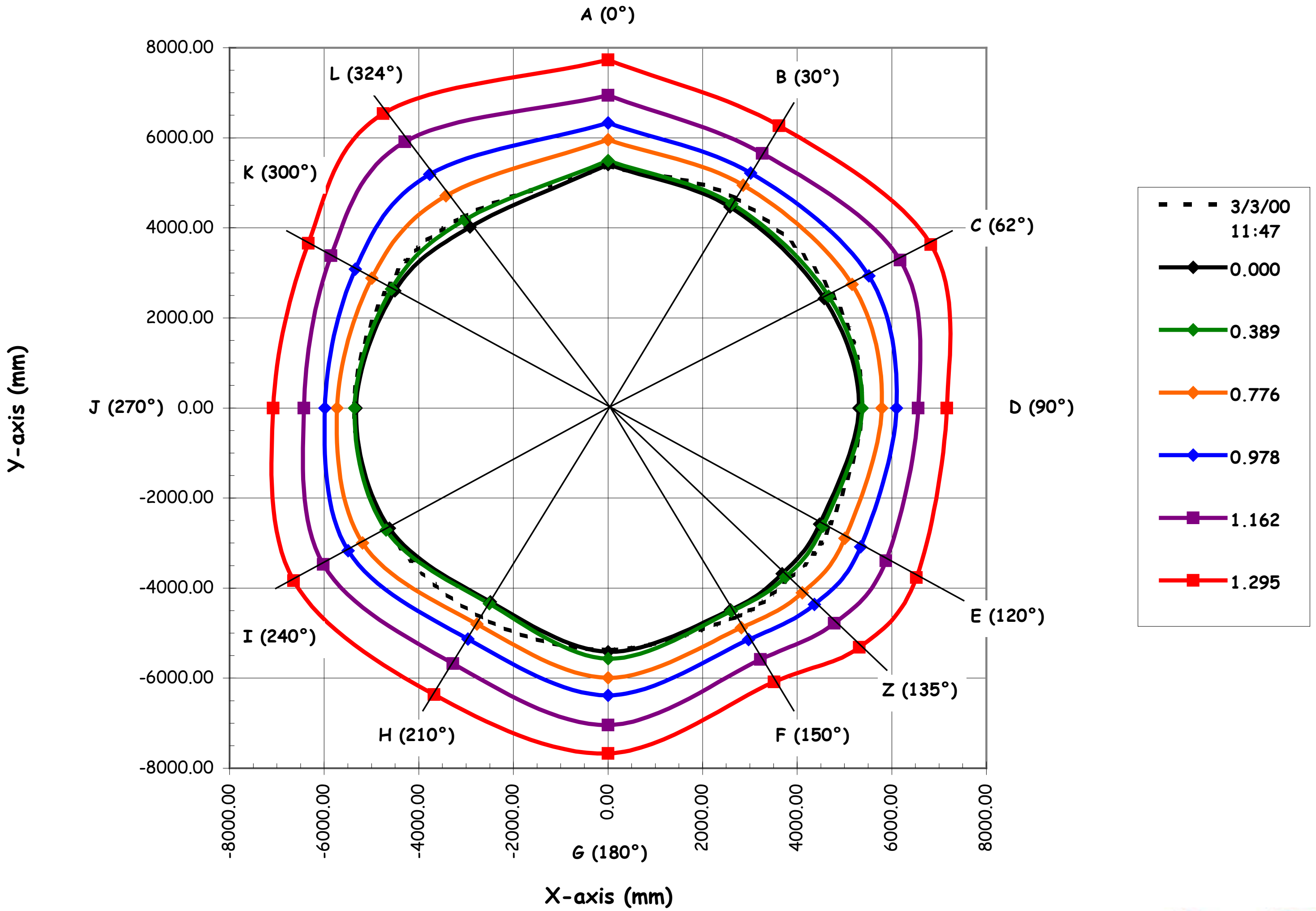


Displacement Profiles





PCCV LST - Deformation @ El 4680 (5) x100



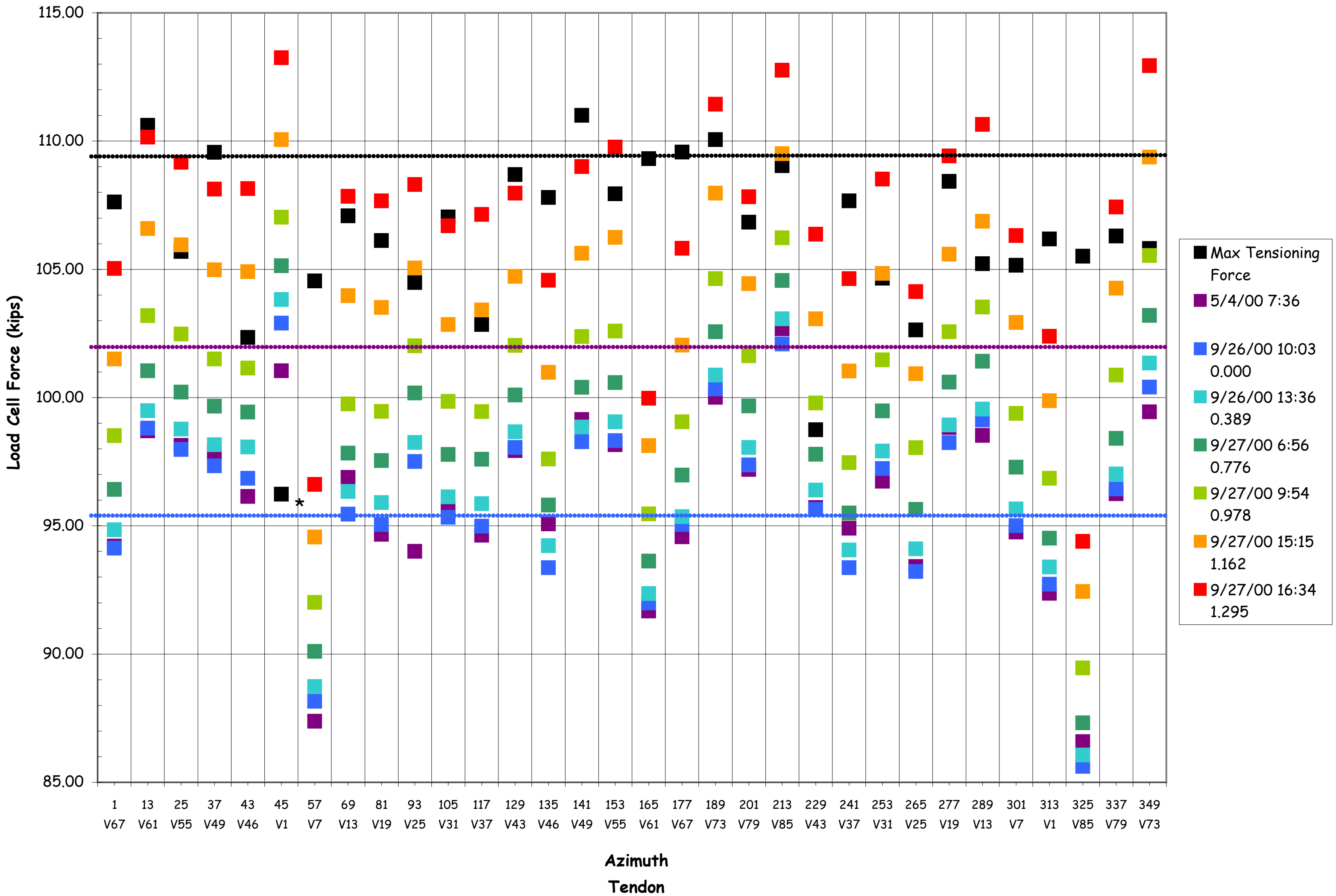
Liner Strains - Summary

• Maximum Free Field Hoop Strain	0.90%
• Maximum Free Field Meridional Strain	0.14%
• Maximum Free Field Meridional Liner Anchor Strain	0.10%
• Maximum Equipment Hatch Strain	3.88%
• Maximum Personnel Airlock Strain	0.75%
• Maximum Main Steam Penetration Strain	4.54%
• Maximum Feedwater Penetration Strain	6.39%
• Maximum Wall-Base Junction Strain	1.97%
• Maximum Miscellaneous Liner Detail Strain	5.75%

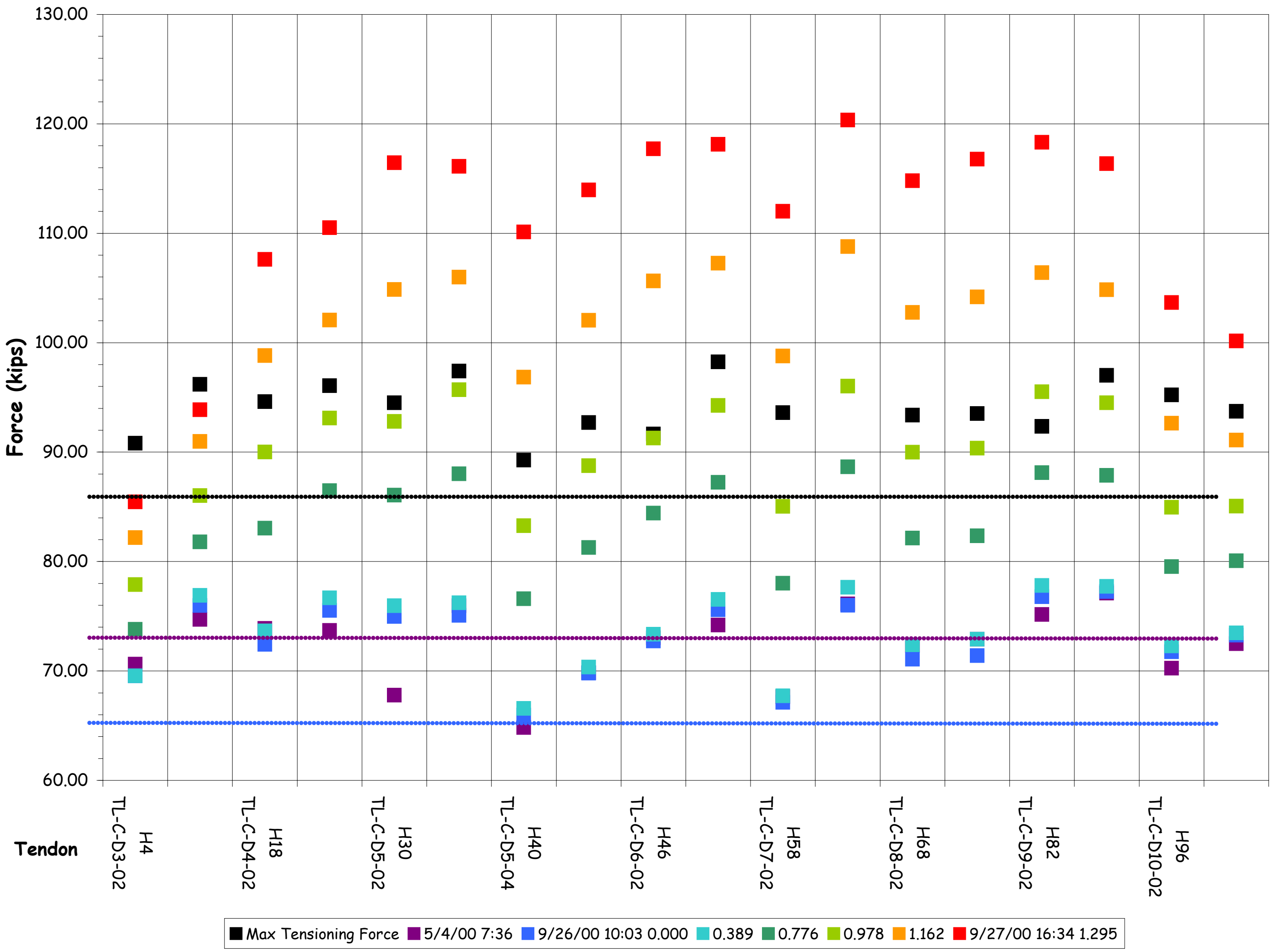
Rebar Strain Summary

- Maximum Free Field Hoop Rebar Strain 1.68%
- Maximum Free Field Meridonal Rebar Strain 0.47%
  - Initial Strain at start of LST = 5.85% *6.11%
  - Maximum Delta 0.27%
- Maximum Free Field Radial Rebar Strain 0.88%
- Maximum Basemat Rebar Strain 0.84%
- Maximum Rebar Strain @ E/H 1.62%
- Maximum Rebar Strain @ A/L 1.50%

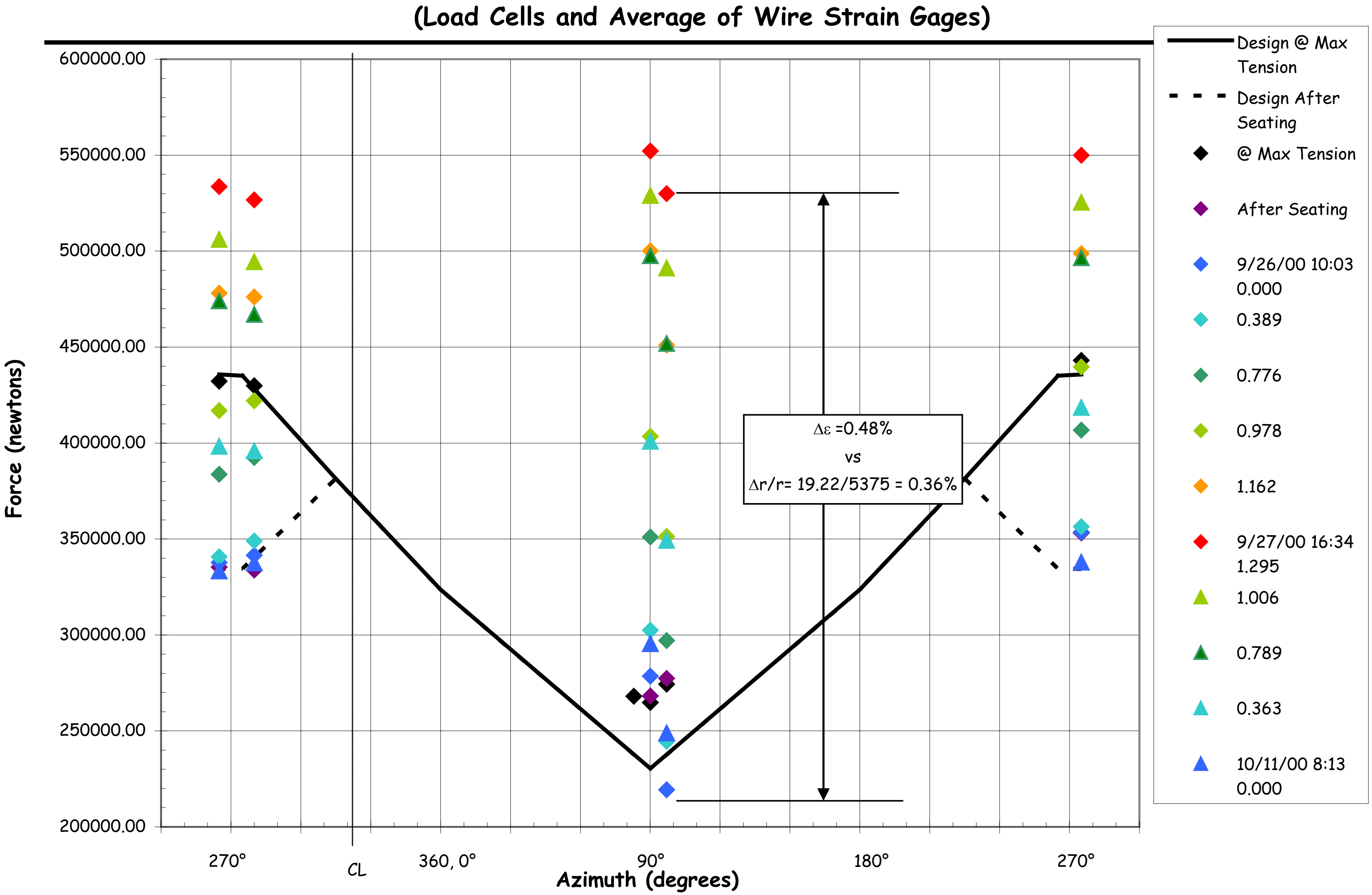
Vertical Tendon Anchors



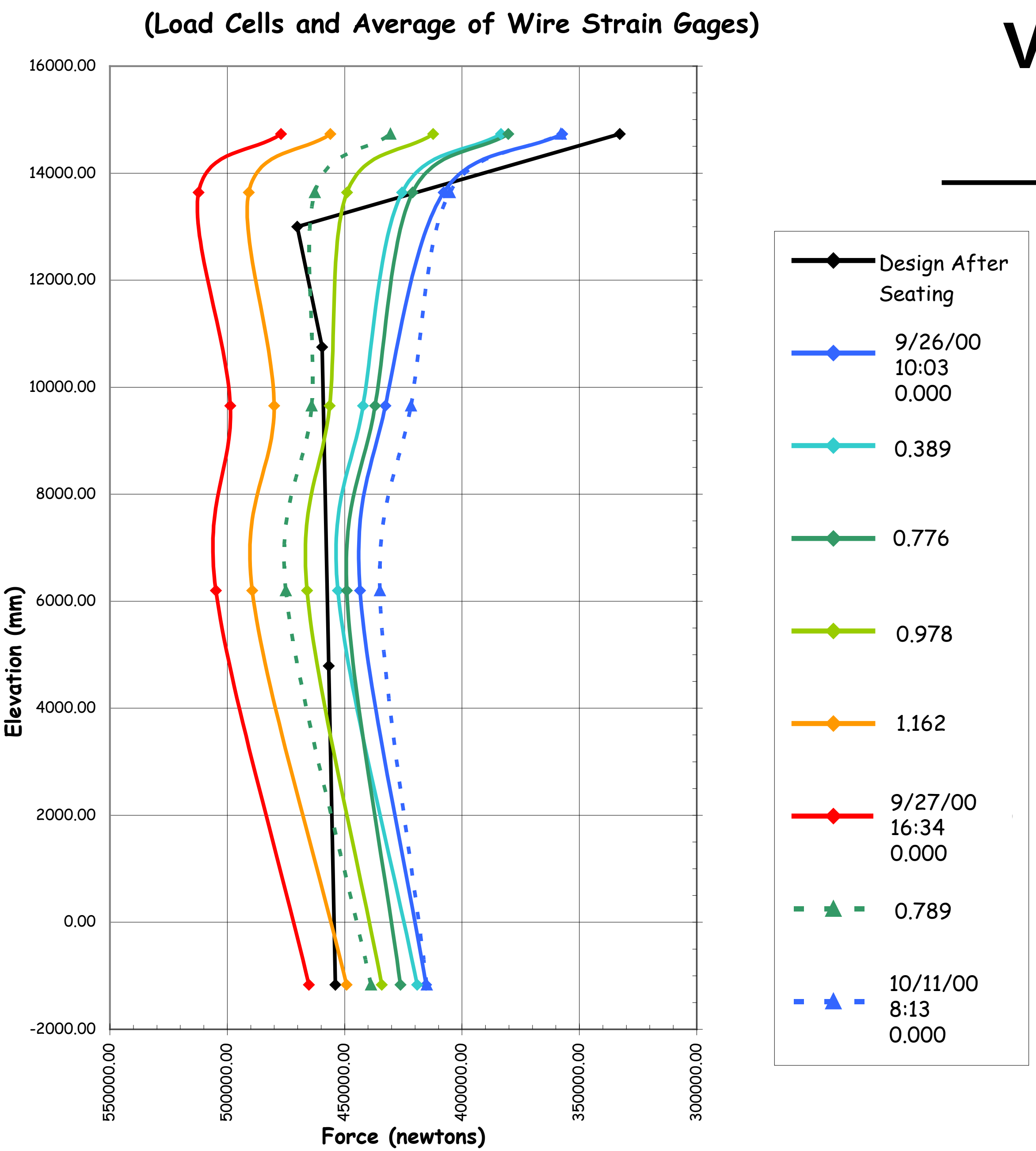
Horizontal Tendon Anchors @ 90°

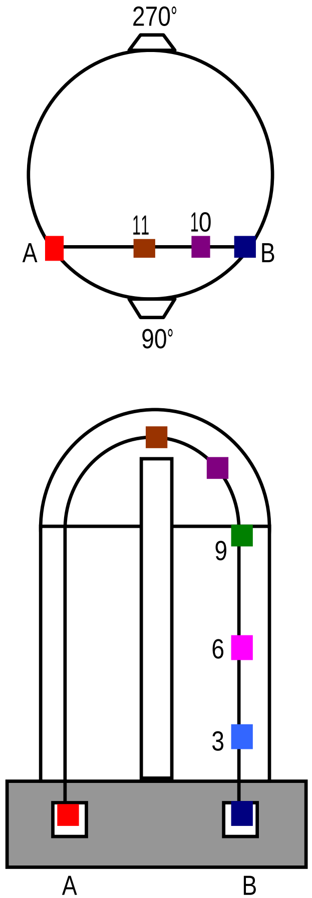


Hoop Tendon (H53) @ Cylinder Mid-height



Vertical Tendon (V46)

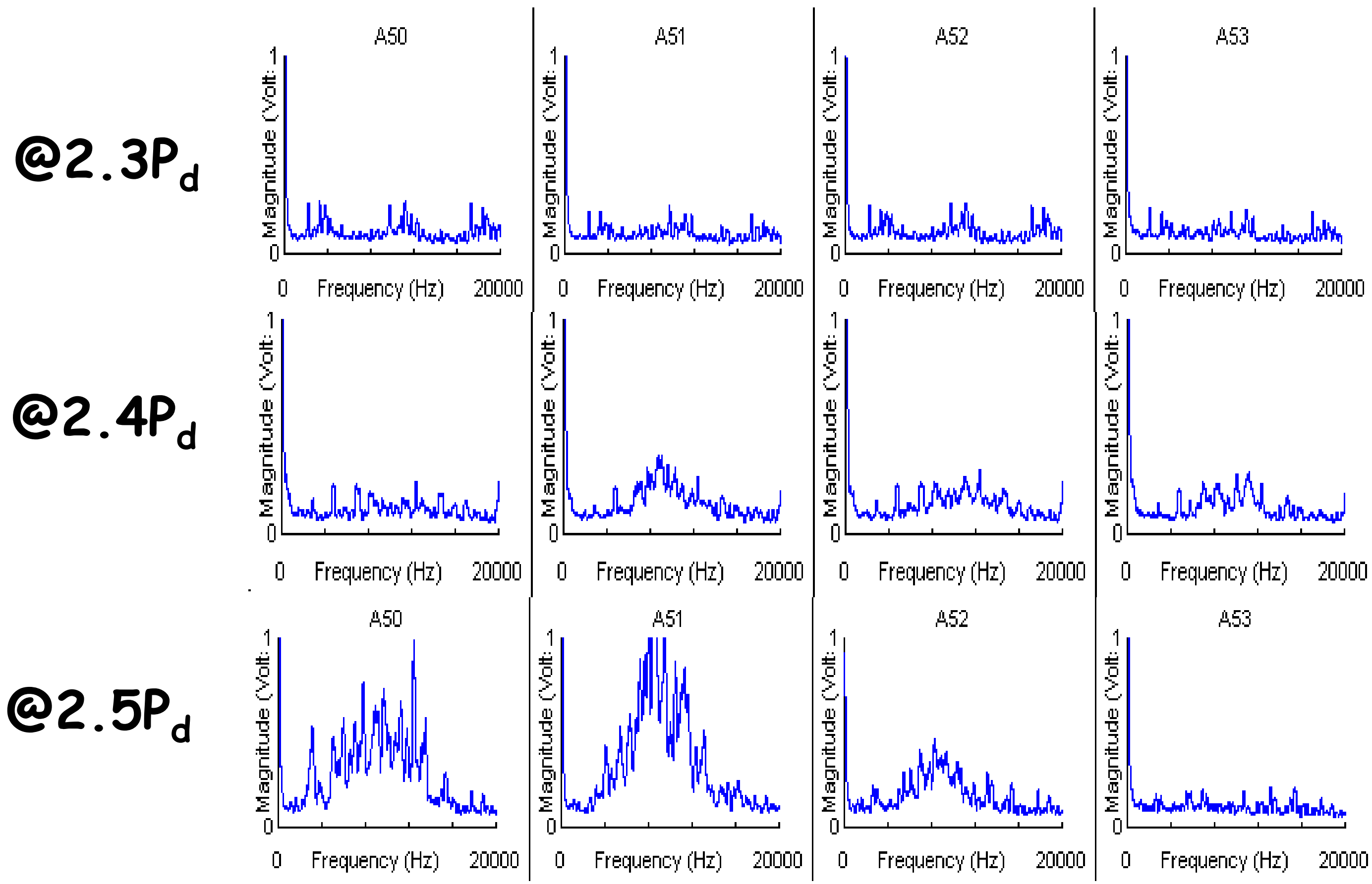




Acoustic System Response

- **Acoustic System Goals:**
  - **Tendon/Wire Failure**
  - **Concrete Crack Development and Location**
  - **Kaiser Effect Cracking**
  - **Leak Development and Location**
- **Acoustic System:**
  - **Soundprint® by Pure Technologies, Ltd.**
- **Acoustic System Results:**
  - **No Tendon Failures were detected**
  - **Concrete Cracking was detected and sources located as the test progressed**
  - **Kaiser Effect cracking rates changed as pressure increased**
  - **First Leak was detected at 2.4 Pd**

Acoustic Sensors at E/H



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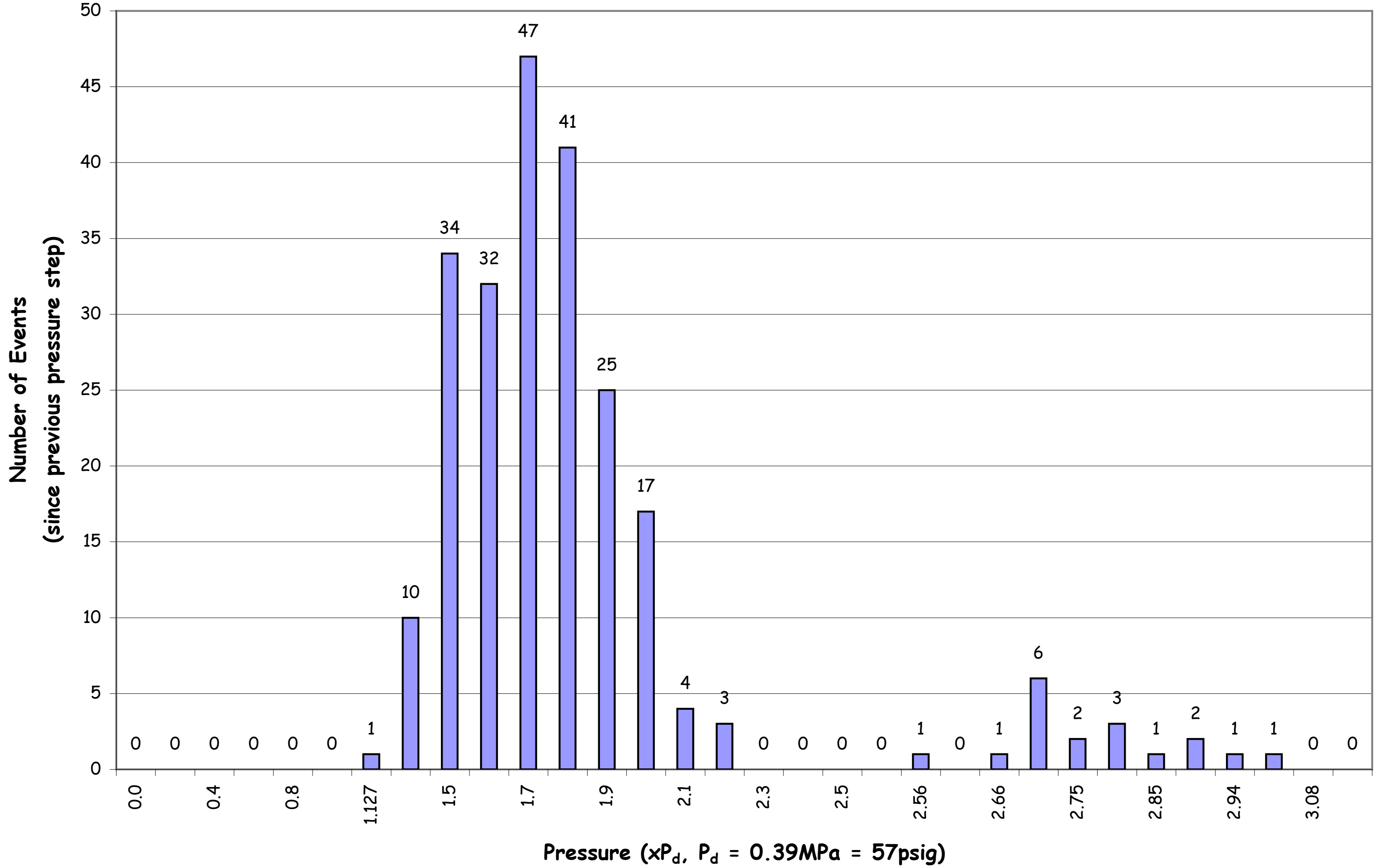
Acoustic Cracking Response

Limit State Test - Concrete Cracking/Crushing Events

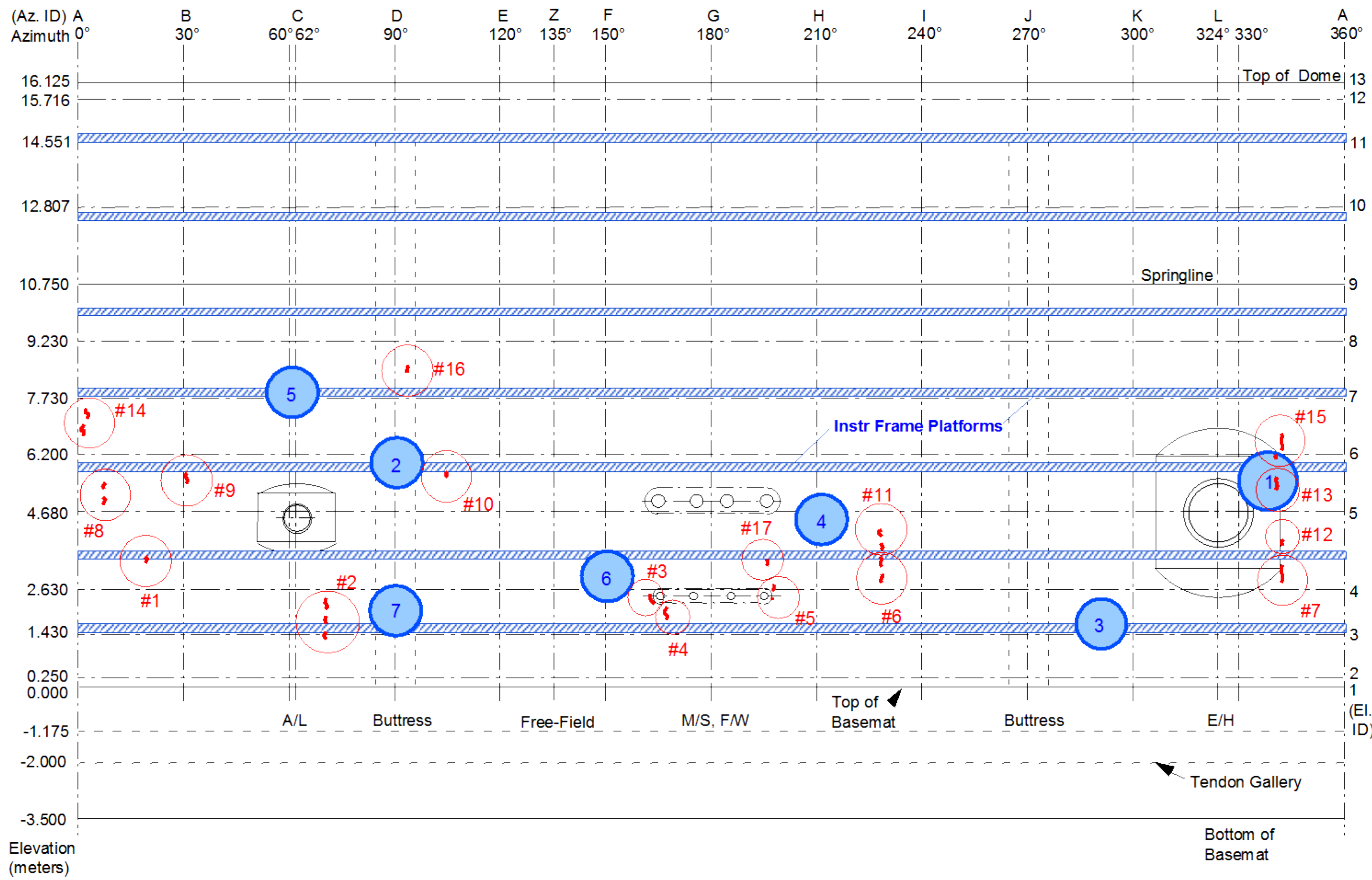


Posttest Inspection

- Liner Inspection
  - In-situ examination (photos/paint removal, thickness measurement, etc.)
  - Destructive examination in progress:
    - 25 specimens removed from the model
    - 18 specimens currently undergoing metallographic analysis.
    - Remaining specimens along with additional liner samples being shipped to NUPEC (MHI) for further testing/examination.
  - Preliminary Metallographic Analysis Results
- Crack Mapping and Photos
- Posttest Measurements
  - Residual Displacements around Equipment Hatch
  - Posttest Survey of Cardinal Coordinates will not be done
    - Of limited value and results perturbed by liner buckling.

Liner Tears and Acoustic Events

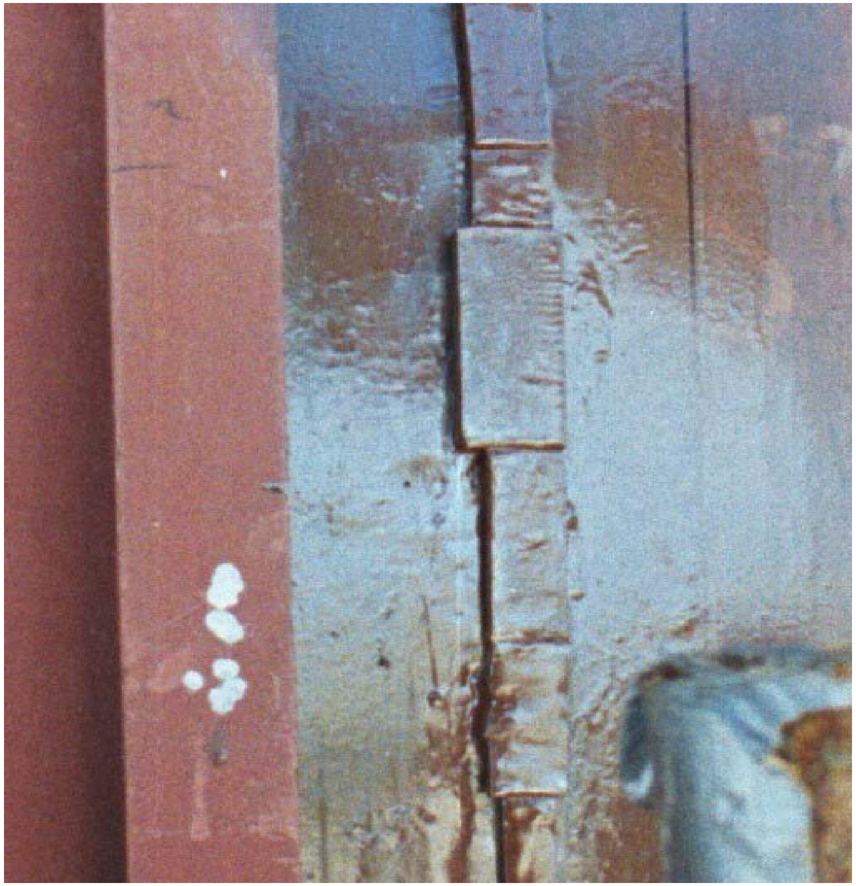
Acoustic Events:
1: 2.4 Pd 5: 2.8 Pd
2: 2.6 Pd 6: 2.8 Pd
3: 2.7Pd 7: 3.0 Pd
4: 2.8 Pd

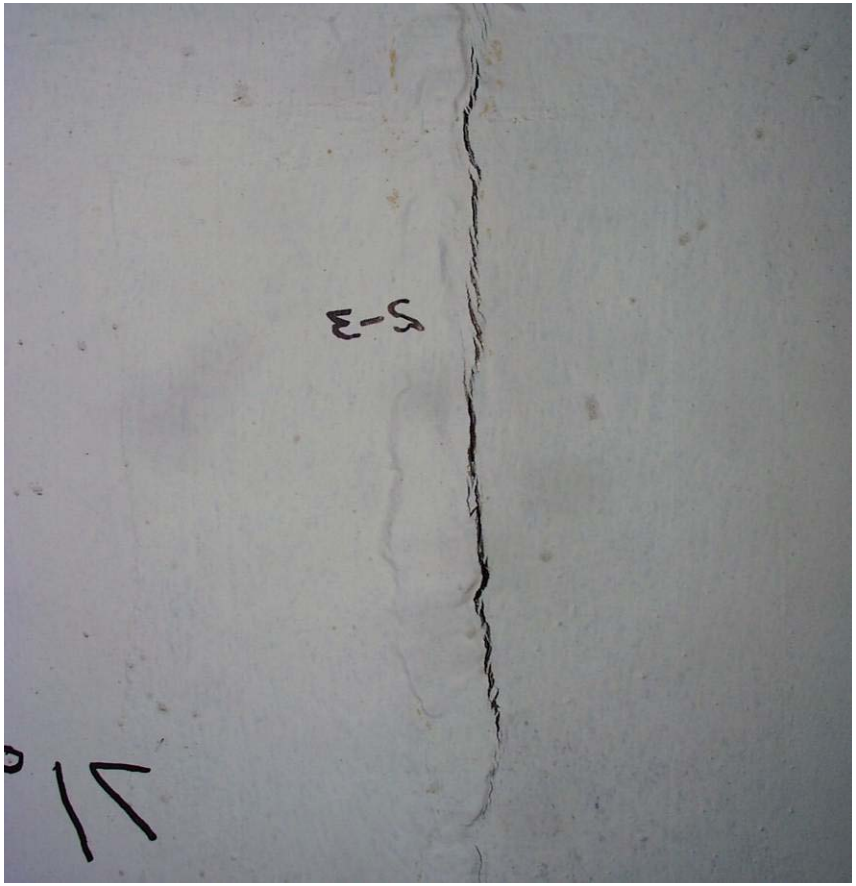


Liner Tear 7 @ E/H

Image reversed for comparison

Liner Tear 2-3 ~ Free-Field

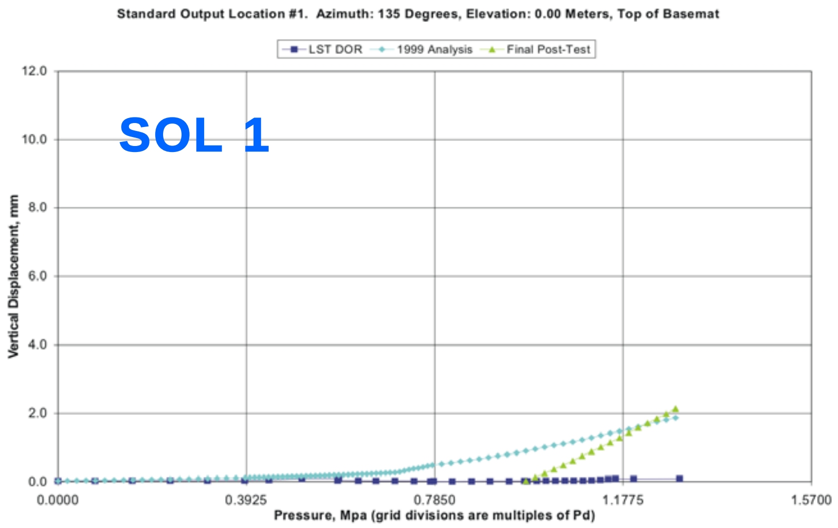


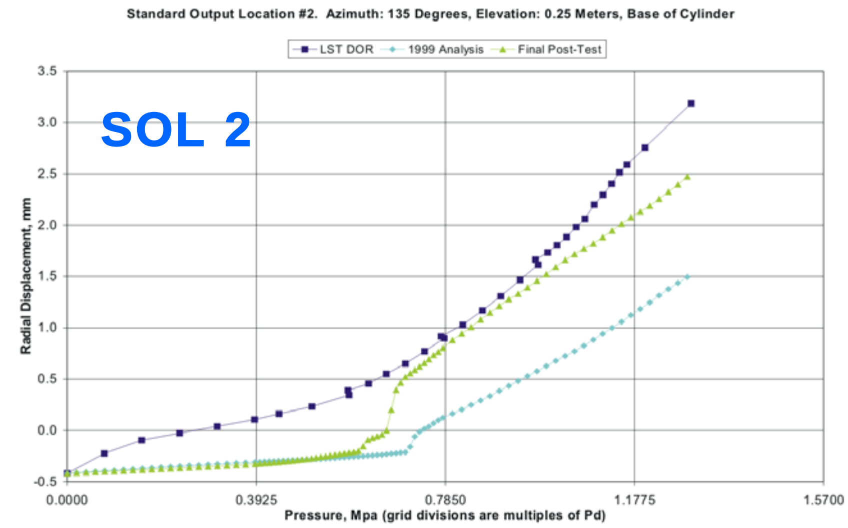


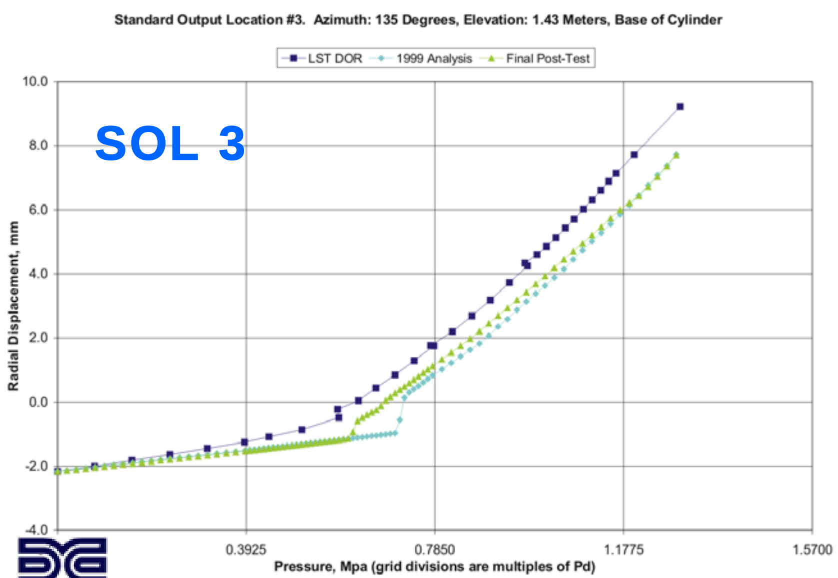
Predictions

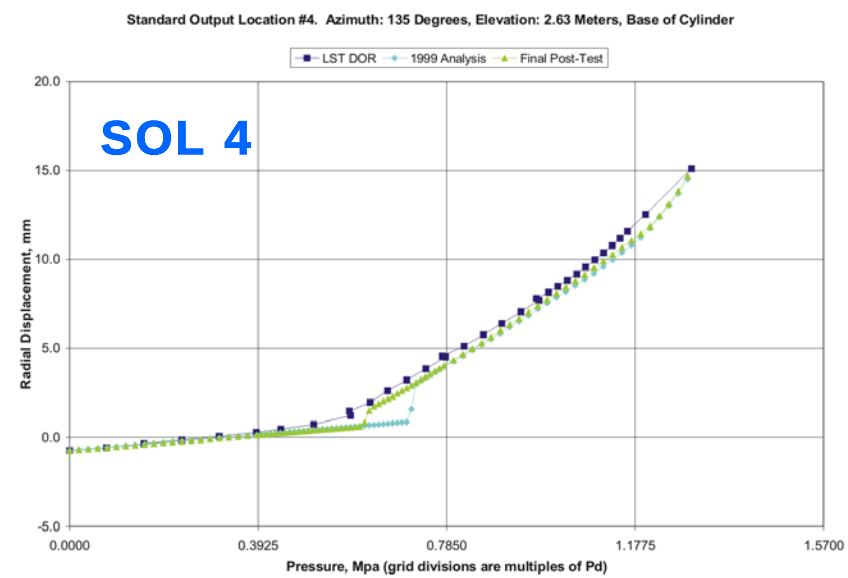
- **AXISYM. MODEL PREDICTED...**
  - **cylinder radial displacement within +/- 4%**
  - **shear and flexure behavior at wall-base**
  - **incorrect (too large) basemat uplift and dome vertical displacement**
- **3DCM MODEL PREDICTED...**
  - **non-axisymmetric distribution of radial displ.**
  - **largest radial displ. occurring at E/H**
  - **initial tendon stress distr. due to friction & anchor set**
  - **incorrect tendon stress distribution at large pressures**
  - **first tendon failure near E/H embossment at 3.5P_d**
- **LOCAL PENETR. & 3DCM MODELS PREDICTED FAILURES AT . . .**
  - **Weld seams adjacent to E/H (3.2 P_d predicted failure pressure)**
  - **Near E/H, M/S & F/W Penetrations**
  - **Weld seams with stiffener "RAT-HOLES" near buttresses**

Pretest and Post-test Analysis Comparisons with Test









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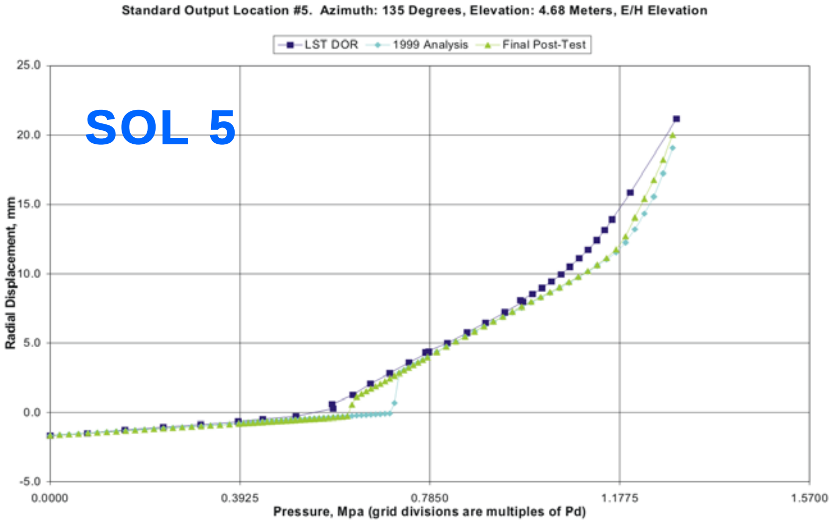
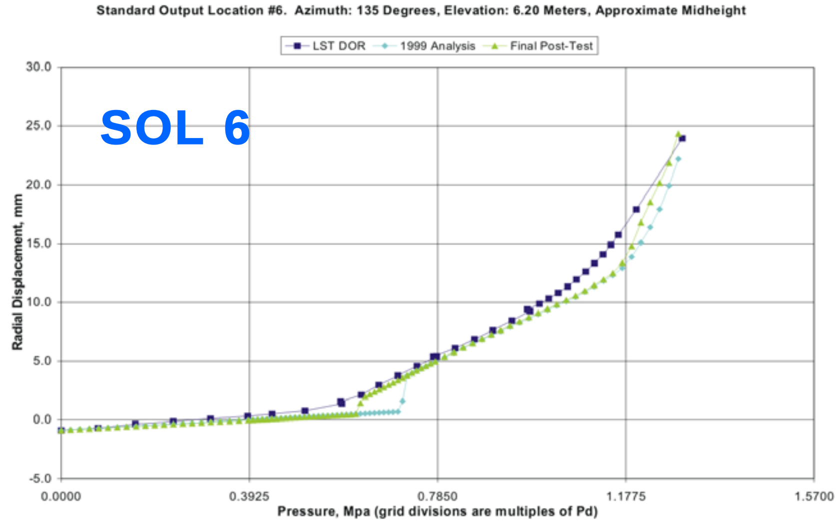
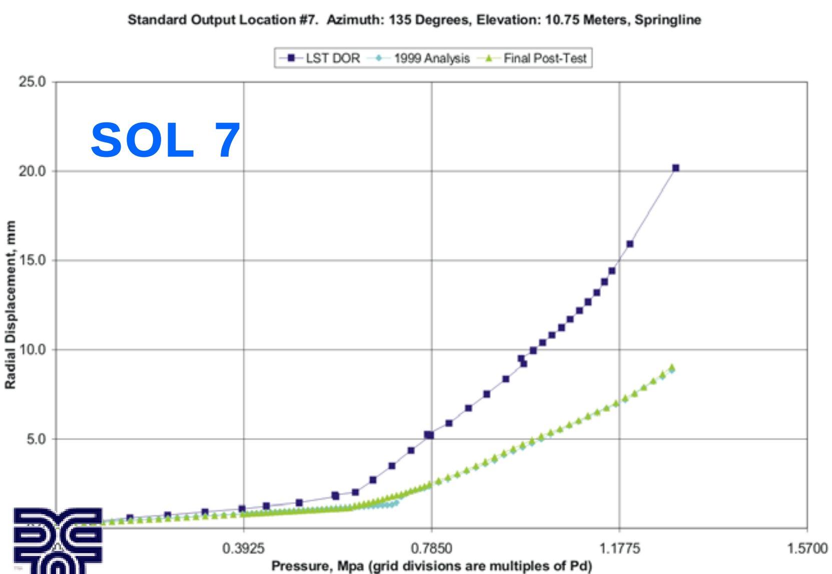
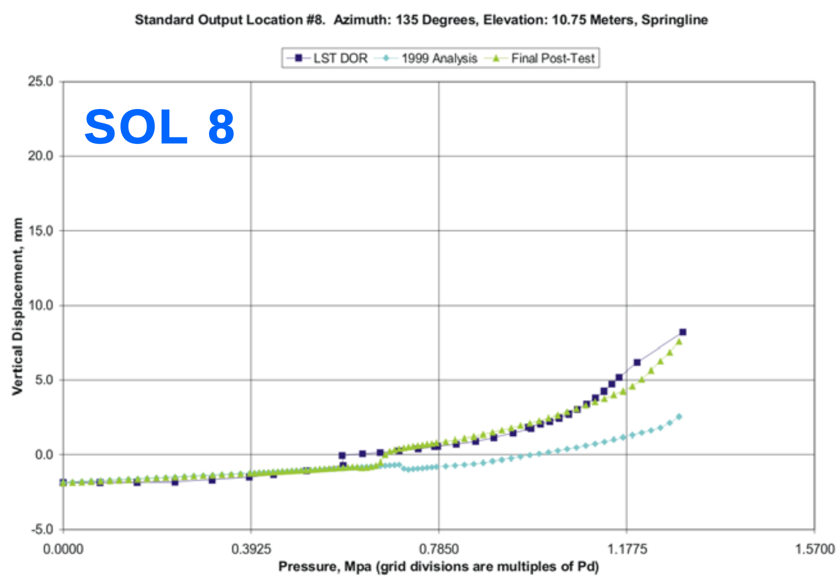
Pretest and Post-test Analysis Comparisons with Test









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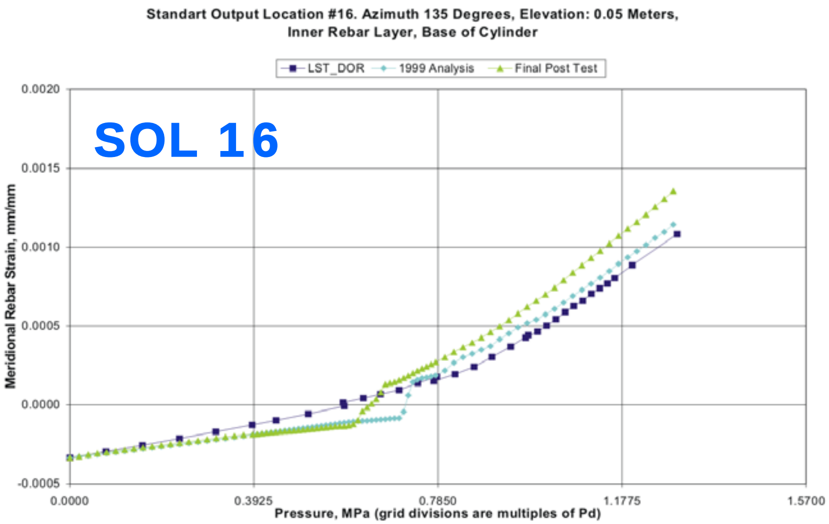
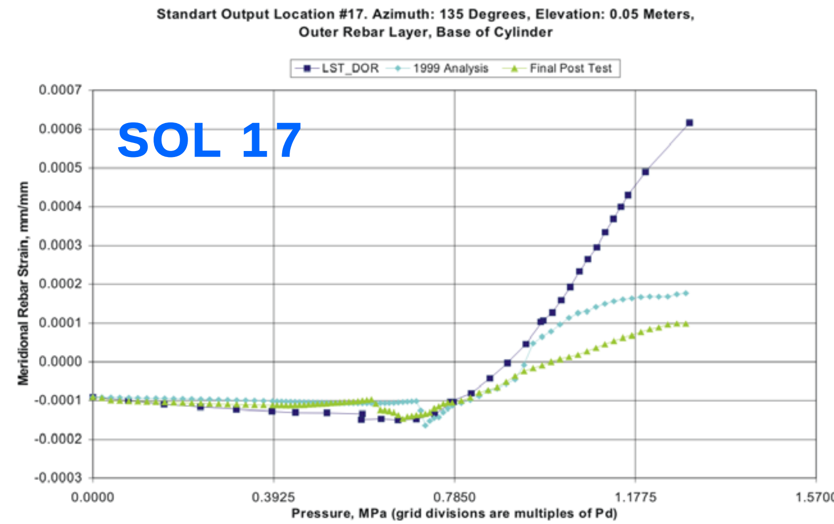
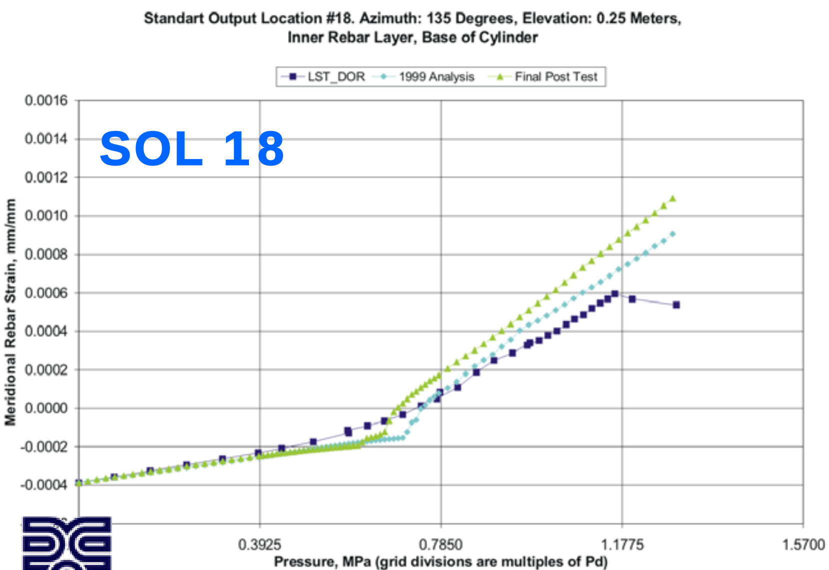
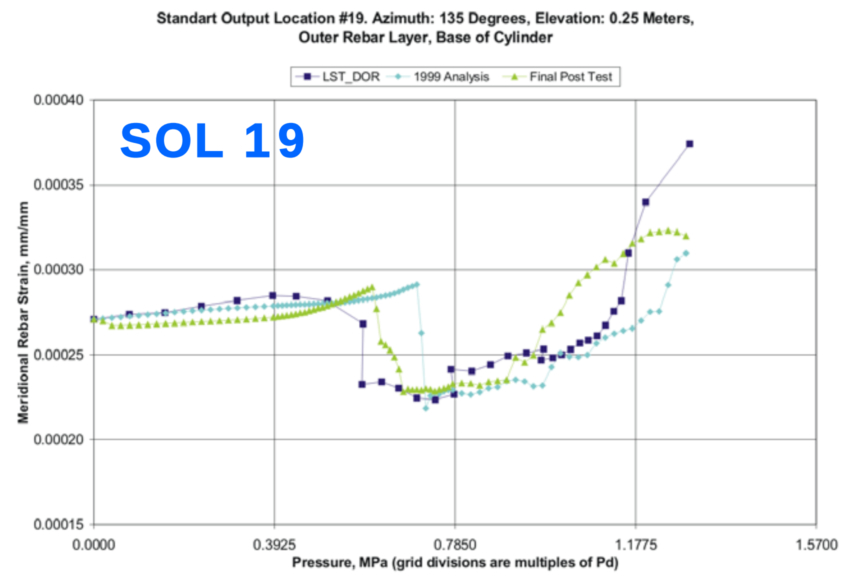
Pretest and Post-test Analysis Comparisons with Test









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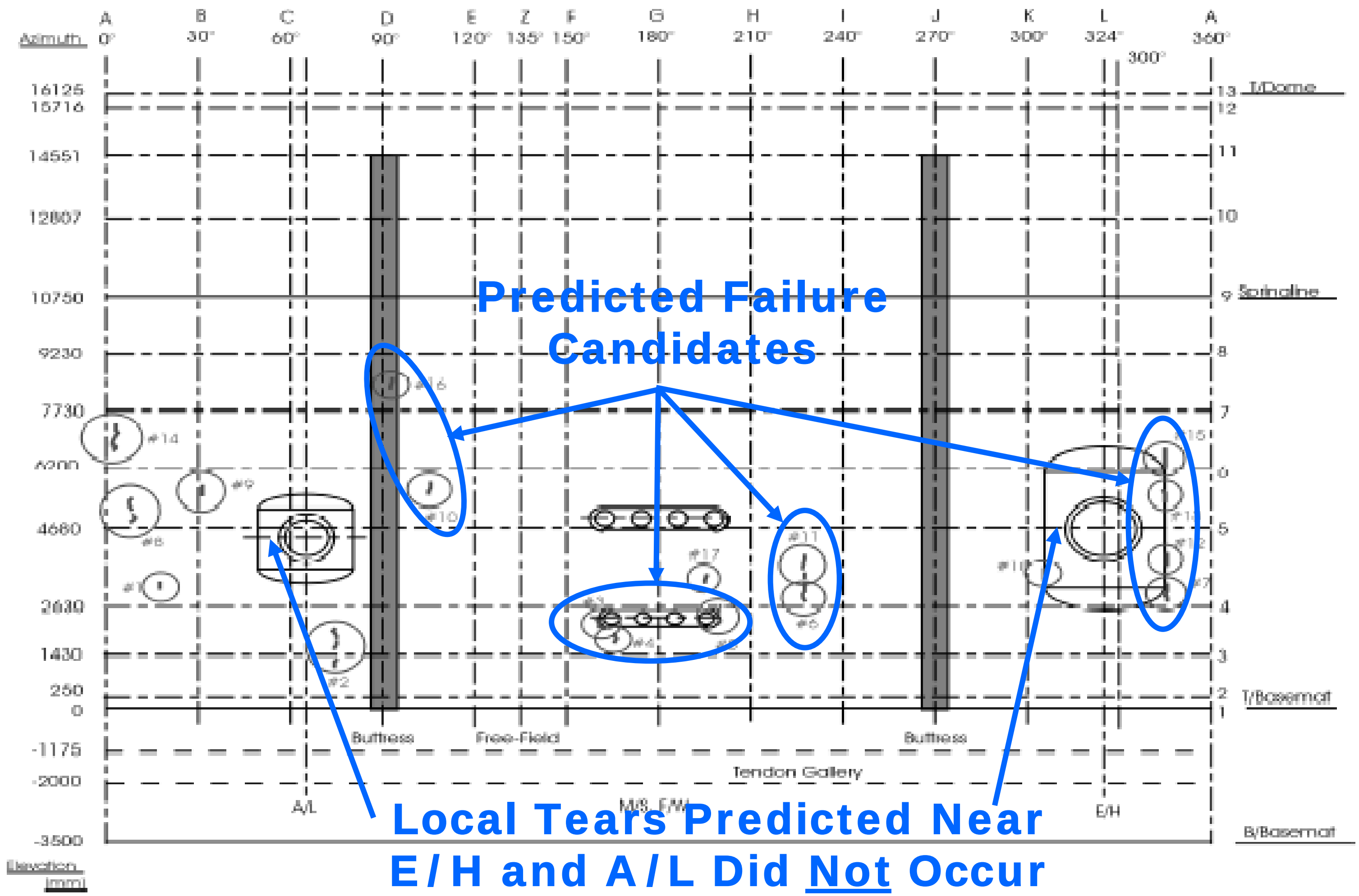
LST - Tear Occurrences Vs. Tear Predictions



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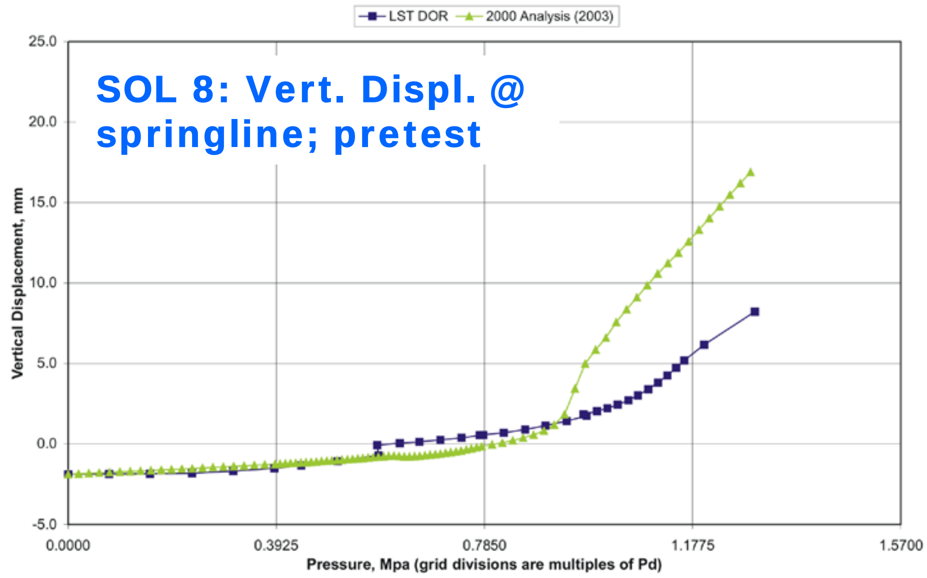
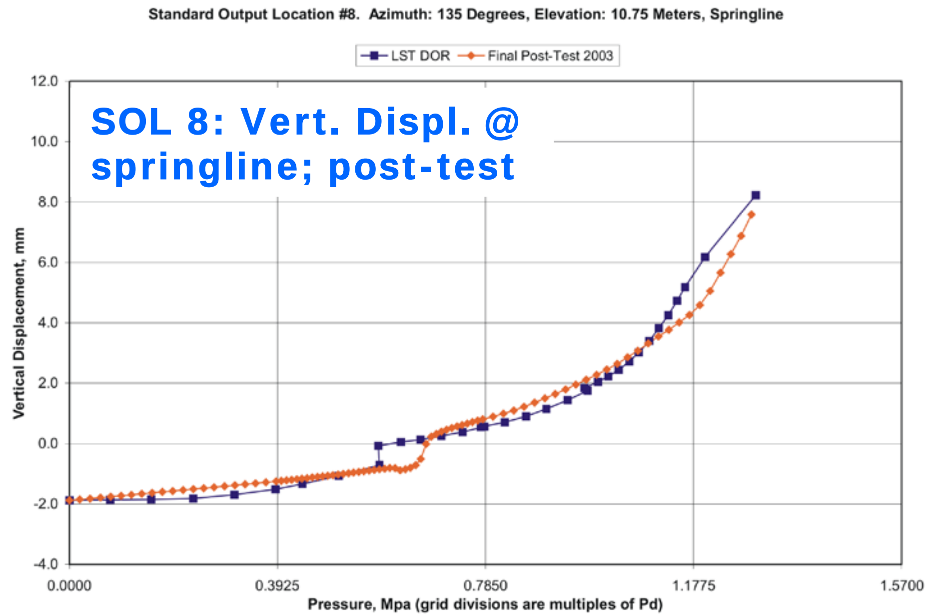
GLOBAL POST-TEST ANALYSIS

- **CHANGES TO PRETEST MODEL**
  - **Increased meridional tendon area in dome**
  - **Refined distribution and stiffness of soil springs under basemat**
  - **Assumed no friction on straight portion of meridional tendons**
- **CONCLUSIONS ON GLOBAL POST-TEST ANALYSIS**
  - **Measured basemat uplift may be misleading; only measures displ. relative to mudmat and mudmat may have moved down. Axism. analysis of basemat uplift now judged to be ok.**
  - **Dome vertical displ. improved but still over-predicted.**
  - **Most other aspects of response reasonably well predicted.**

Pretest and Post-test Analysis Comparisons with Test





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3DCM MODEL POST-TEST ANALYSIS

- **POST-TEST CHANGES**
  - **Buttress Springs**
  - **Tendon Friction Modeling**
- **BUTTRESSES ABOVE AND BELOW 3DCM BOUNDARIES WERE ASSIGNED VERTICAL "BEAM" STIFFNESS**
- **LST TENDON OBERVATIONS GUIDED POST-TEST FRICTION STUDIES. BEST ANALYSIS :**
- **Run 9. After prestress, add new friction elements in reverse orientation so that if tendon moves relative to concrete in reverse direction, reverse friction occurs.**

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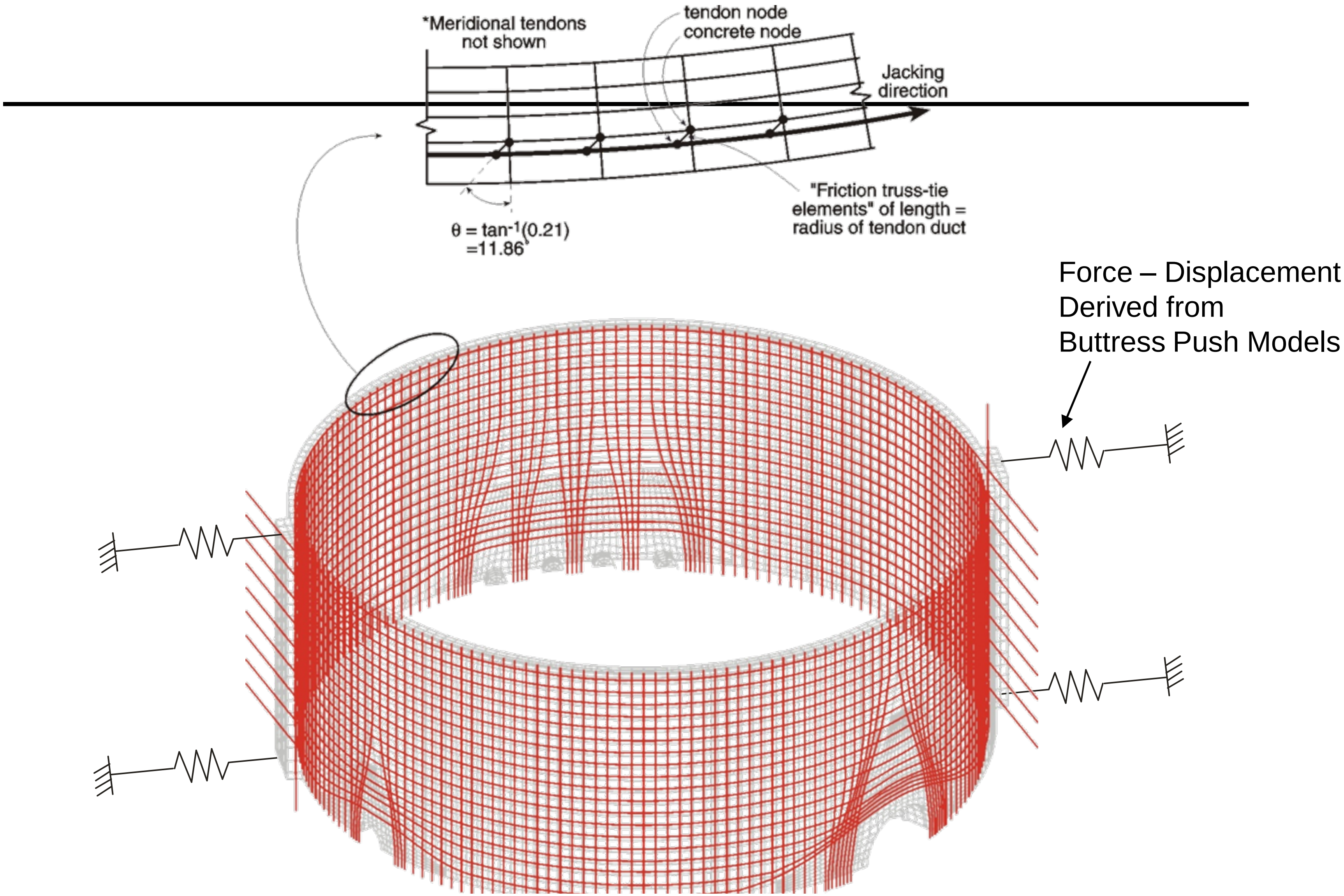
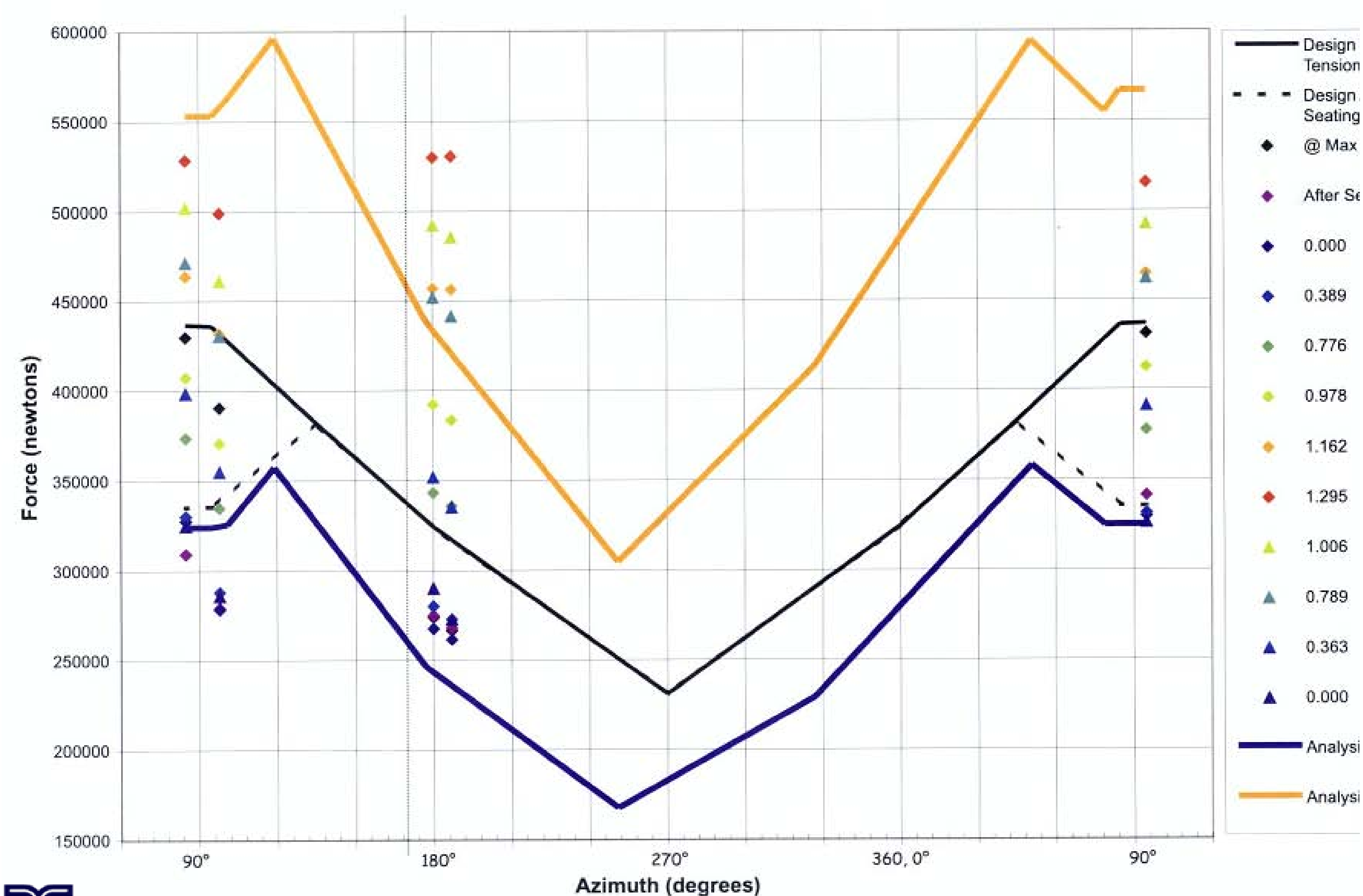


Isometric View-3DCM Model (Post-test) and Tendon Modeling

H53 Tendon Force Comparison to Pretest Analysis



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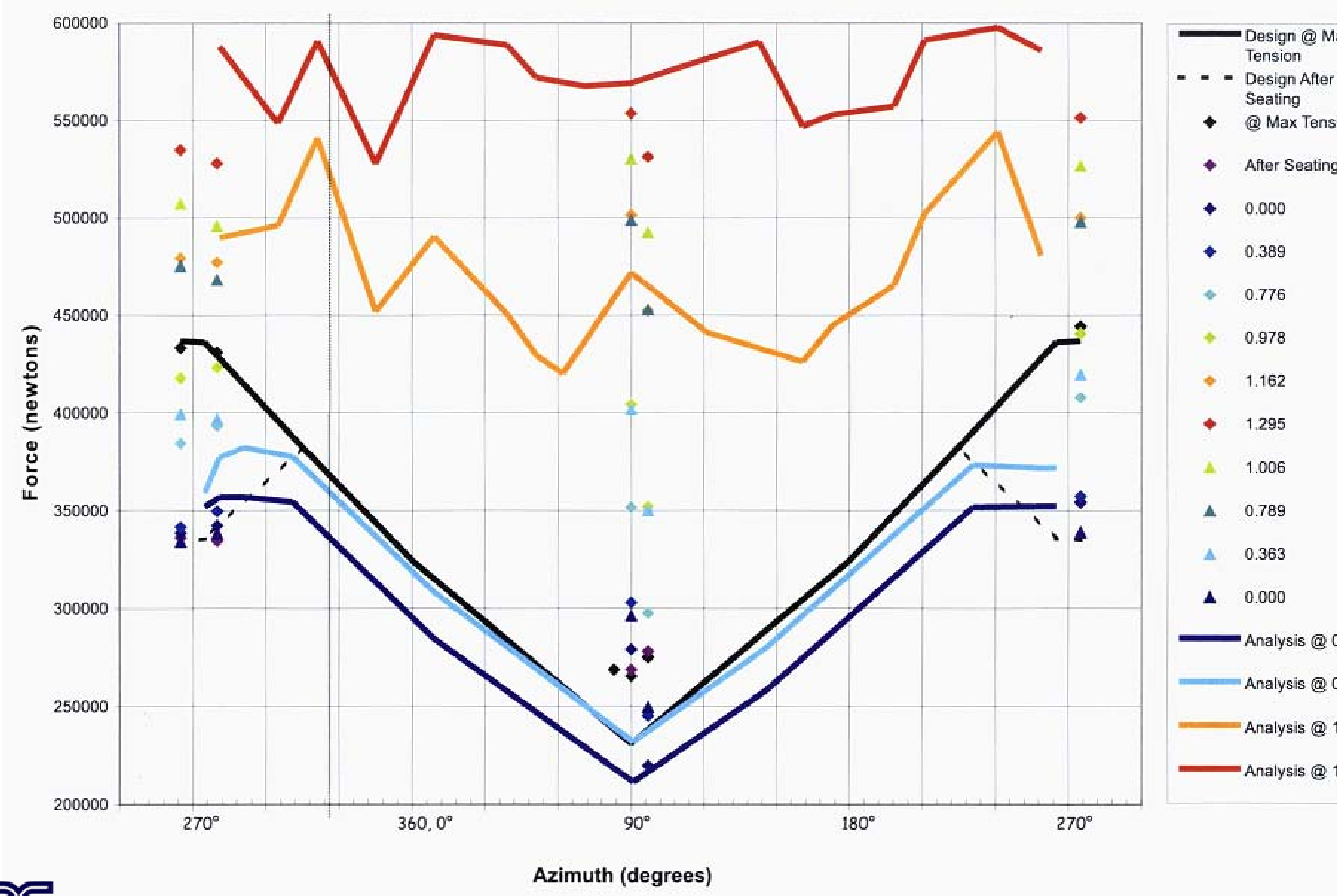
POST-TEST 3DCM ANALYSIS, CONT'D

- **TENDON FRICTION SIMULATION RUNS 6, 7, 9 SHOW PROGRESSIVELY BETTER AGREEMENT WITH TEST; RUN 9 SHOWS BEST AGREEMENT**
  - **Based on these observations Run 9 used for driving the local penetration post-test analyses**
- **TENDON FRICTION BEHAVIOR CONCLUSIONS:**
  - **Tendon friction is important to simulating tendon behavior, but traditional design formulas break down once pressurization exceeds pressure that "overcomes" prestress (in this case, roughly 1.5Pd)**
  - **Coefficient of angular friction must reverse direction to allow sliding and force redistribution as the vessel expands**

H53 Tendon Force Comparison to Post-test Analysis #9 (With two-way friction)



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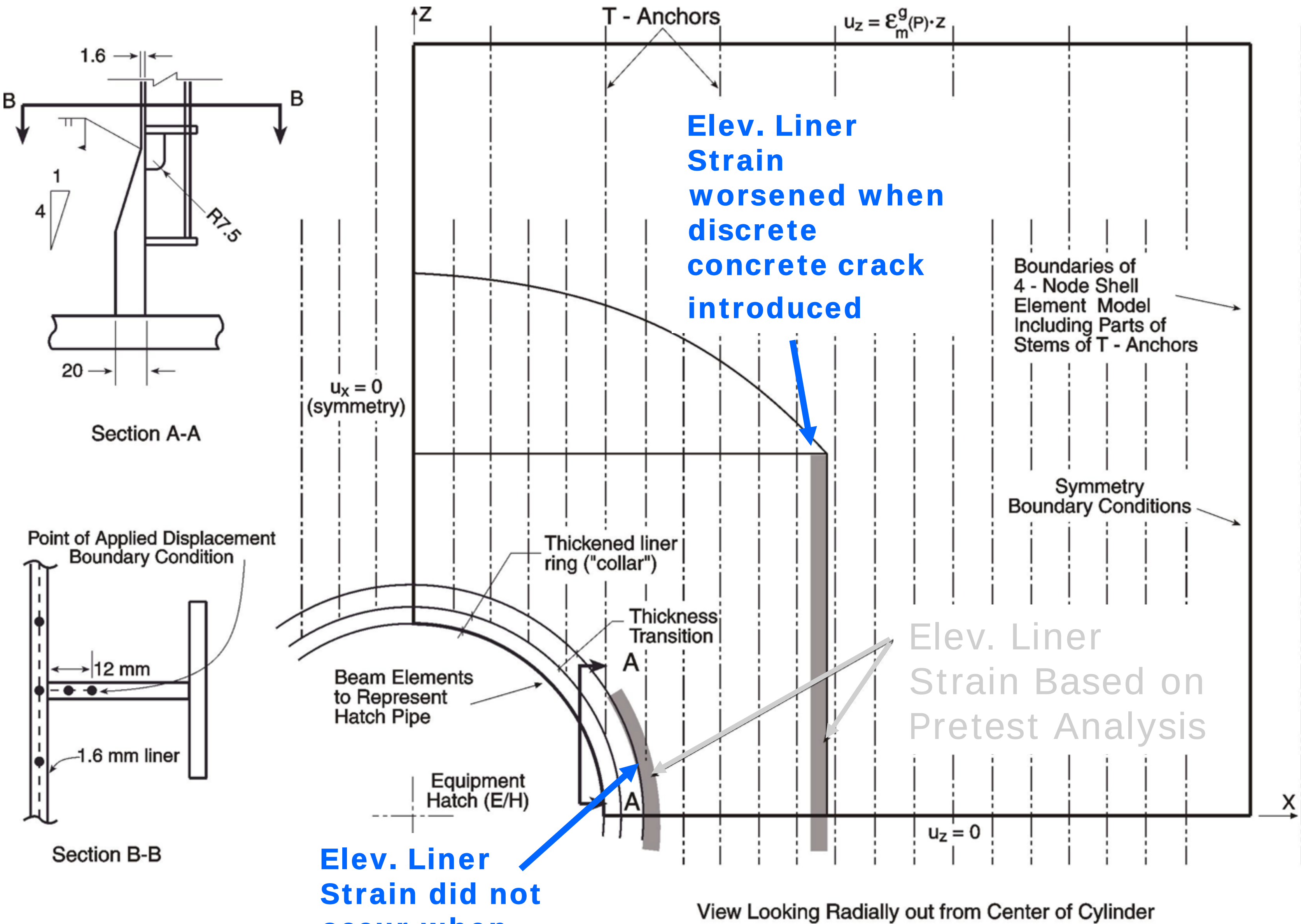
E/H POST-TEST ANALYSIS

- **LINER STRAINS MEASURED NEAR PENETRATION COLLAR WERE MUCH LOWER THAN PREDICTED**
  - **Key change:**
    - **Prevent slip between liner and concrete in E/H area**
- **POST-TEST MODEL WITH NO SLIP BETWEEN LINER AND CONCRETE:**
  - **BEHAVIOR AWAY FROM HATCH UNCHANGED, BUT ELEVATED STRAINS CLOSE TO COLLAR DID NOT OCCUR**
- **DIRECTED CRACKS AND A DISCRETE CRACK ADDED WITH DOUBLE ROWS OF NODES ALONG ASSUMED CRACK LINE:**
  - **caused an additional strain concentration in liner which coincides with rat-hole weld seam details, where numerous tears occurred.**
  - **Additional strain probably enough to predict a tear at embossment edge.**
  - **with discrete crack and local rat-hole modeling, liner tear could have been predicted as early as 2.8p_d.**



E/H (View from Inside PCCV Looking Out Radially)

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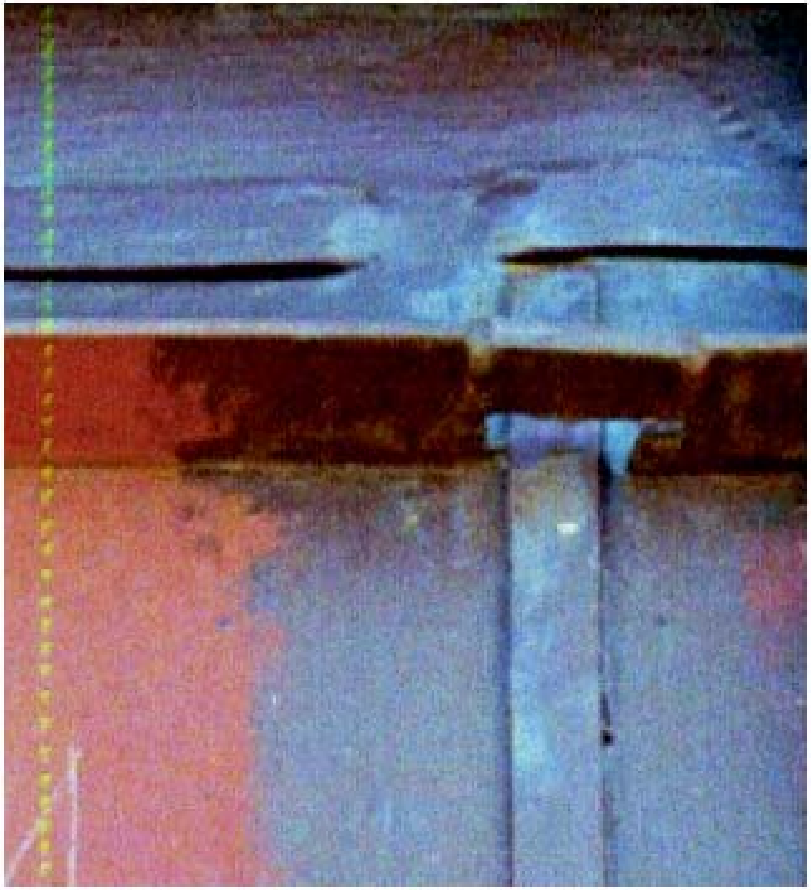
LOCAL LINER ANALYSIS

- **POST-TEST LINER SEAM MODEL STUDIED:**
  - **why tears occurred at some rat hole locations and not others**
  - **further evidence (analytical) on the beneficial effects/necessity of backup bars**
  - **Establishing confidence in procedure to model and predict elevated strains and/or tests in an actual plant**
  - **Quantifying effects of welding irregularities and distinguishing these from strain concentration effects solely related to geometry.**

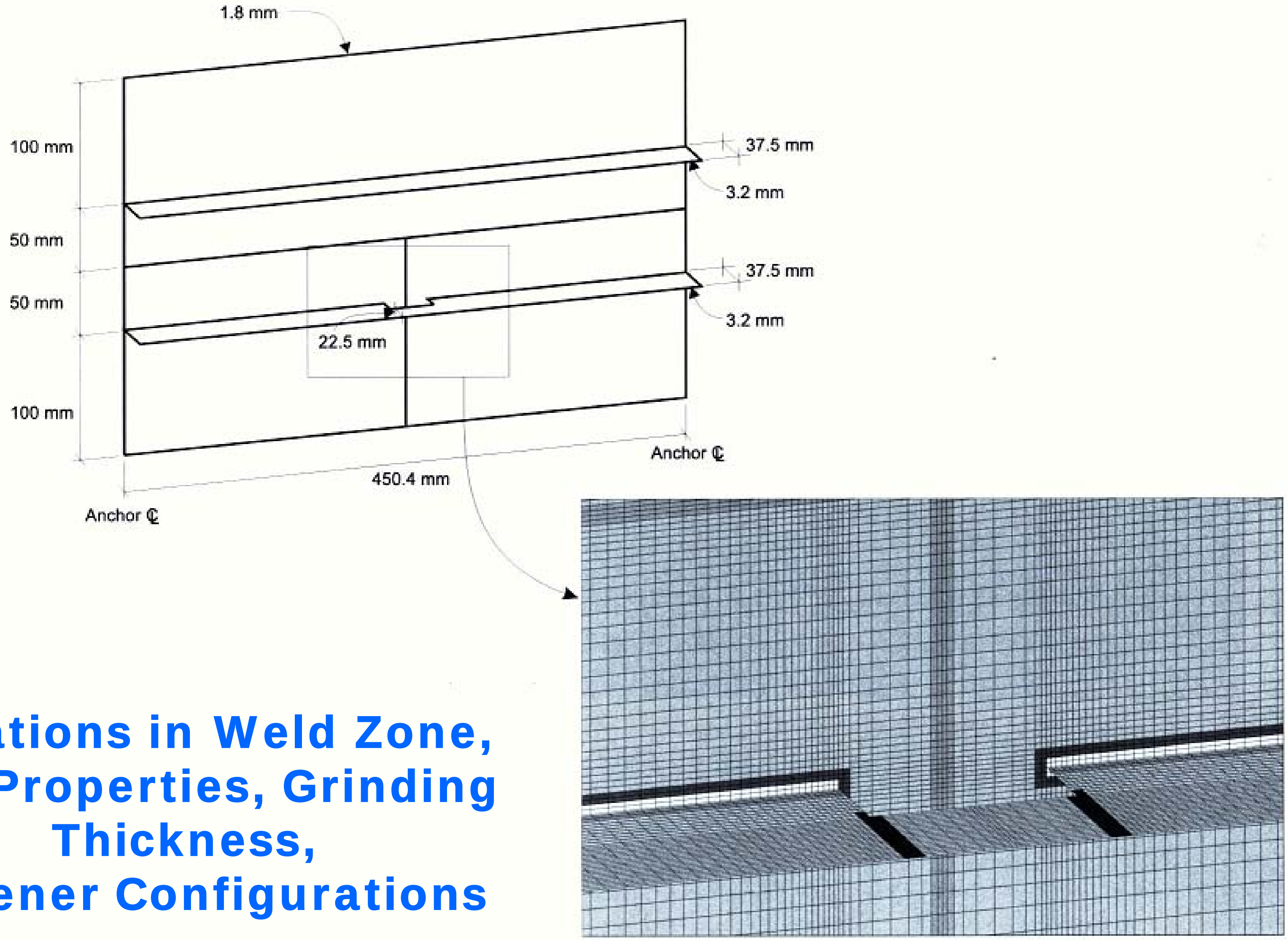
LST - Typical Tear Location

Liner Tear #16



(Image reversed for comparison)

Local Line Seam Analysis Model



Variations in Weld Zone, HAZ Properties, Grinding Thickness, Stiffener Configurations

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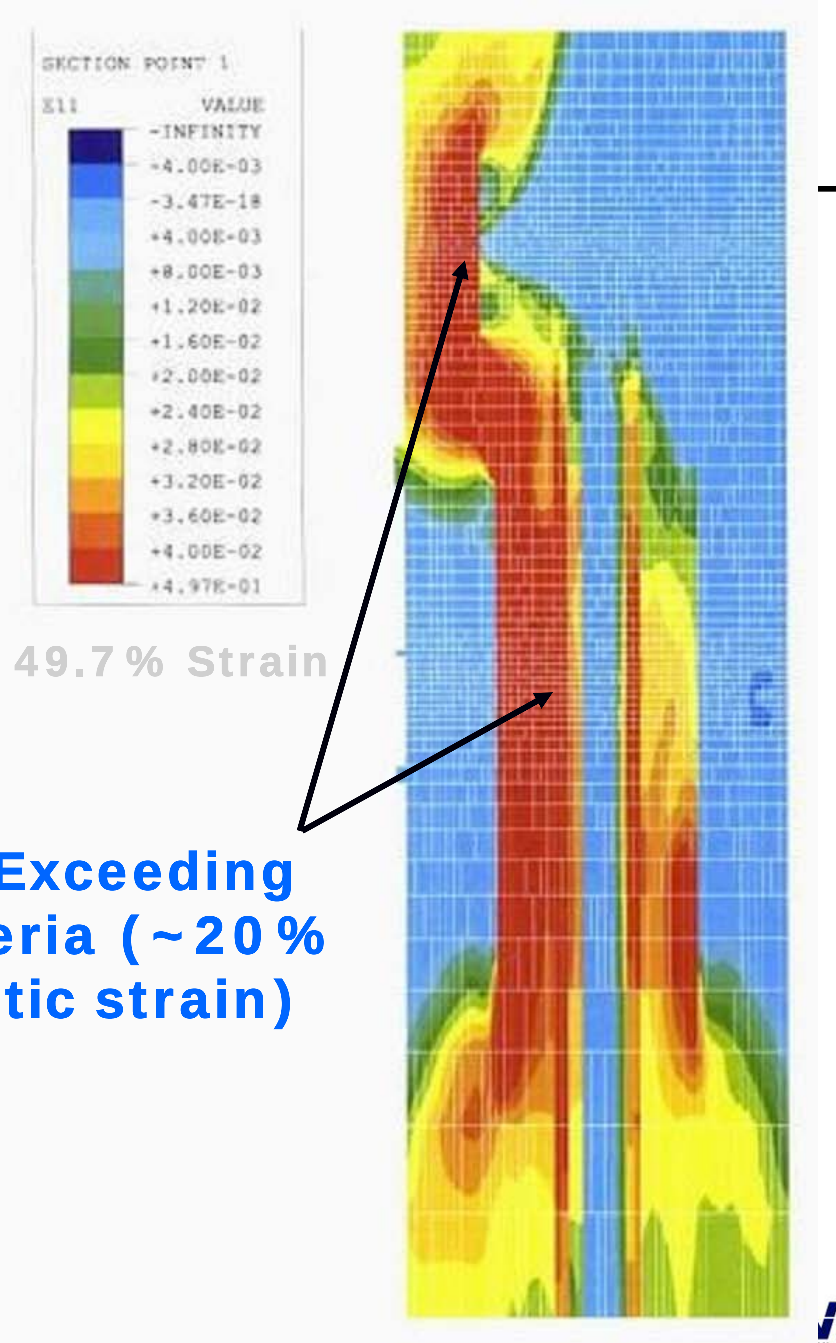
Local Liner Seam Analysis Model (Simulation of Tear 16)



Strains Exceeding Tear Criteria (~20% Eff. Plastic strain)

LOCAL LINER ANALYSIS, CONT'D

- **CONCLUSIONS OF LINER SEAM/RAT-HOLE STUDY:**
  - **Weld seam models with thinned material captured strain concentrations around the rat-holes and liner welds well.**
  - **There are competing mechanisms (hot-spots) at weld zones and at stiffener ends.**
  - **Yield and ultimate strength adjustments at HAZ necessary to correctly predict strain concentration location and intensity.**
  - **With back-up bars, nominal thickness and best estimate materials predicted behavior of defect-free rat-hole/weld-seam details.**
  - **Models with severe (~40%) thinning provided best simulation of tears that had severe repair grinding and back-up bars absent.**
  - **Rat-hole/seam analysis without defects, such as location "D-7", show liner tears still would have developed by pressure of 3.4P_d, so liner tearing and leakage would still have been the failure mode (for quasi-static pressurization) even without defects.**

Summary of PCCV RR Pretest Results

	Pressure (MPa)	Failure Mode
• ANL	1.51-1.62	local liner tear/hoop tendon failure @ El. 6.4 m
• AECL	0.94-1.24	complete cracking/axisymmetric yield
• CEA	1.60-1.70	numerically unstable
• EDF	1.95	
• INER	0.81	
• JAERI		buckling @ dome or local fracture by bending in cylinder
• JAPC	1.45-1.55	hoop tendon/rebar/liner rupture @ El. 7 m
• KINS	1.25-1.44	tendon rupture
• KOPEC	1.30-1.51	tendon rupture (@3.55% strain)
• HSE/NNC	1.98	liner tear w/ extensive concrete cracking @ buttress
• NUPEC	1.49-1.57	tendon rupture
• IBRAE	1.26	tendon rupture
• Principia	1.30	tendon yielding
• RINSC	1.50	hoop failure of vessel
• ANATECH/SNL	1.25	liner tearing (16%) @ E/H
	1.40	tendon rupture
• Test	0.98	1.5% mass/day leak through liner tear @ E/H
	1.30	limit of pressurization capacity during LST
	1.42	hoop tendon and rebar rupture during SFMT

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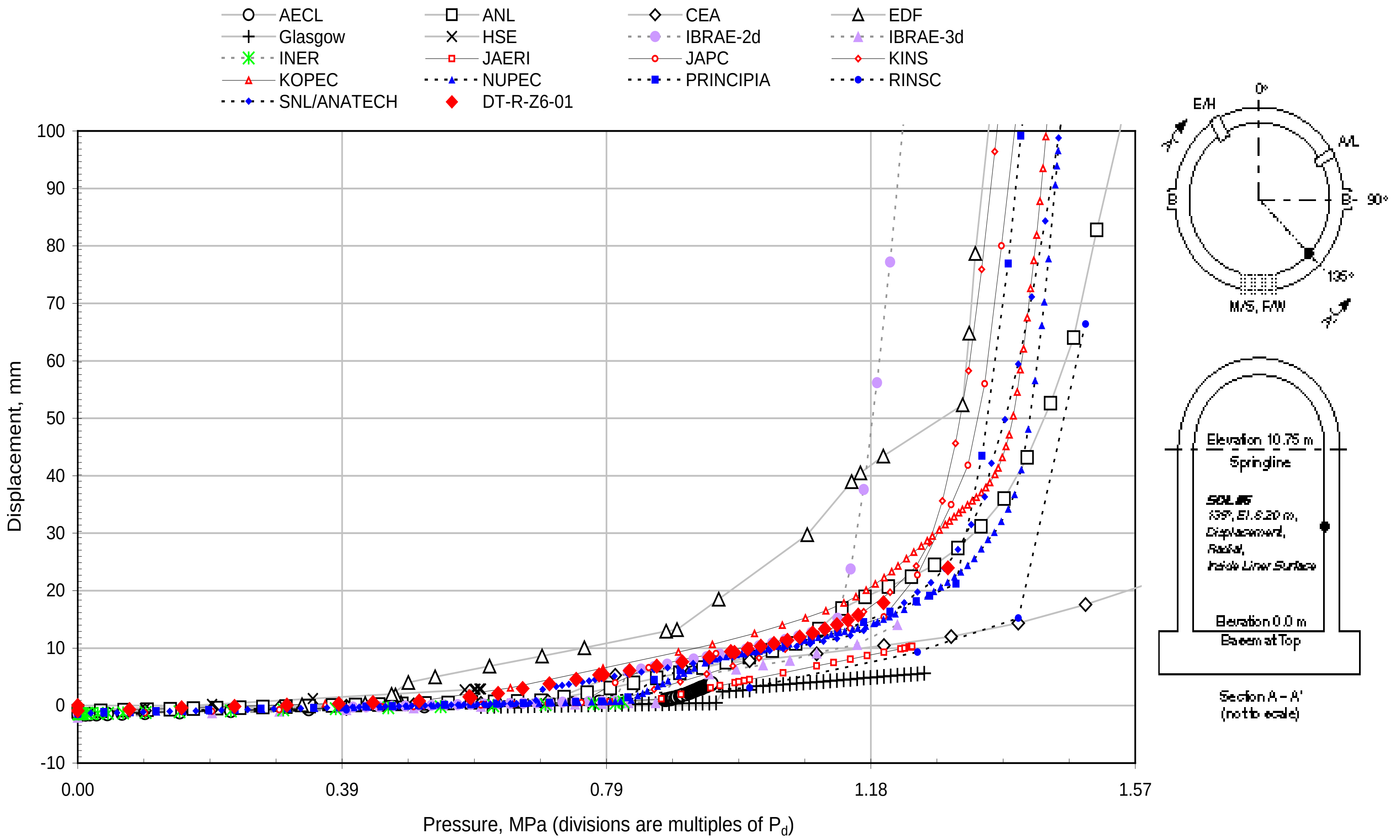
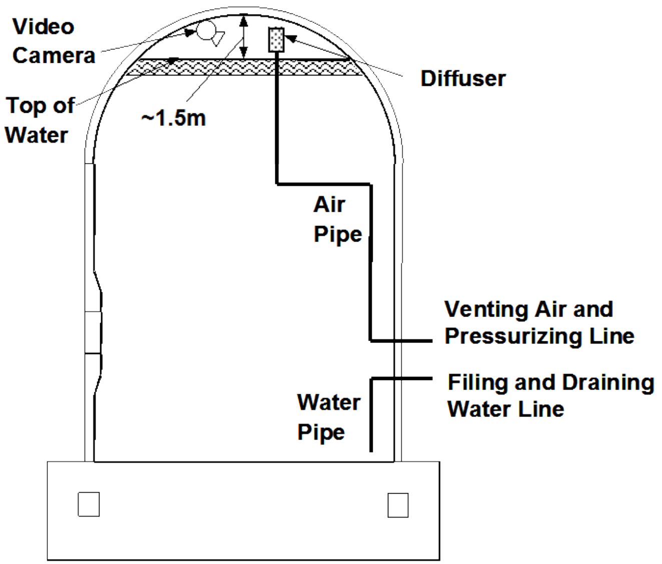
PCCV Limit State Test

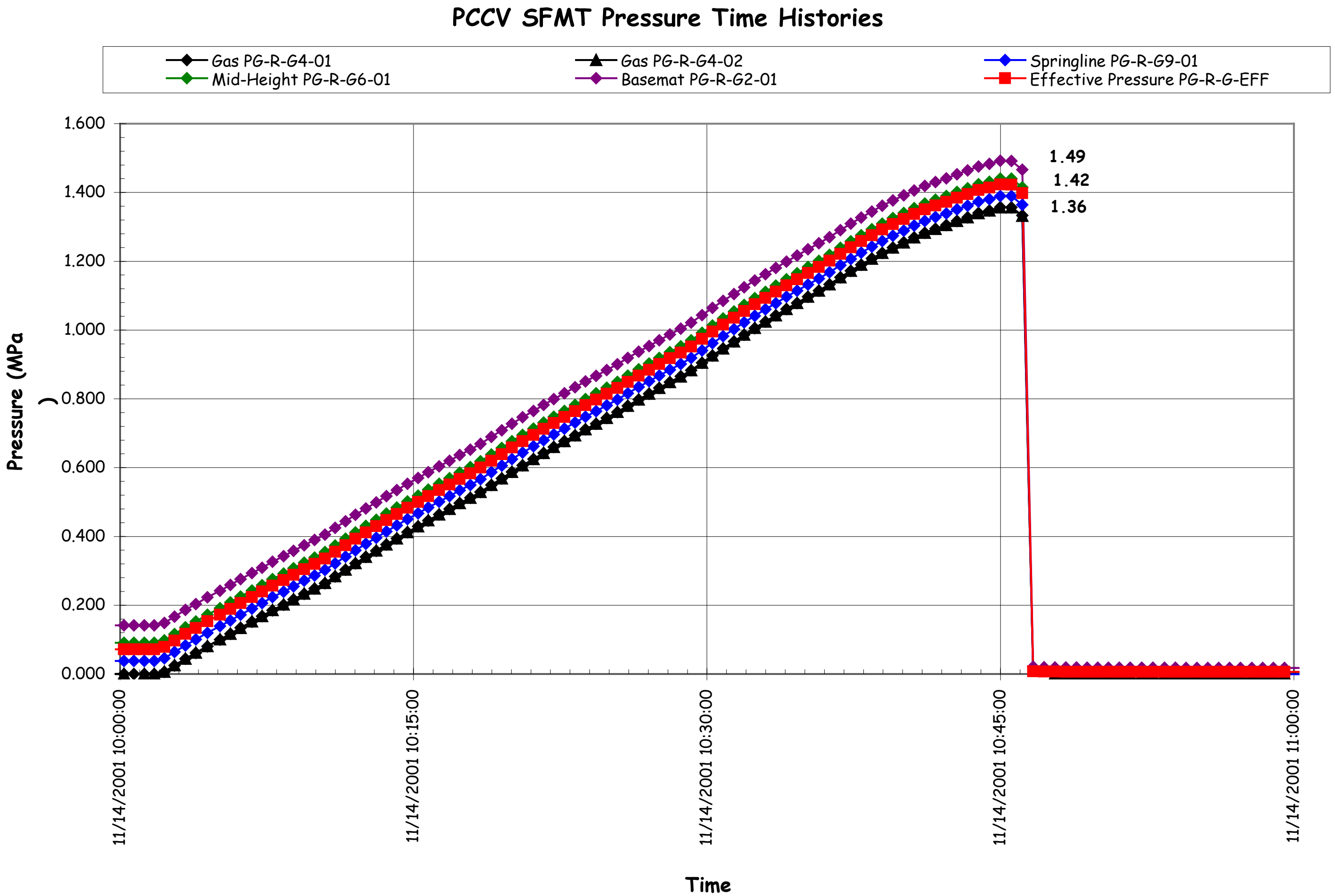


Summary of SFMT Results

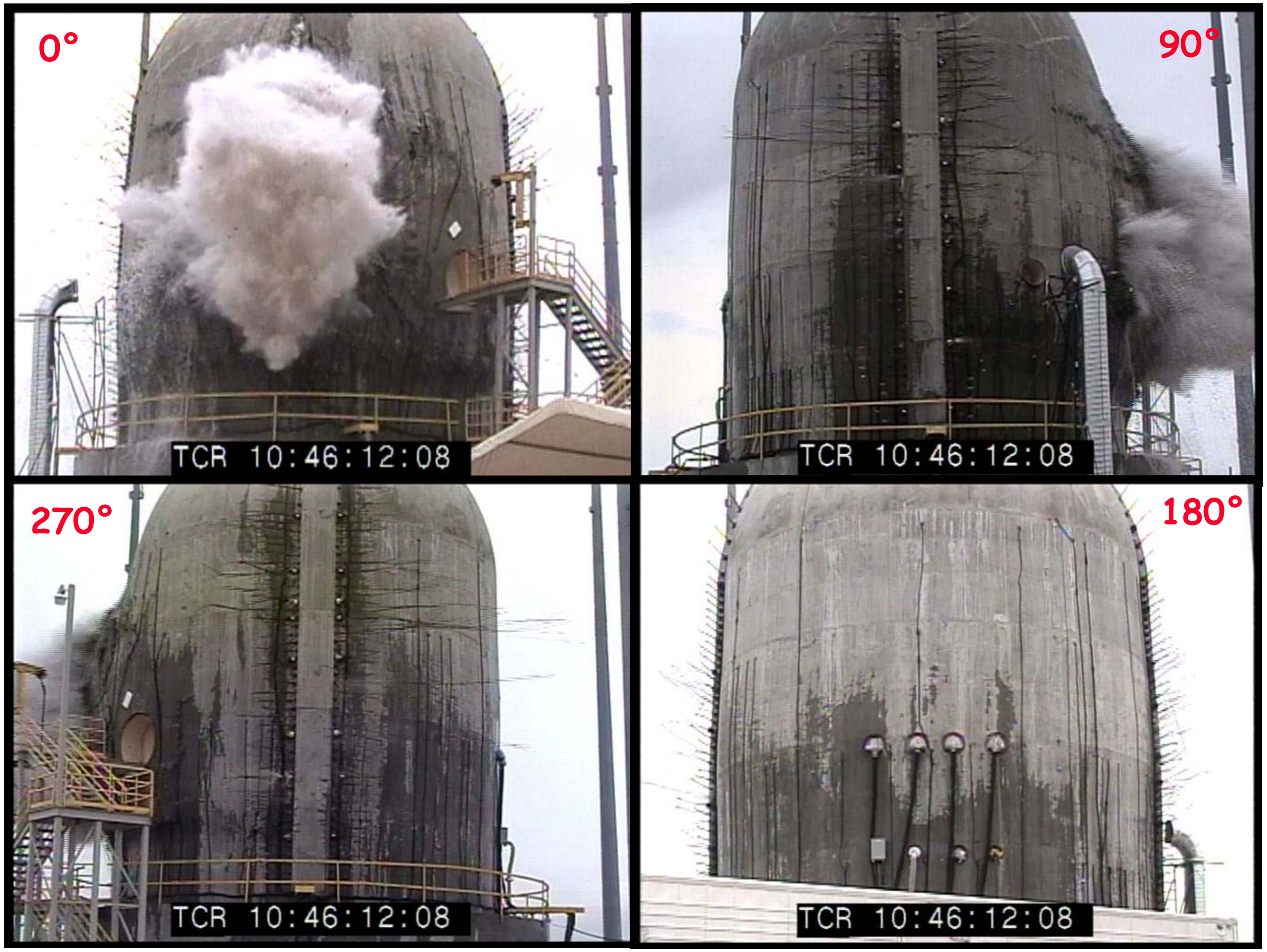
- Structural Failure Mechanism Test (SFMT):
  - Justification: LST did not completely satisfy pre-test objective of providing data to validate response predictions 'well into the in-elastic regime'.
- Procedure:
  - Sprayed-on polyurethane elastomeric liner (200 mil min. thickness) applied to interior surface of model.
  - Pneumatic leak test conducted Oct. 3, 2001
    - Leak rate at 30 psi was ~70% mass/day
  - Model filled with water beginning November 6, 2001 after initial data scan and continued to November 8.
  - SFMT started at 10:00, Nov. 14, 2001 with an initial pressurization rate of 5 psi/min, scanning continuously (approximately every 30 seconds).



Pressure Time History



PCCV Model Structural Failure Mode Test
November 14, 2002, 10:46:12 AM



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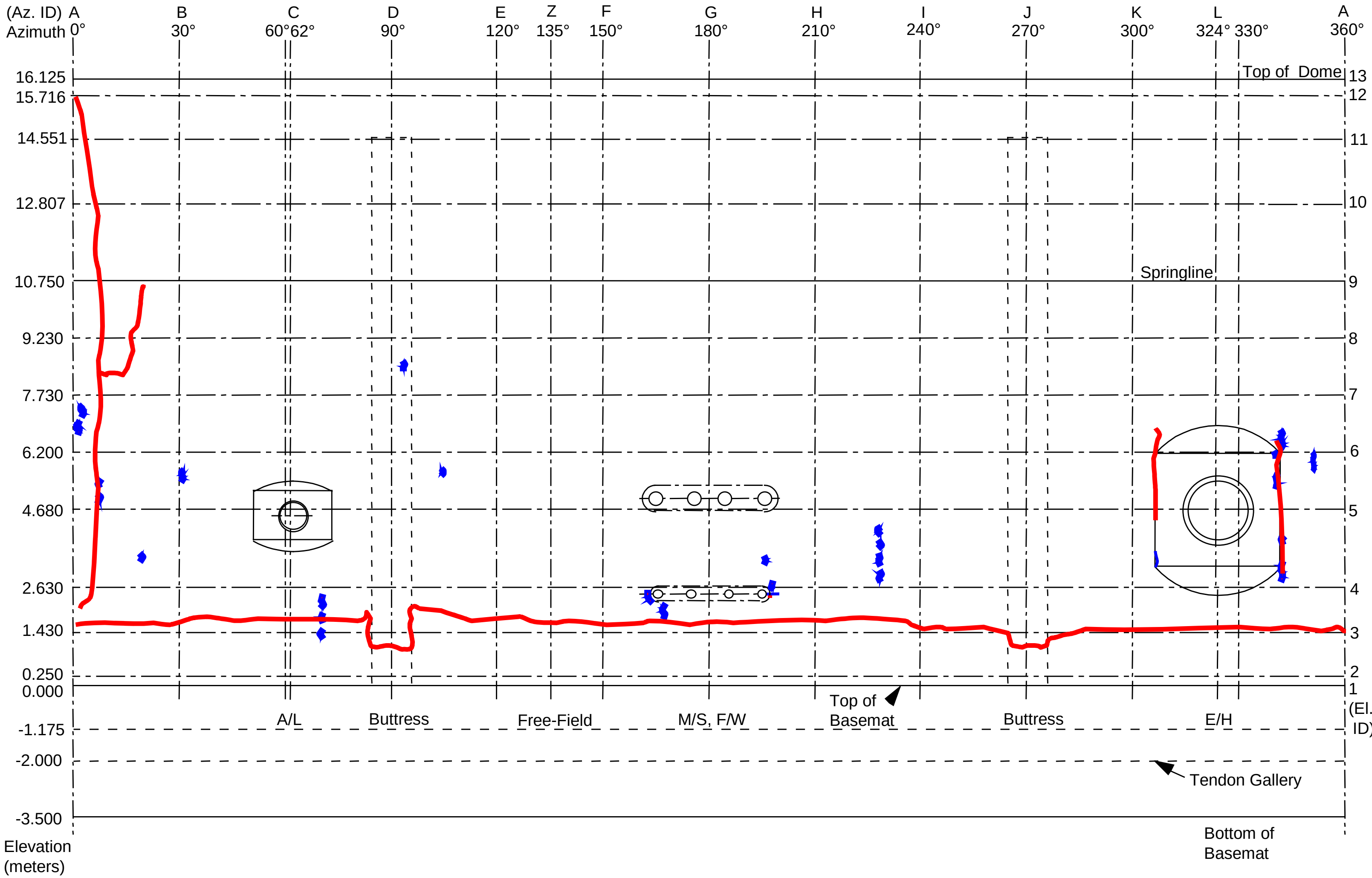
PCCV Model after SFMT
November 14, 2002

PCCV SFMT

- **Posttest Observations:**
  - **Water level inside model appeared to drop shortly before the rupture of the PCCV.**
  - **4 to 6 tendons were observed to 'fail' in the final minute before the vessel ruptured.**
  - **Rupture initiated at approximately mid-height of the cylinder at Azimuth 6°, radiated vertically in both directions then radiated circumferentially approximately 7' above the top of the basemat. Vessel 'telescoped' over stem of cylinder wall and came to rest on the Instrumentation frame.**
  - **Approximately 12 tendon segments were completely ejected from the model (all remained within test site boundaries)**
  - **Hoop tendons and rebar at the rupture line exhibited significant necking indicating that rupture was essentially ductile in nature.**
  - **Model displaced 3" horizontally and tipped in the opposite direction of the rupture.**

Rupture Map



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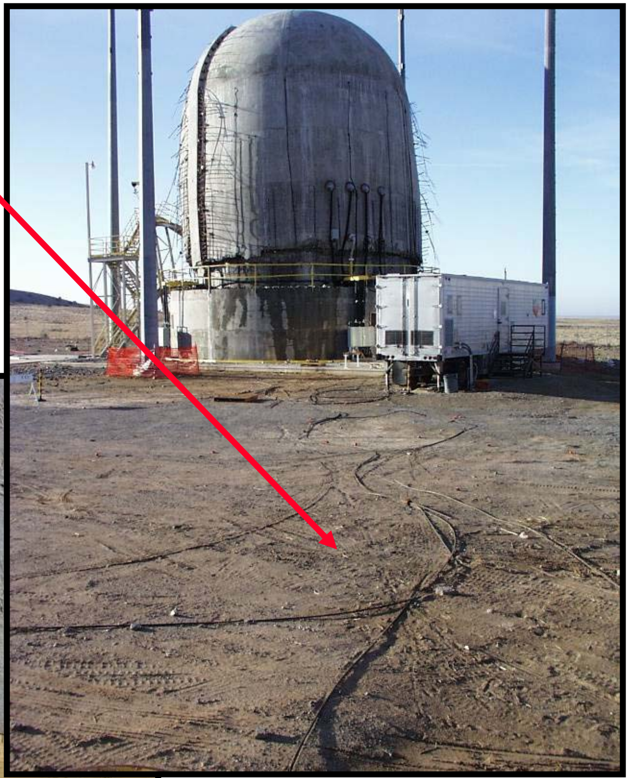
Rebar and Tendons

Model Displacement

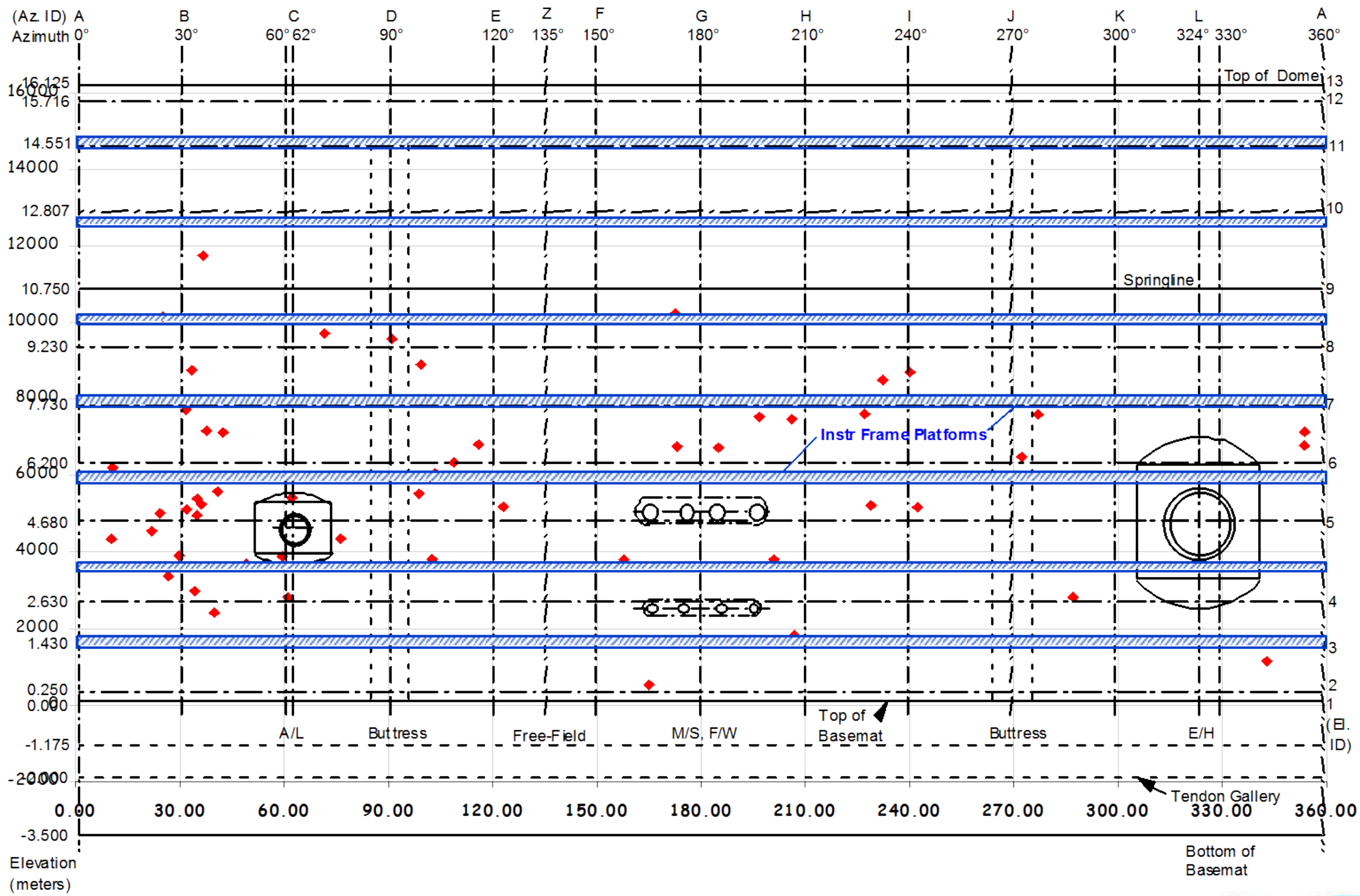
Displacement of PCCV Model Basemat

Tendons ejected From PCCV During SFMT



SFMT Acoustic Response – Wire Breaks

Acoustic Events - SFMT Wire Breaks



Strain Summary

- **Displacements:**
  - **$\Delta r/R$ = 1.4% @ 4680 (Level 5)**
- **Exterior Liner Strains**
  - **Gages @ Wall-Base Junction appear to have failed at 0.5Pd**
  - **Maximum Free-field Hoop Liner strain: 1.5% @ Z6, 1.9% @Z5**
- **Rebar Strain**
  - **Max Free-field Hoop Rebar strain: 1.4% (RS-C-Z6-02)**
  - **Gage Bar strain data: all gages appear to have failed prior to 0.5 Pd**
- **Concrete Strain (SOFO):**
  - **Max Free-field Hoop strain: 1.1% (CE-C-Z6-01)**

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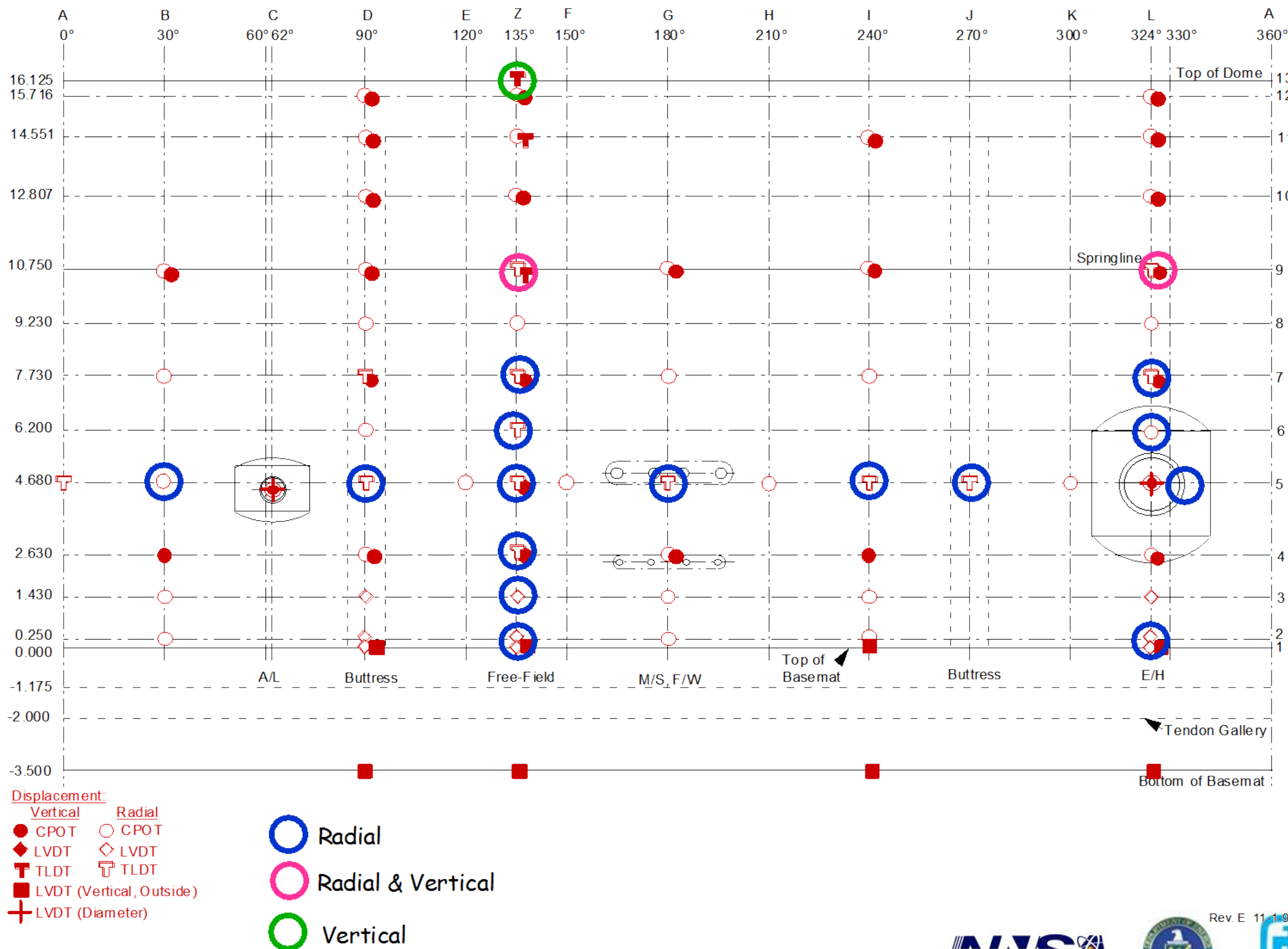
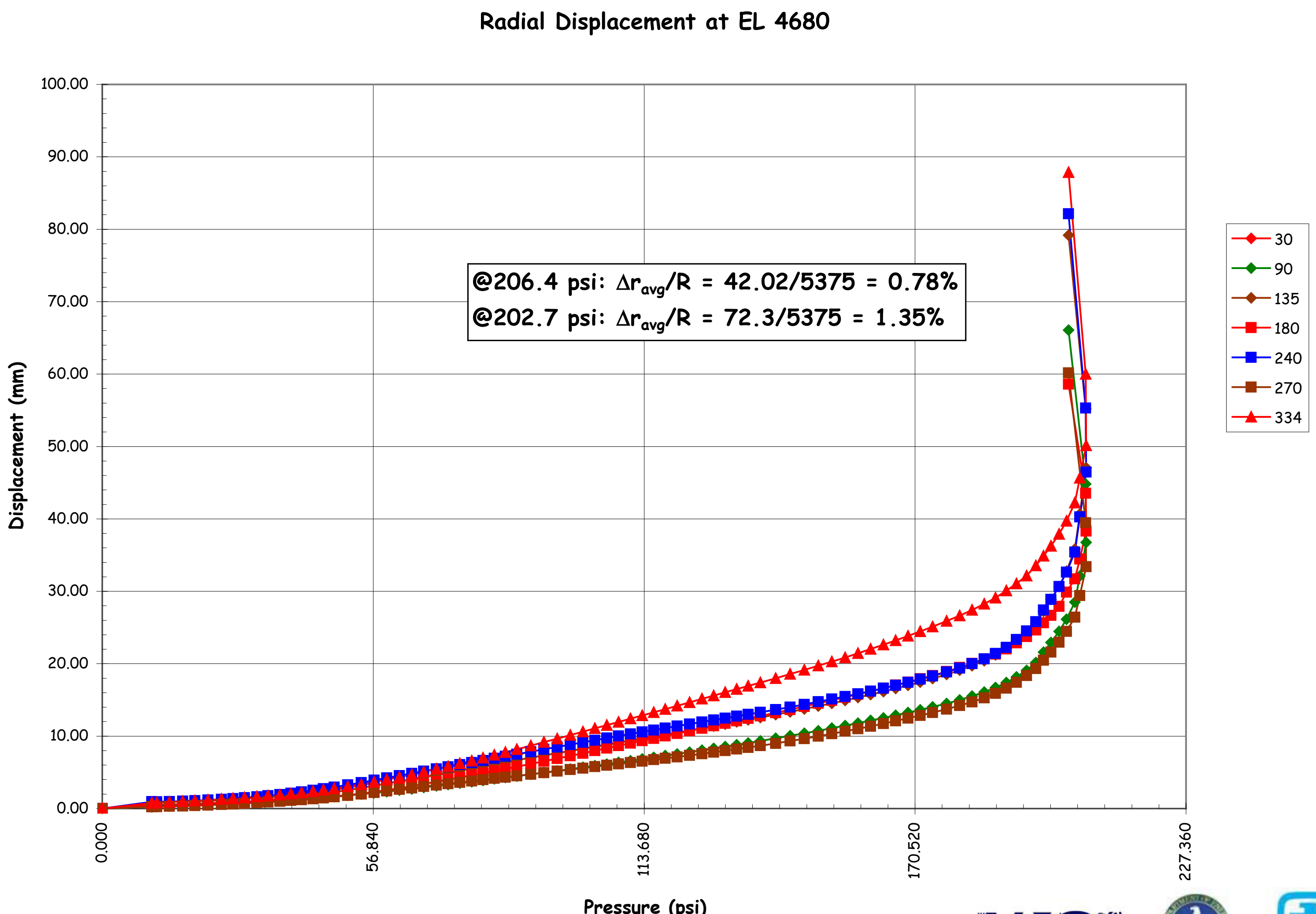
Displacements



Displacements



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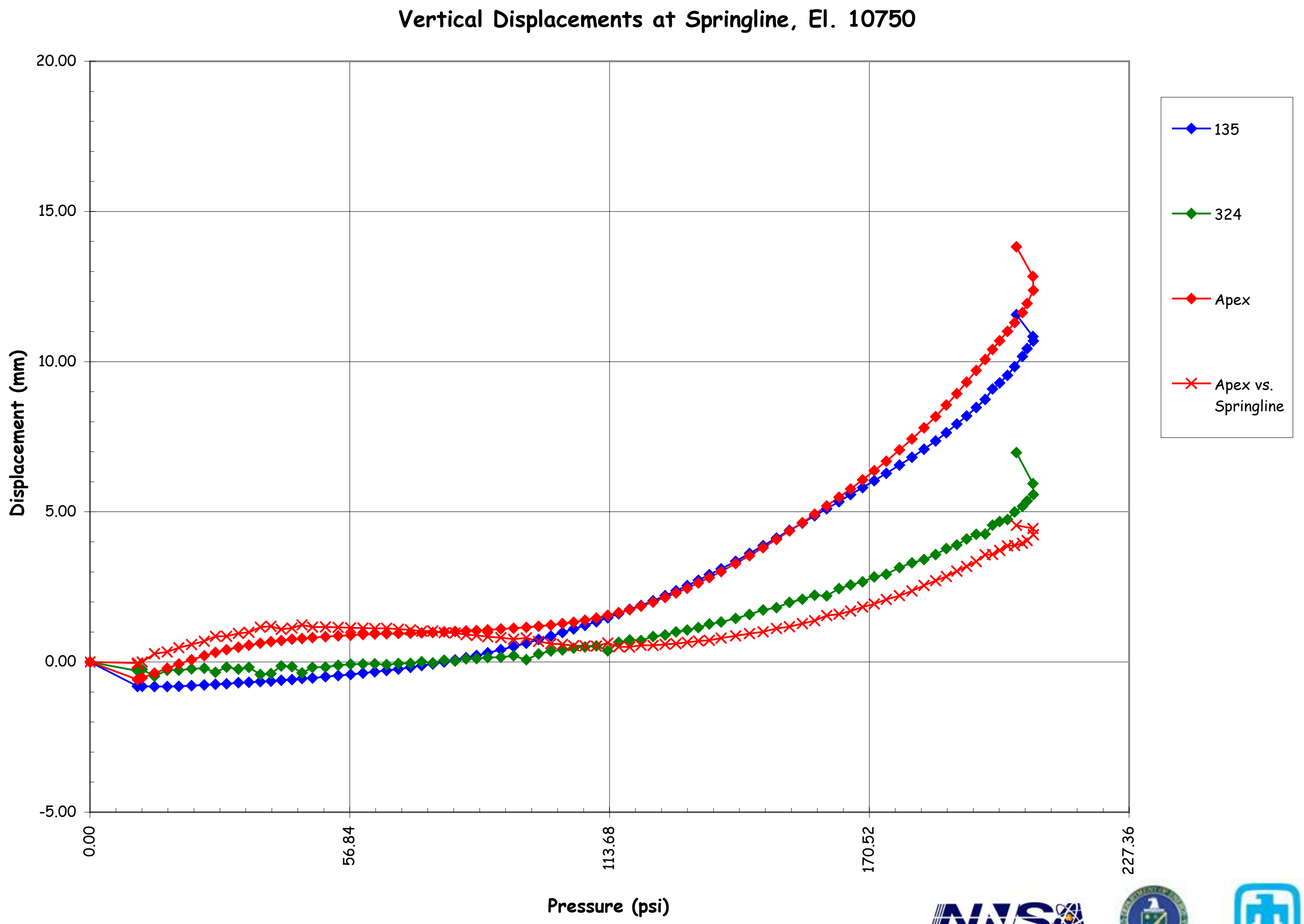

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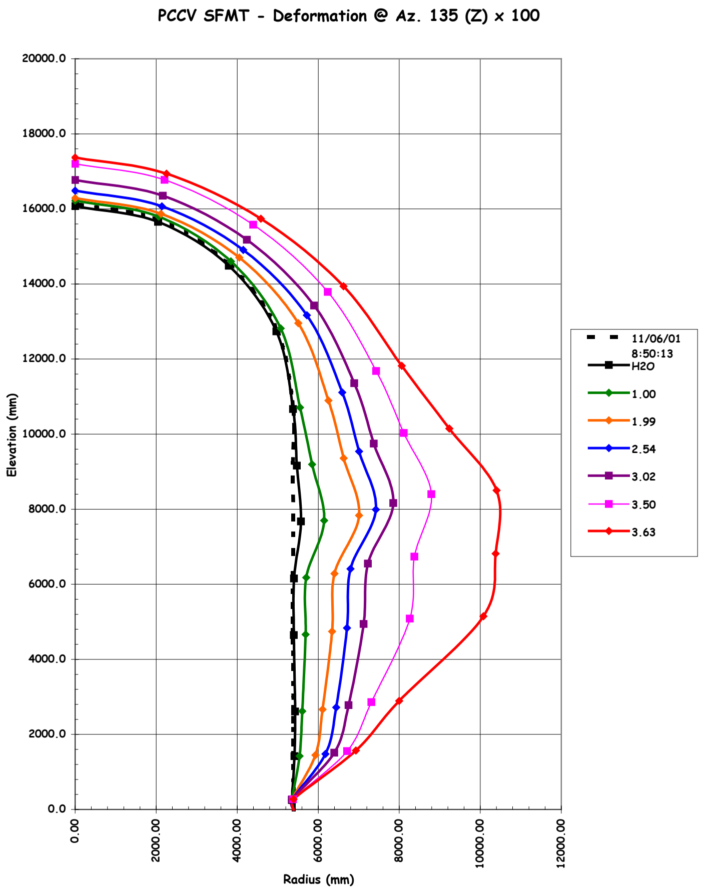

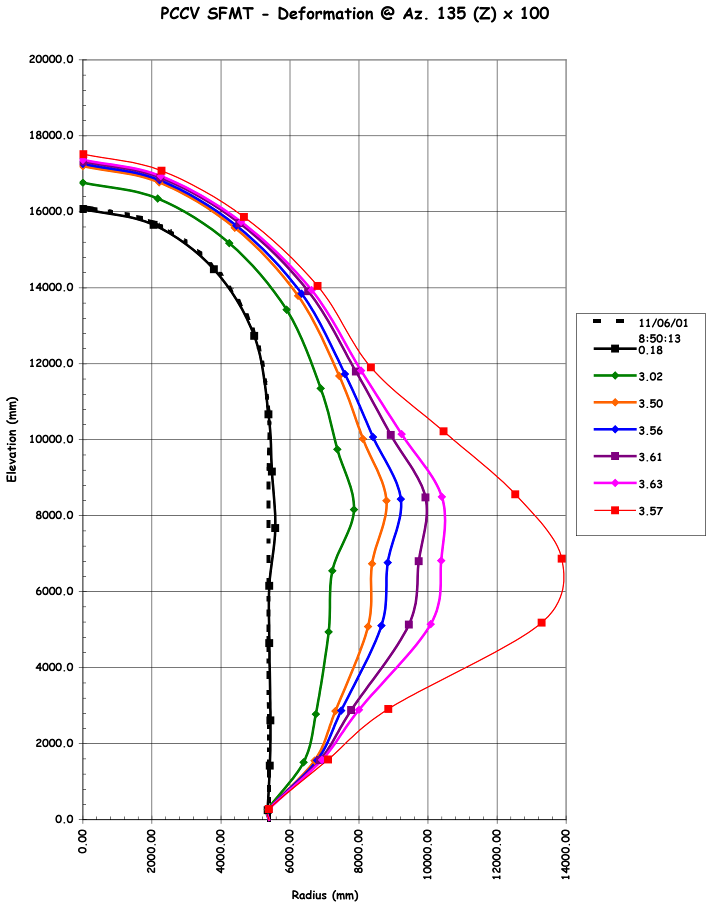

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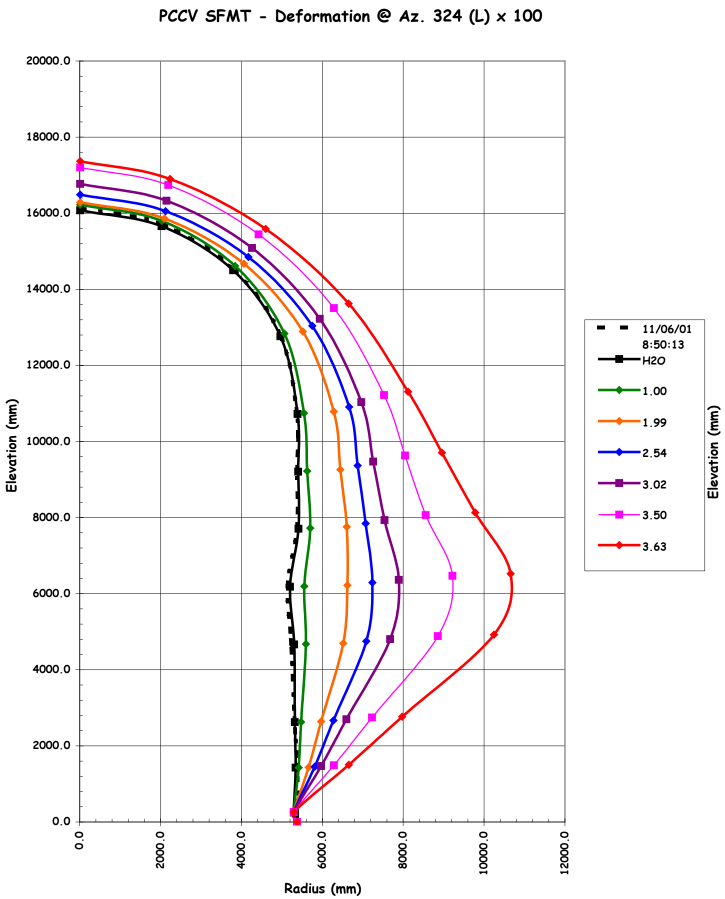

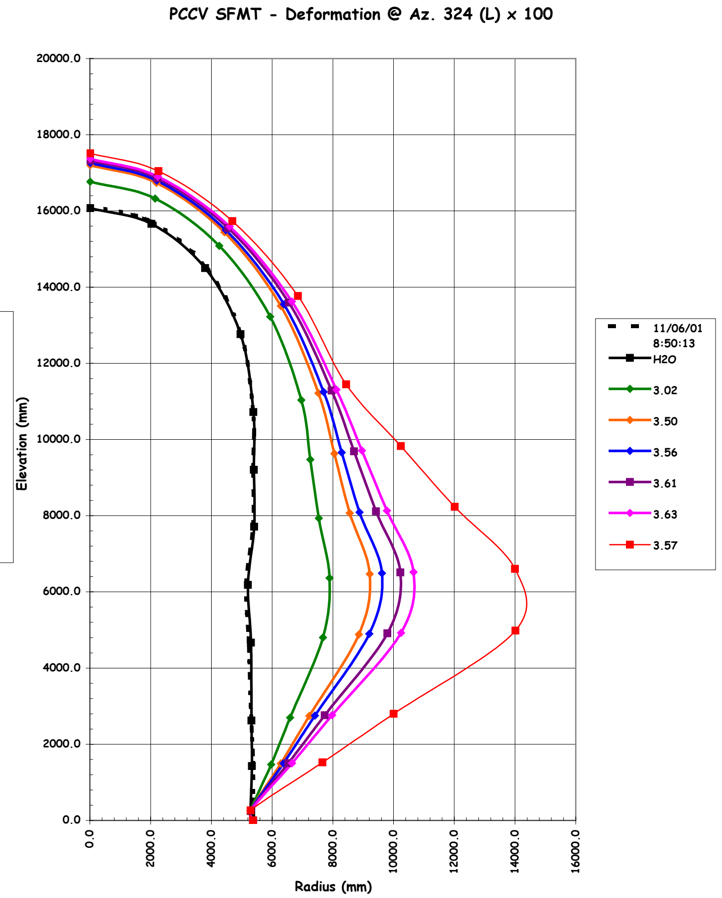

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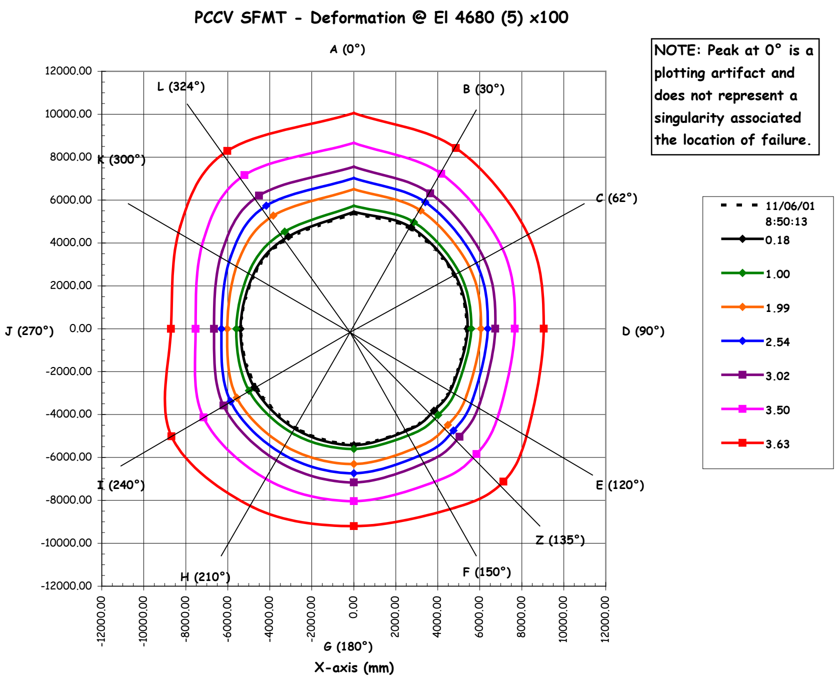
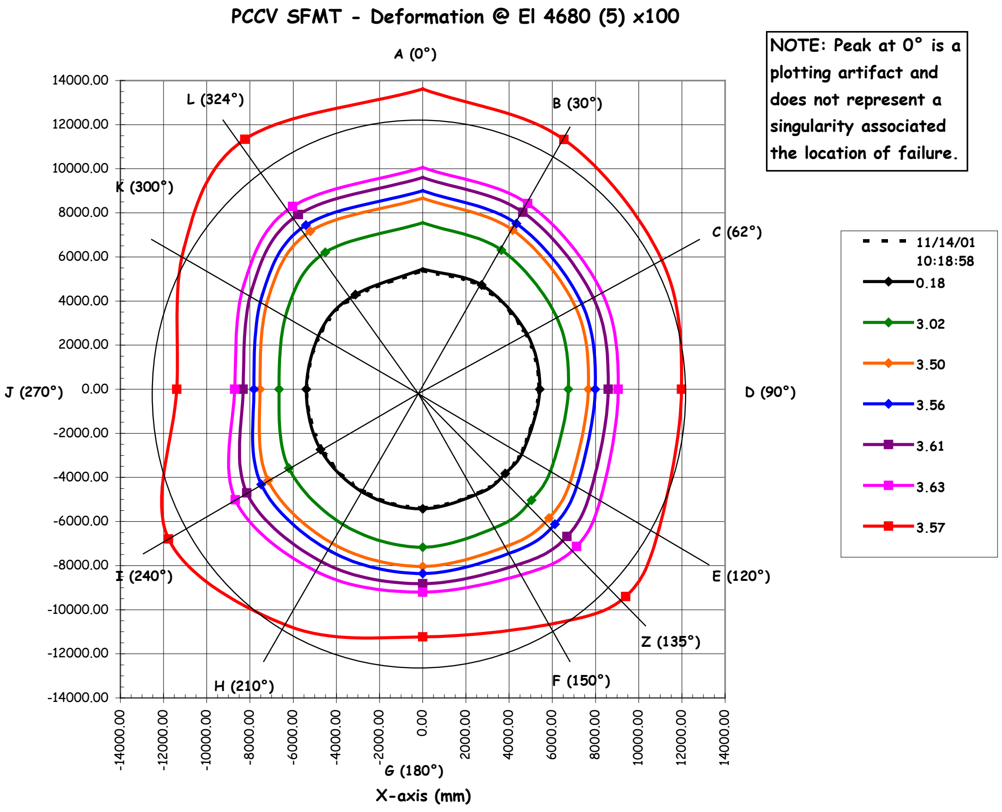
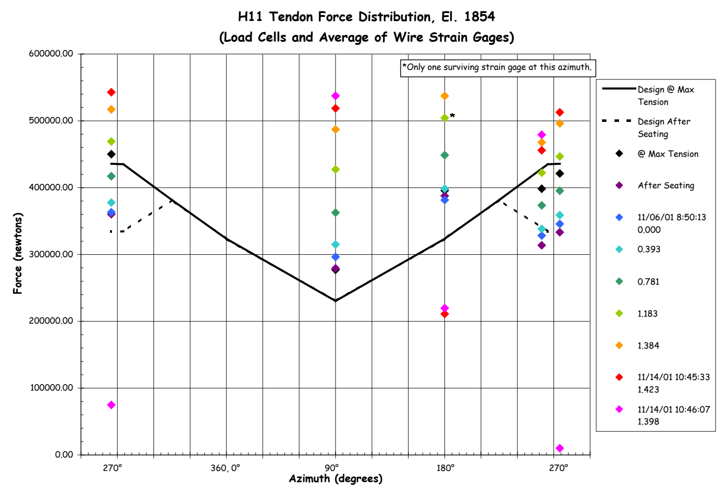
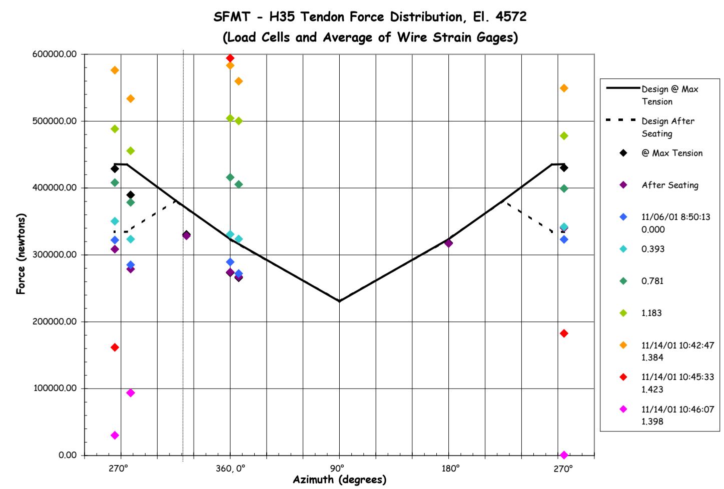
Displacements

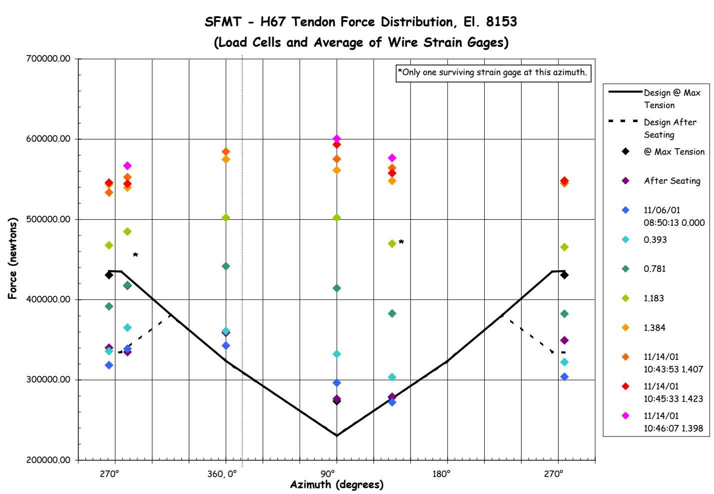


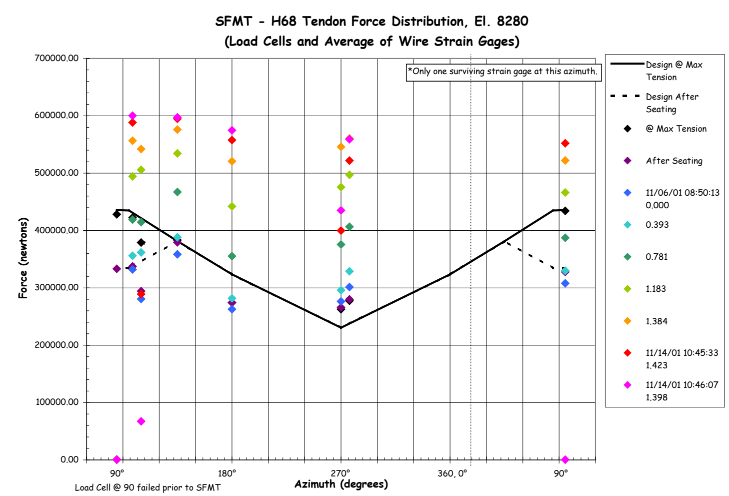


Tendon Forces

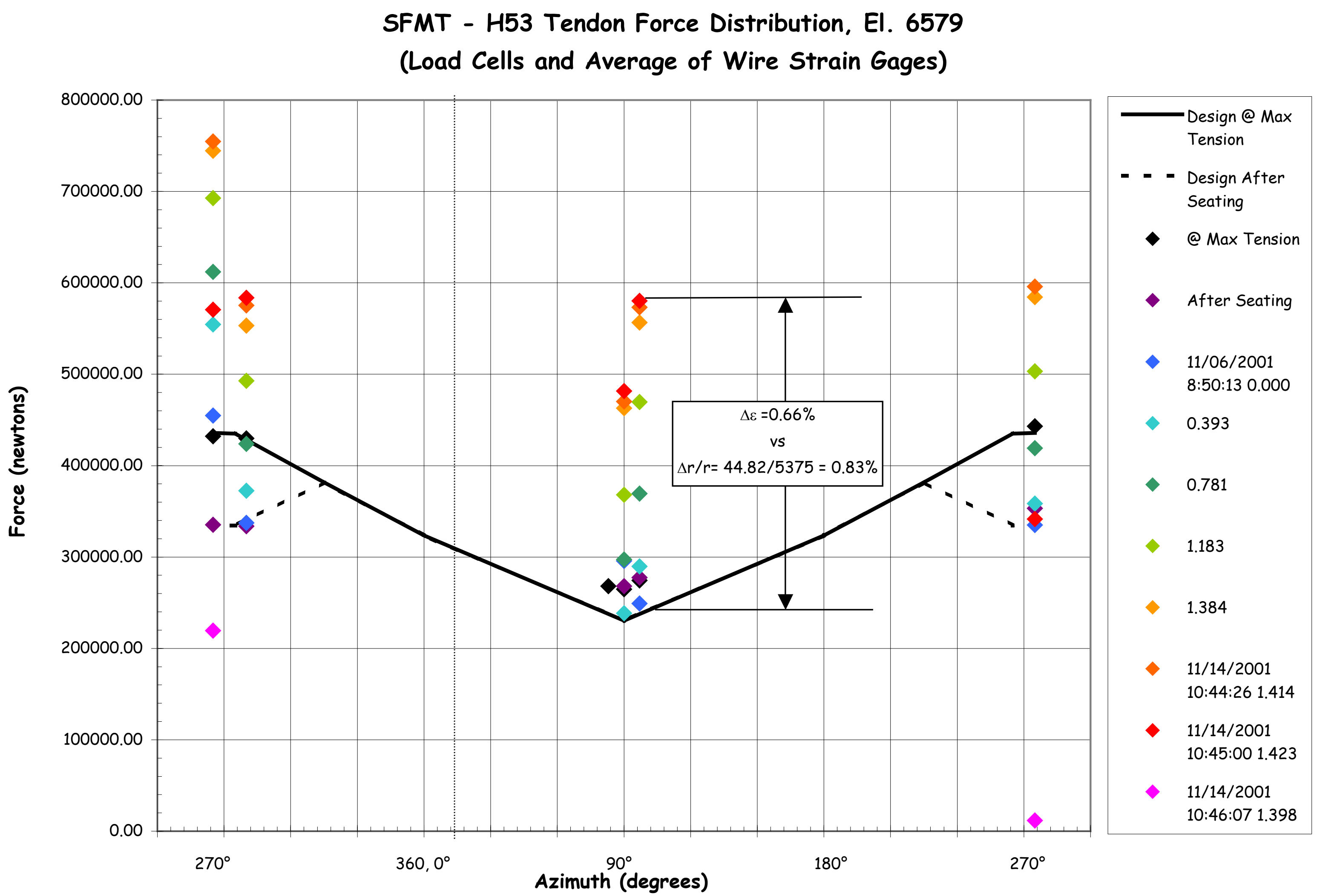




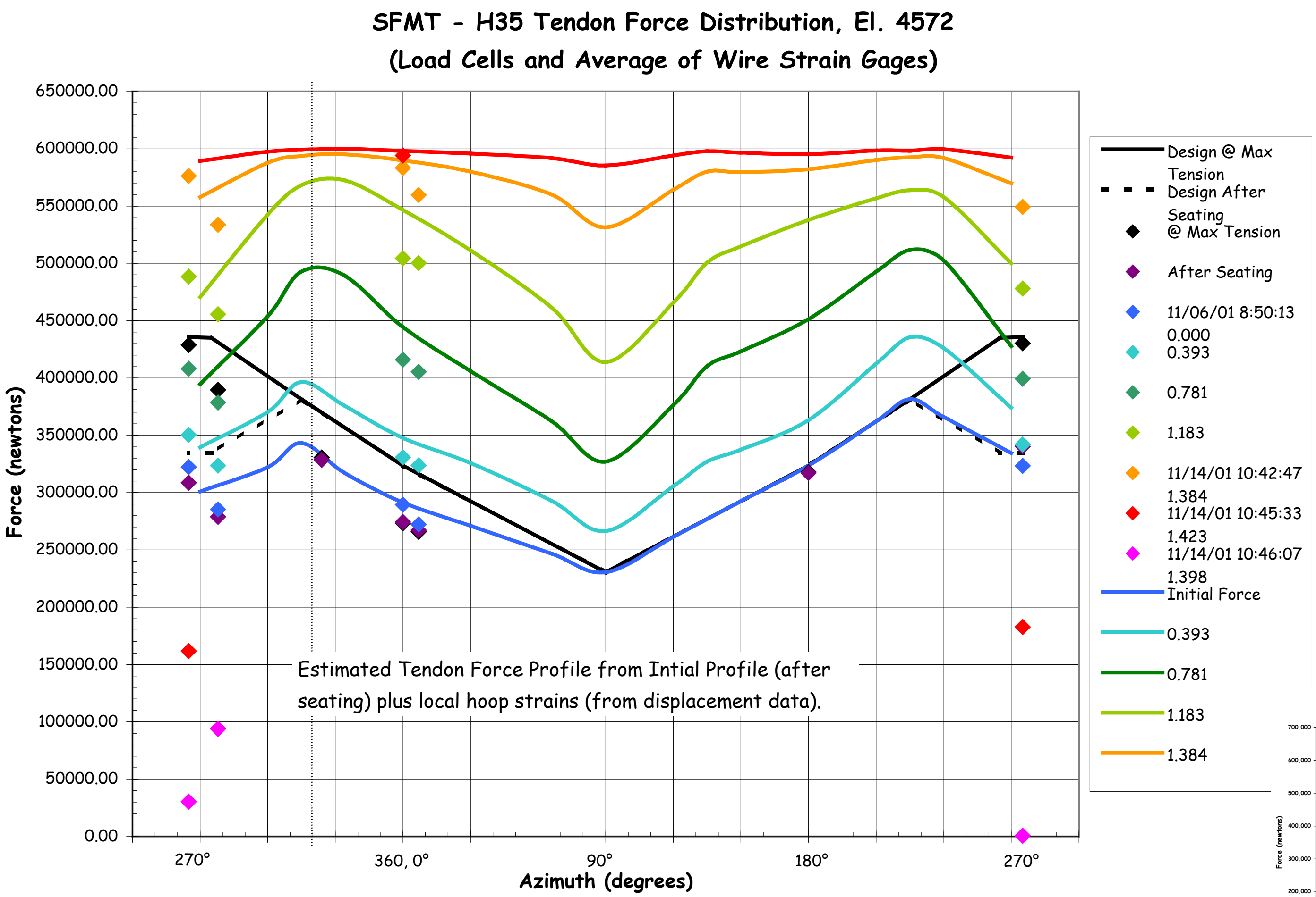


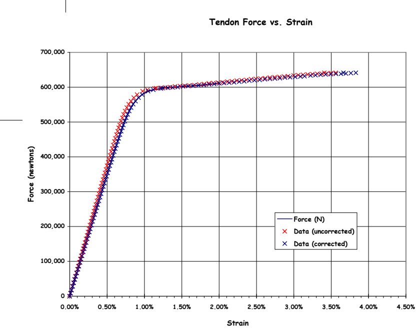


Tendon Forces



Tendon Forces





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3D SHELL SFMT SIMULATION MODEL

- **3D SHELL MODEL DEVELOPED USING:**
  - **ABAQUS S4R shells with separate layers, concrete/liner**
  - **Rebar modeled as subelements at appropriate depth**
  - **Tendons modeled as subelements (strain compatible with concrete, so no “slip”)**
  - **Tendon stress distribution run two ways: uniform stress, and with initial friction “design” profile**
- **LOADING**
  - **LST pressurization**
  - **LST unloading**
  - **Hydrostatic**
  - **Added Pressure of SFMT**

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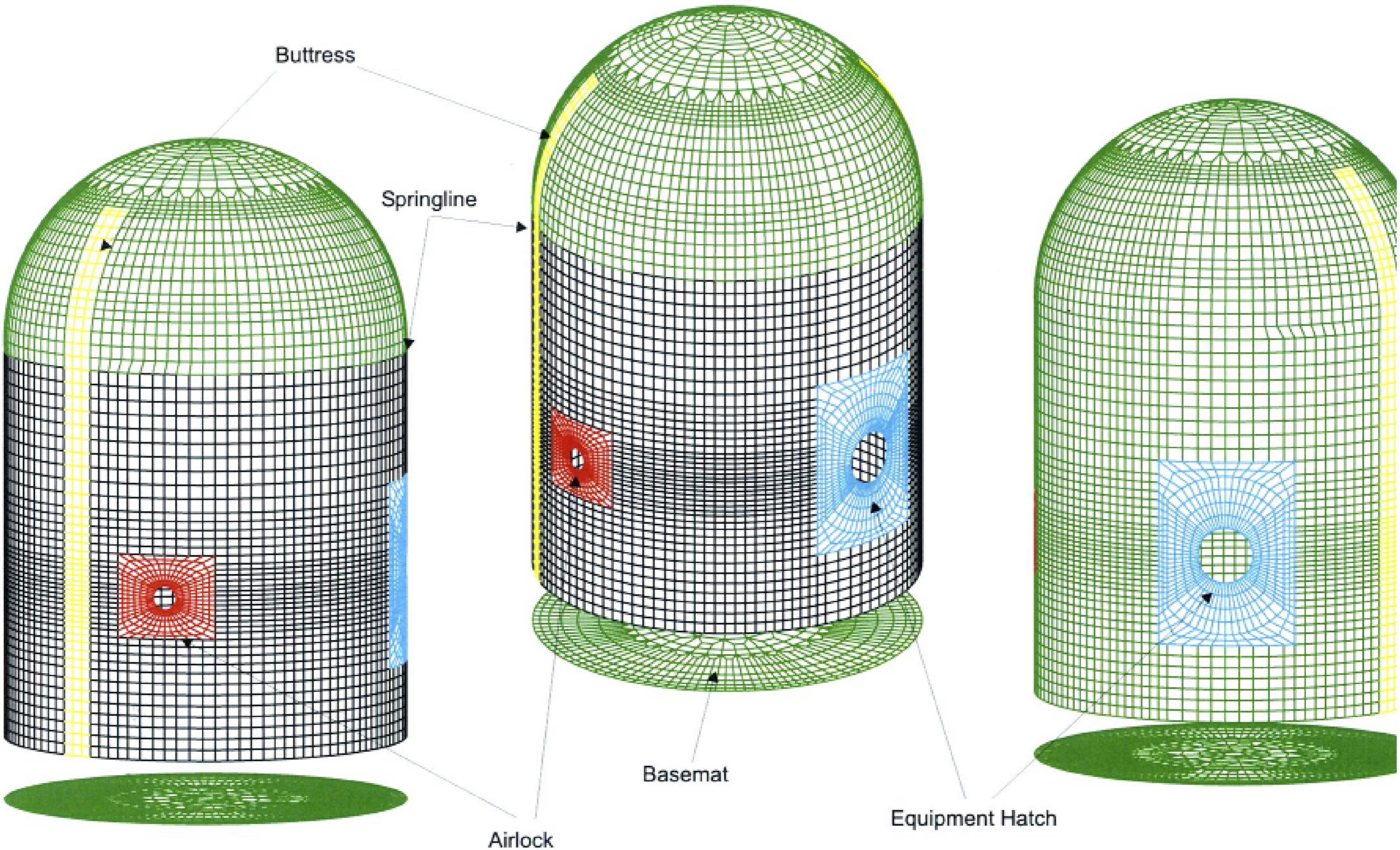
3D Shell Model of SFMT



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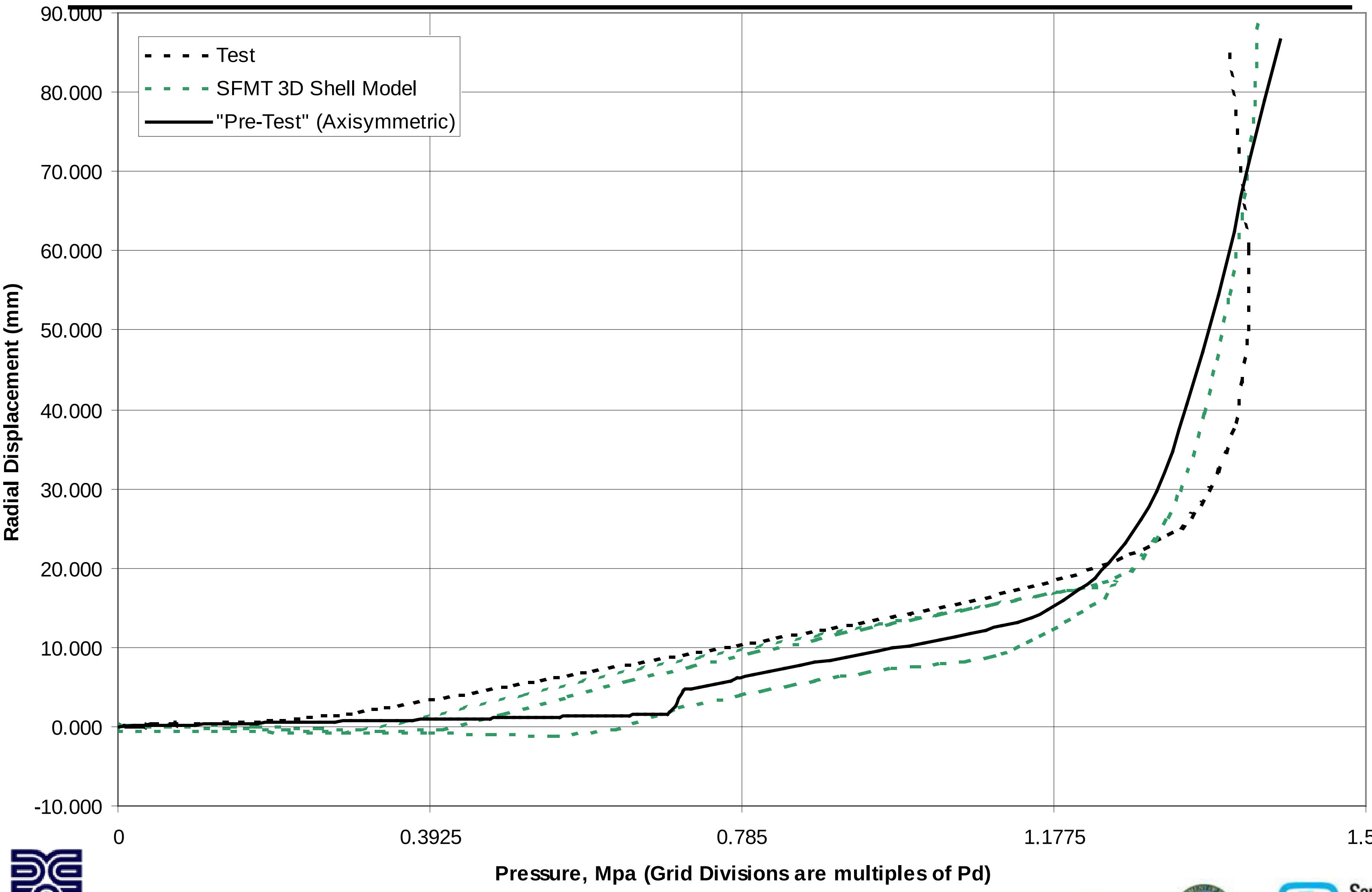
Radial Displ. At Elev. 6.2m, 3D Shell Model Compared to SFMT



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3D SHELL SFMT SIMULATION RESULTS

- **OBTAINED A GOOD MATCH TO MOST DISPLACMENT MEASUREMENTS THROUGH P=3.5Pd**
- **HIGHEST TENDON STRAIN WAS HOOP TENDON AT BETWEEN O° AND 6° AZIMUTH AND 5 M ELEV. – REACHES 5% AT ~ 3.6Pd**
- **WHEN TENDON RUPTURE CRITERIA ADJUSTED DOWNWARD TO 2%, TENDON RUPTURE OCCURS AT ~3.5Pd AND POST-RUPTURE "LOCAL BULGING" OCCURS: SIMILAR TO SFMT OBSERVATIONS**

SFMT - Photo of Exterior of PCCV after Failure

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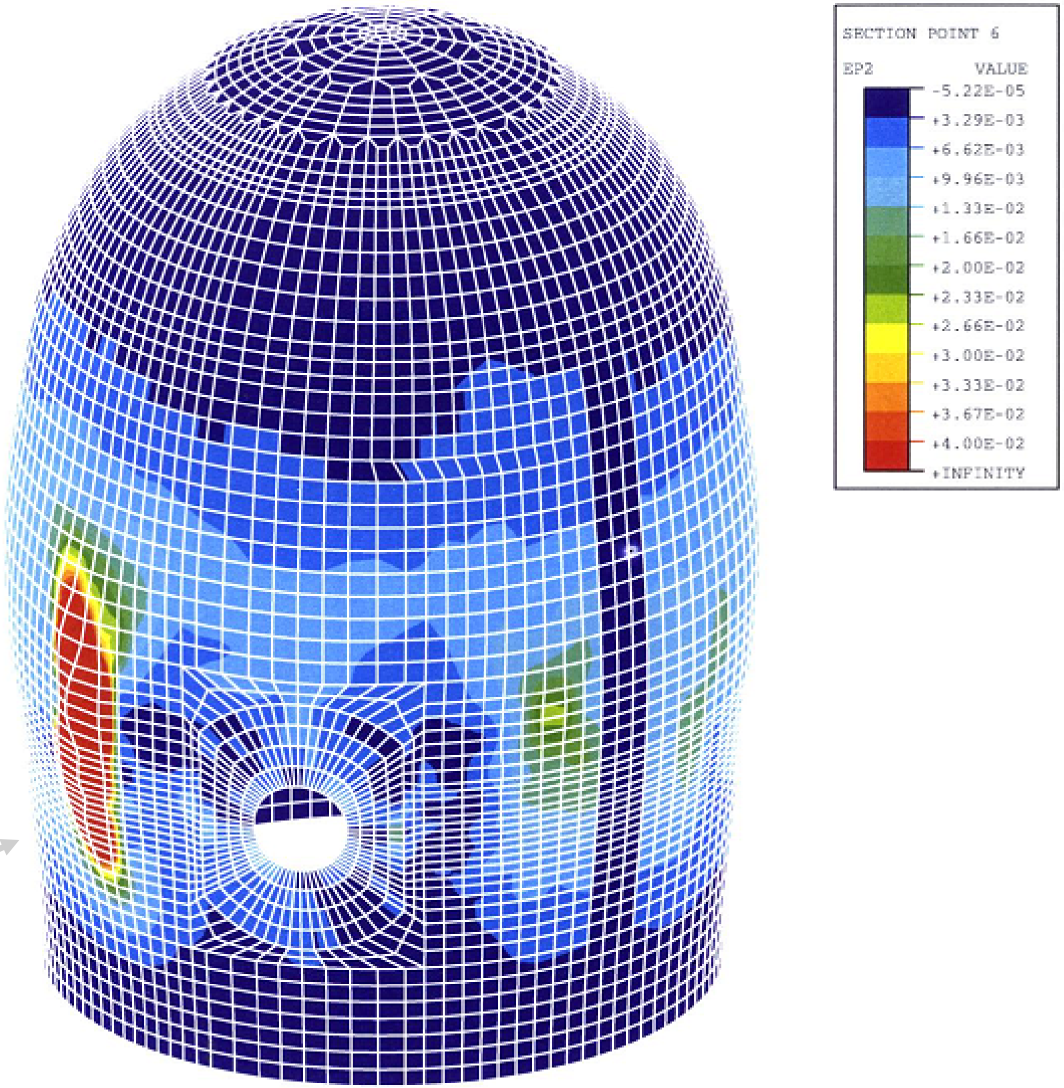
SFMT, 3D Global Shell Model, Showing Max Princ. Strain For 1.381 Mpa (3.51Pd) Pressure

(Displ. X 10)



Tendon Rupture (Strain ~4%)

1.381 MPa

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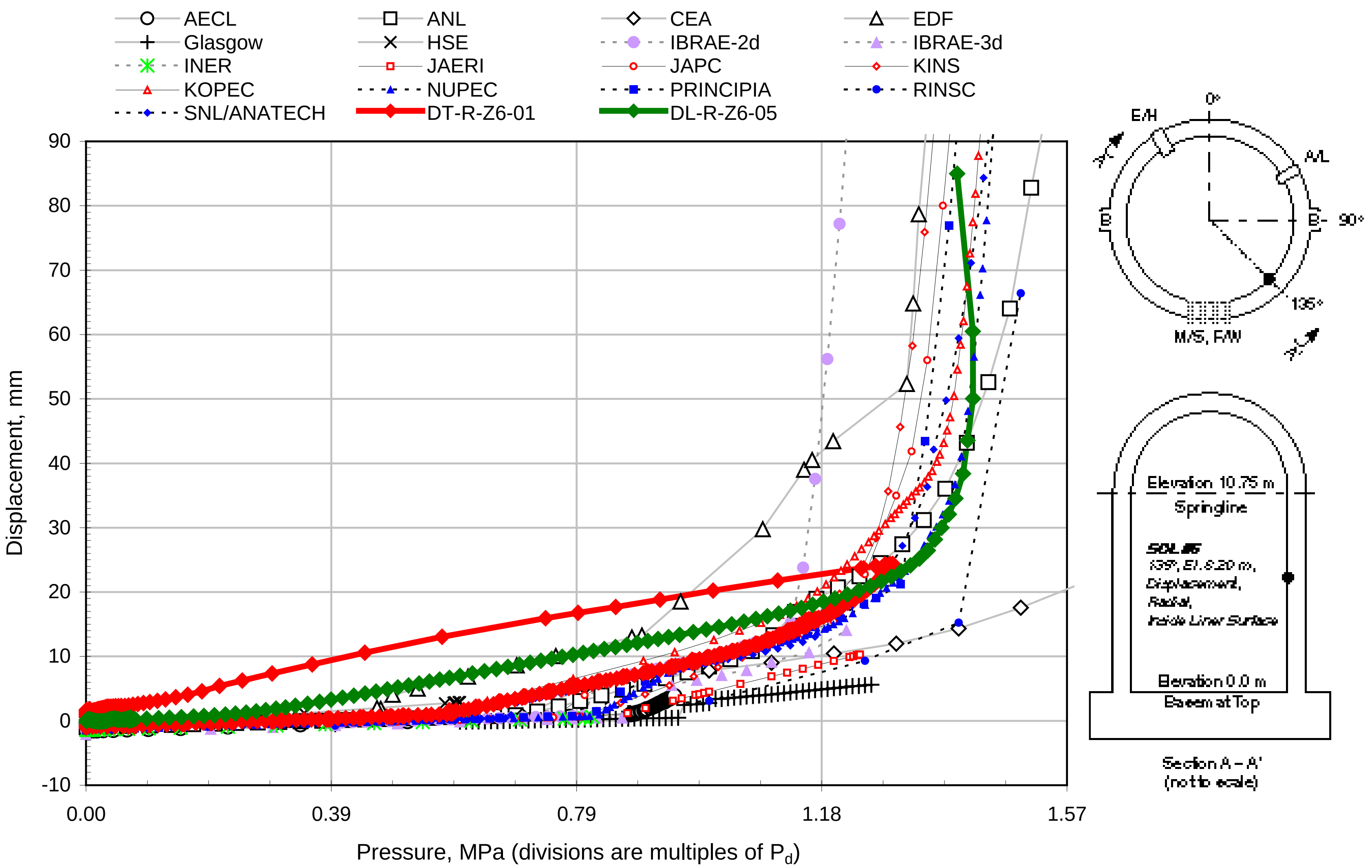
CONCLUSIONS AND LESSONS LEARNED FROM PCCV ANALYSIS

- THE DRIVING RESPONSE QUANTITY WHICH LEADS TO LIMIT STATE OF THE VESSEL IS RADIAL EXPANSION OF THE CYLINDER
- THIS ASPECT OF RESPONSE MUST BE PREDICTED CORRECTLY TO PREDICT VESSEL CAPACITY AND LOCAL RESPONSE
- WITH THIS TEST, AS WITH THE 1:6 SCALE RCCV MODEL, MANY COMPETING STRAIN CONCENTRATIONS OCCUR AROUND THE MIDHEIGHT OF THE CYLINDER
- IT REMAINS DIFFICULT TO PREDICT WHICH LOCAL LINER DETAIL WILL TEAR FIRST BECAUSE OF MANY FACTORS
- RADIAL EXPANSION OF CYLINDER WAS PREDICTED ACCURATELY
- CYLINDER WALL-BASE FLEXURE AND SHEAR ALSO WELL PREDICTED. (IF PREDICTED INCORRECTLY, THIS COULD ALSO LEAD TO INCORRECT CAPACITY/FAILURE MODE CONCLUSIONS.)
- MINIMUM REQUIREMENT FOR CONTAINMENT OVERPRESSURE EVALUATION IS A ROBUST AXISYMMETRIC ANALYSIS.

Round Robin Predictions



SFMT Conclusions

- **SFMT objectives were met:**
  - **Additional data on the response of the PCCV model ‘well beyond’ the elastic limit were obtained.**
  - **Structural failure mode was demonstrated.**
  - **Structural failure mode does not appear to be a result of any flaw in the structure but appears to represent a true structural limit.**

Analysis References

Dameron, R. A., et al., “Methods for Ultimate Load Analysis of Concrete Containments, 4th Phase: Concrete Containment Leakage Predictions - A Probabilistic Approach with Applications to NUREG-1150”, ERPI RP-2172-1, Electric Power Research Institute, Palo Alto.

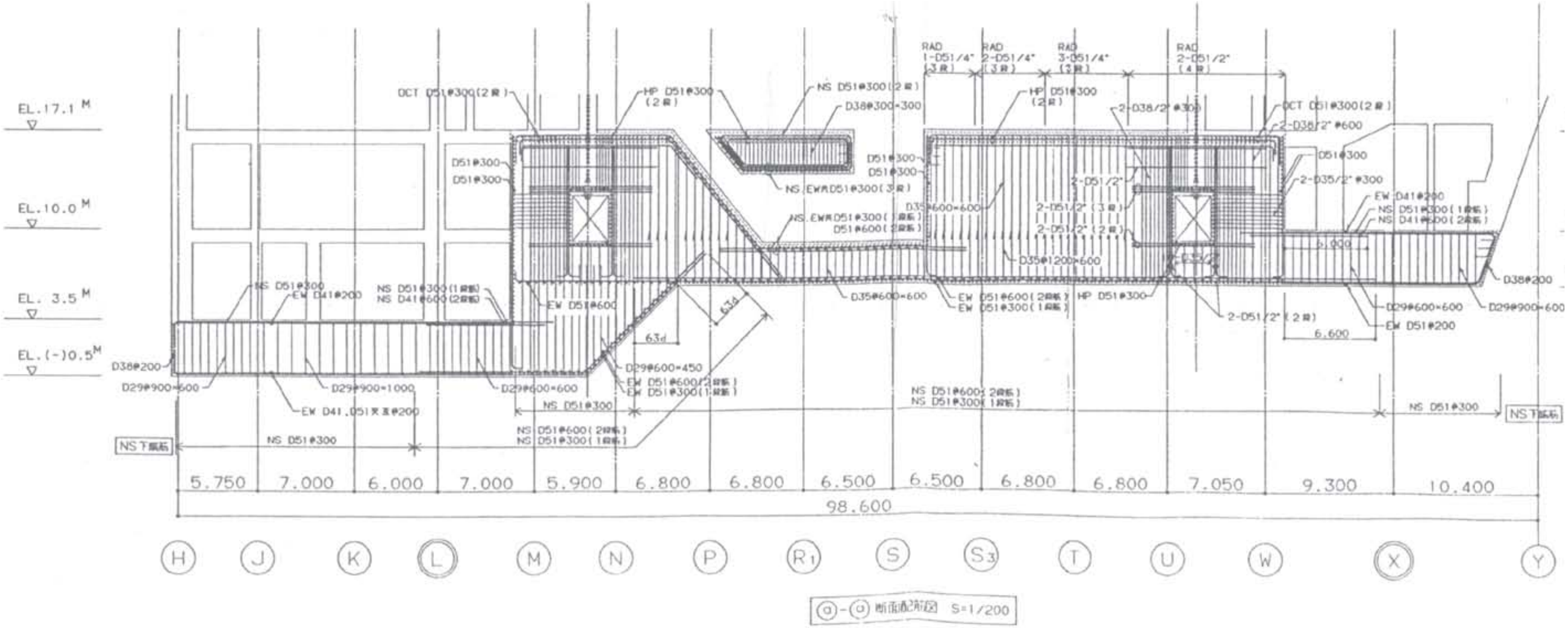
Dunham, R. S., Rashid, Y. R., Yuan, K. A. and Lu, Y. M., “Methods for Ultimate Load Analysis of Concrete Containments,” EPRI NP-4046, Electric Power Research Institute, Palo Alto, 1985.

Dameron, R. A., Rashid, Y. R. and Sullaway, M. F., “Pretest Prediction Analysis and Posttest Correlation of the Sizewell-B 1:10-Scale Prestressed Concrete Containment Model Test”, SAND90-7117,Sandia National Laboratories, July 1998.

RECENT STUDIES OF MODEL ARTIFACTS AND SCALING ISSUES

- **Full Scale Liner Rat-hole**
  - **strain concentrations significantly reduced because “thinning” due to overgrinding does not “scale-up” to full scale**
- **Full Scale Axisymmetric**
  - **hoop response of cylinder was “identical”**
  - **uplift was reduced at full-scale; may be partly gravity effects**
  - **wall-base flexure response shows effects of difficulty in scaling shear/flexure relationship**
    - **Neutral axis has shifted & flexural strains are reduced**
  - **implies increased separation of cylinder midheight versus wall-base failure modes for full scale**
- **Full scale axisymmetric w/ Reactor Pit**
  - **modifications (mesh block-outs) produce virtually no affect on predicted behavior**

Cross-Section of Typical Containment Basemat Showing Reactor Pit



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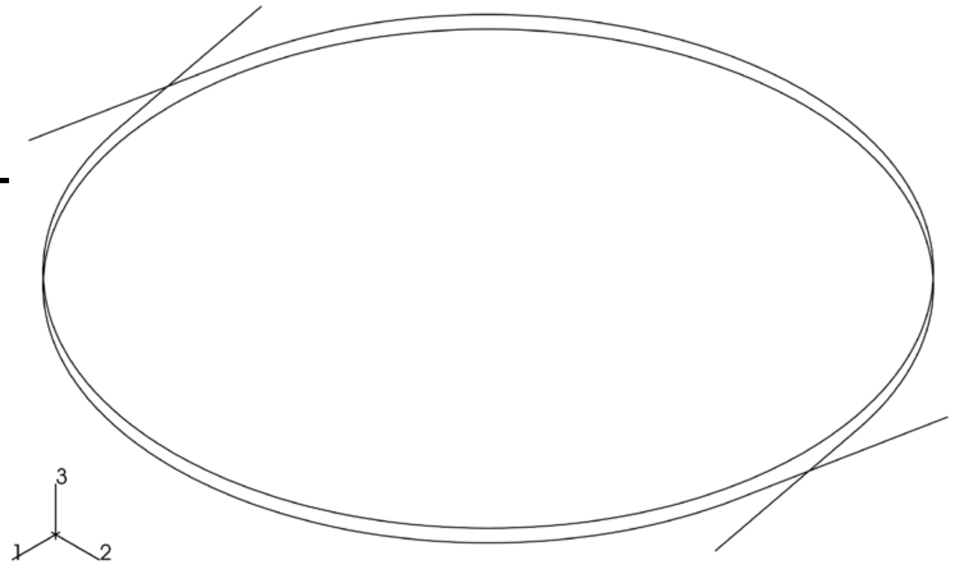
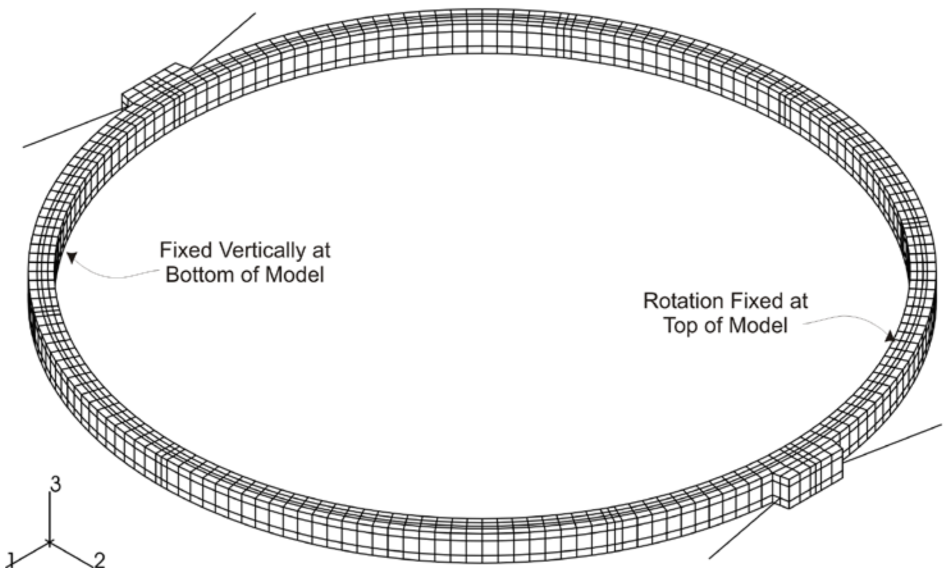
SCALING ISSUES, Cont’d - Tendon Behavior Studies

- **Ring Model for Tendon Friction Study**
  - **Used top “slice” of 3DCM model, but completely changed tendon friction modeling approach: contact surface**
  - **first verified could “match” 3DCM results using “truss-ties”**
  - **after initial numerical difficulties the technique found to work well**
  - **Now friction applied “naturally;” just analytically prestress the ends - then for anchor set, in Step 2, release some stress at ends**
- **Deformed shapes generally agree much better with test observations; improved prediction over “truss-tie” approach**
- **sensitivity analyses with friction and anchor sets explored tendon friction scaling issues**



Tendon Groups H67 and H68

Ring Model for Tendon Behavior Studies



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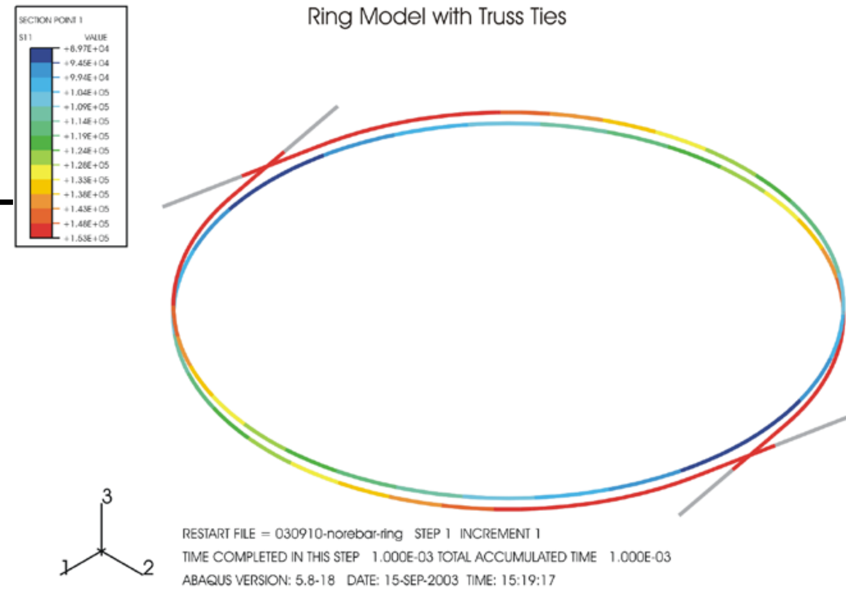
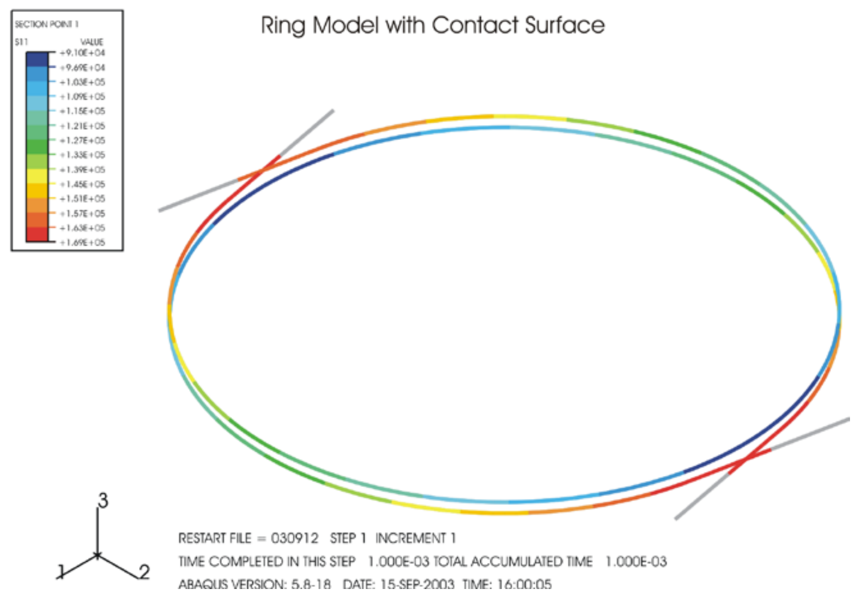
Tendon Stress Distr. - Comparison of Truss Tie & Contact Surface Methods





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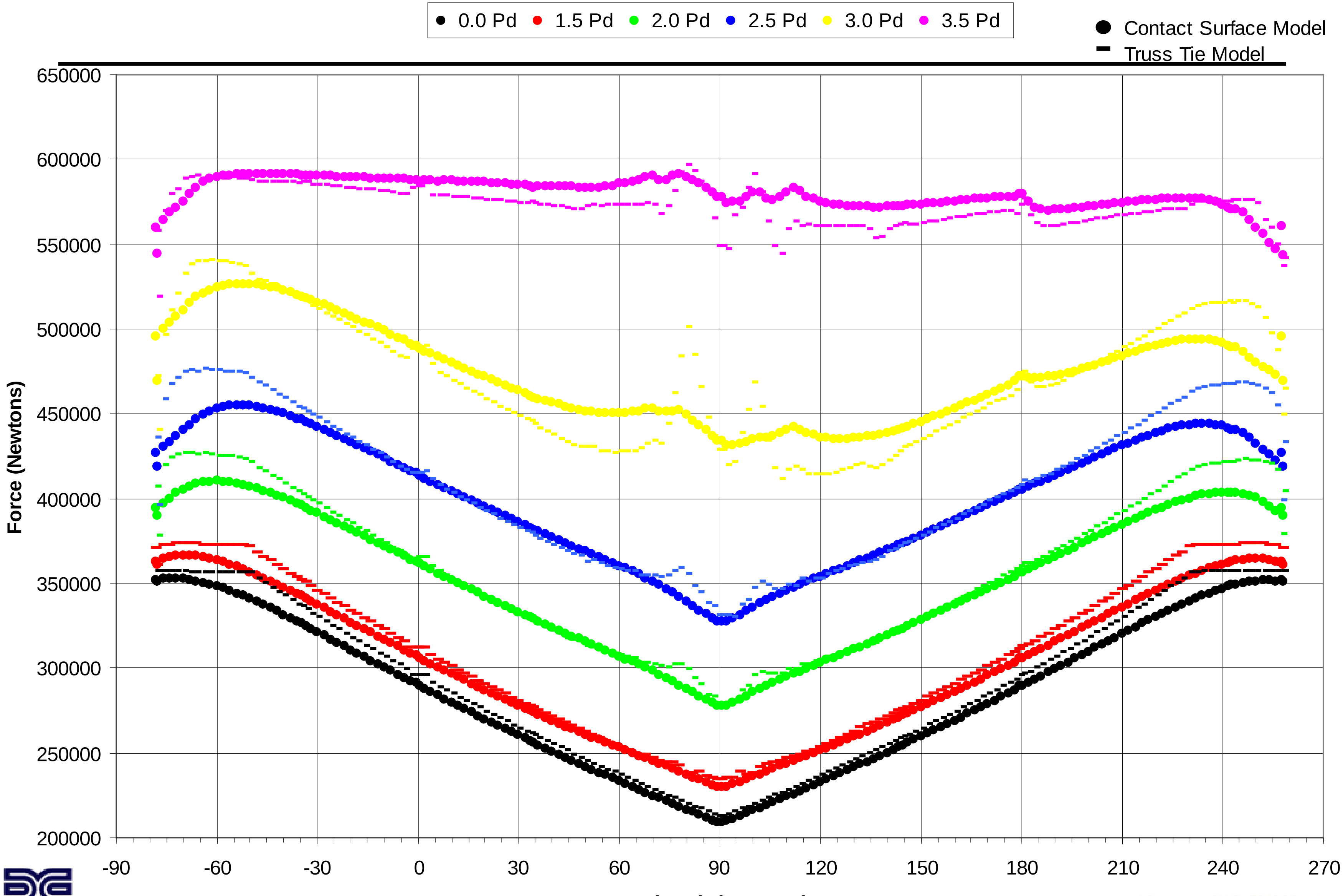
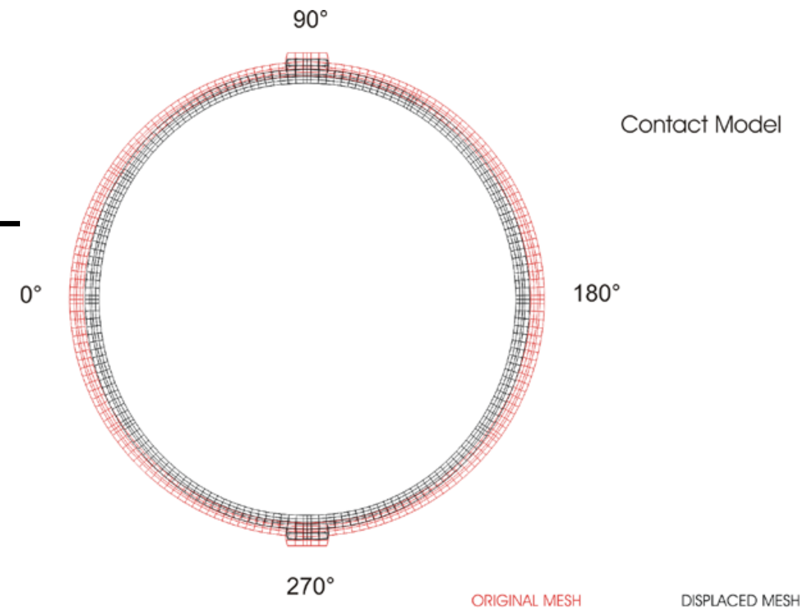
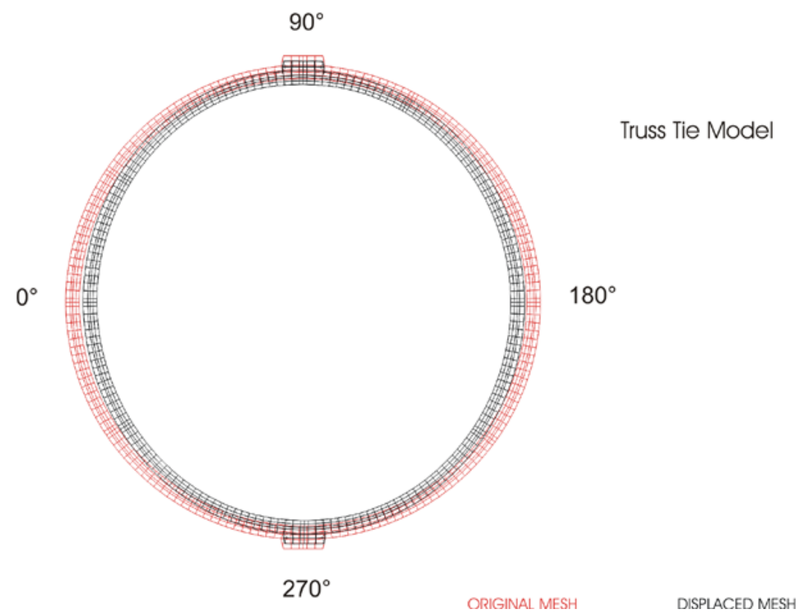
Tendon Force Distr. (1/4 Scale PCCV) - Comparing Methods



1 / 4 Scale PCCV Tendon Study - Deformed Shape After Prestress (x200)





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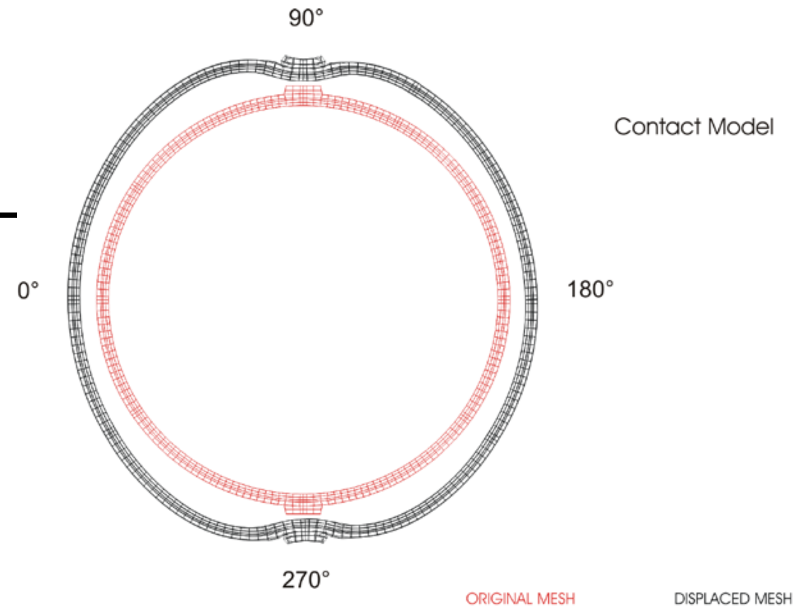
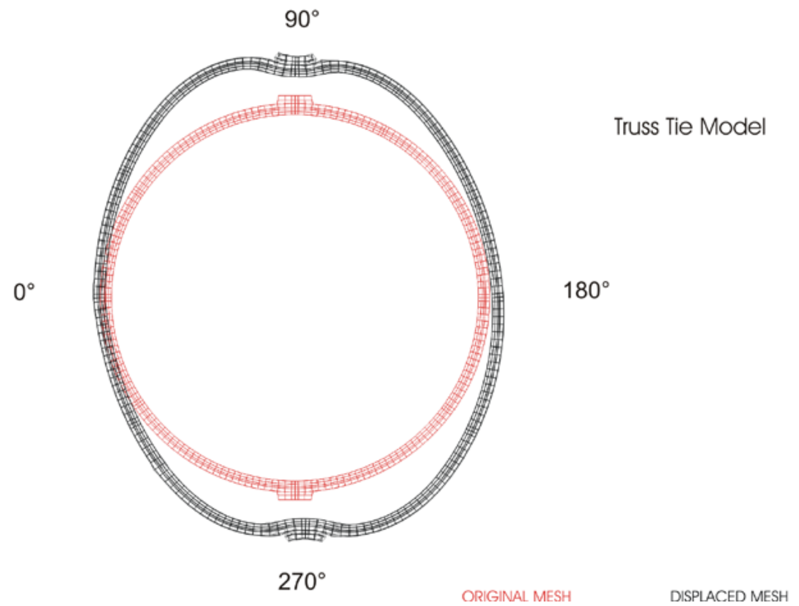
1/4 Scale PCCV Tendon Study - Deformed Shape After at P=2Pd (x200)





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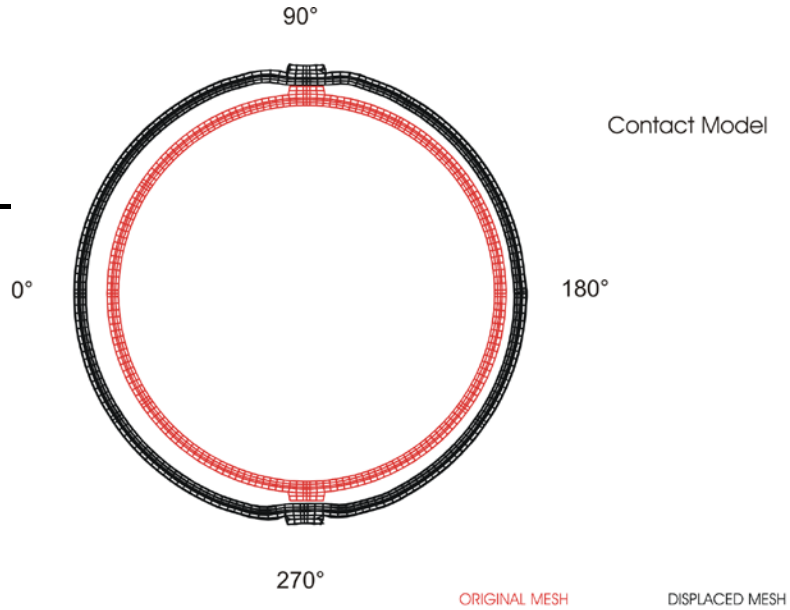
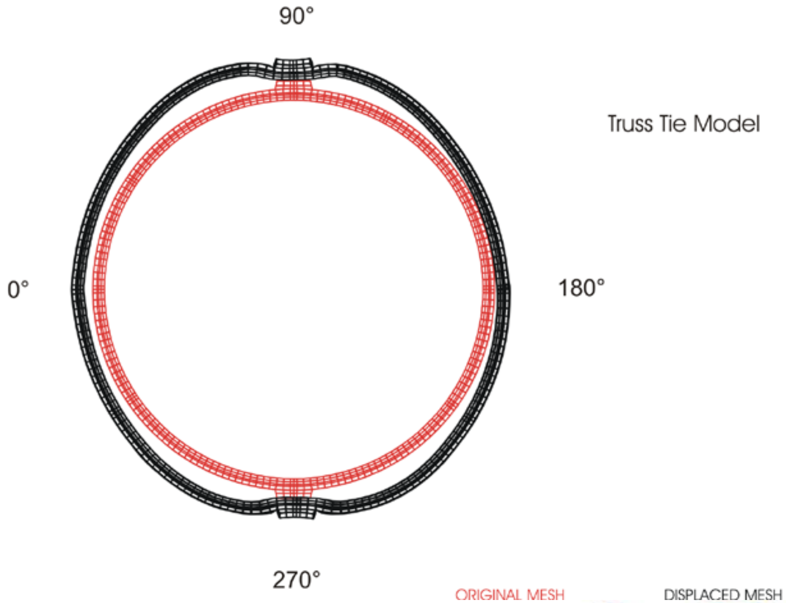
1/4 Scale PCCV Tendon Study - Deformed Shape After at P=3.5Pd (x20)





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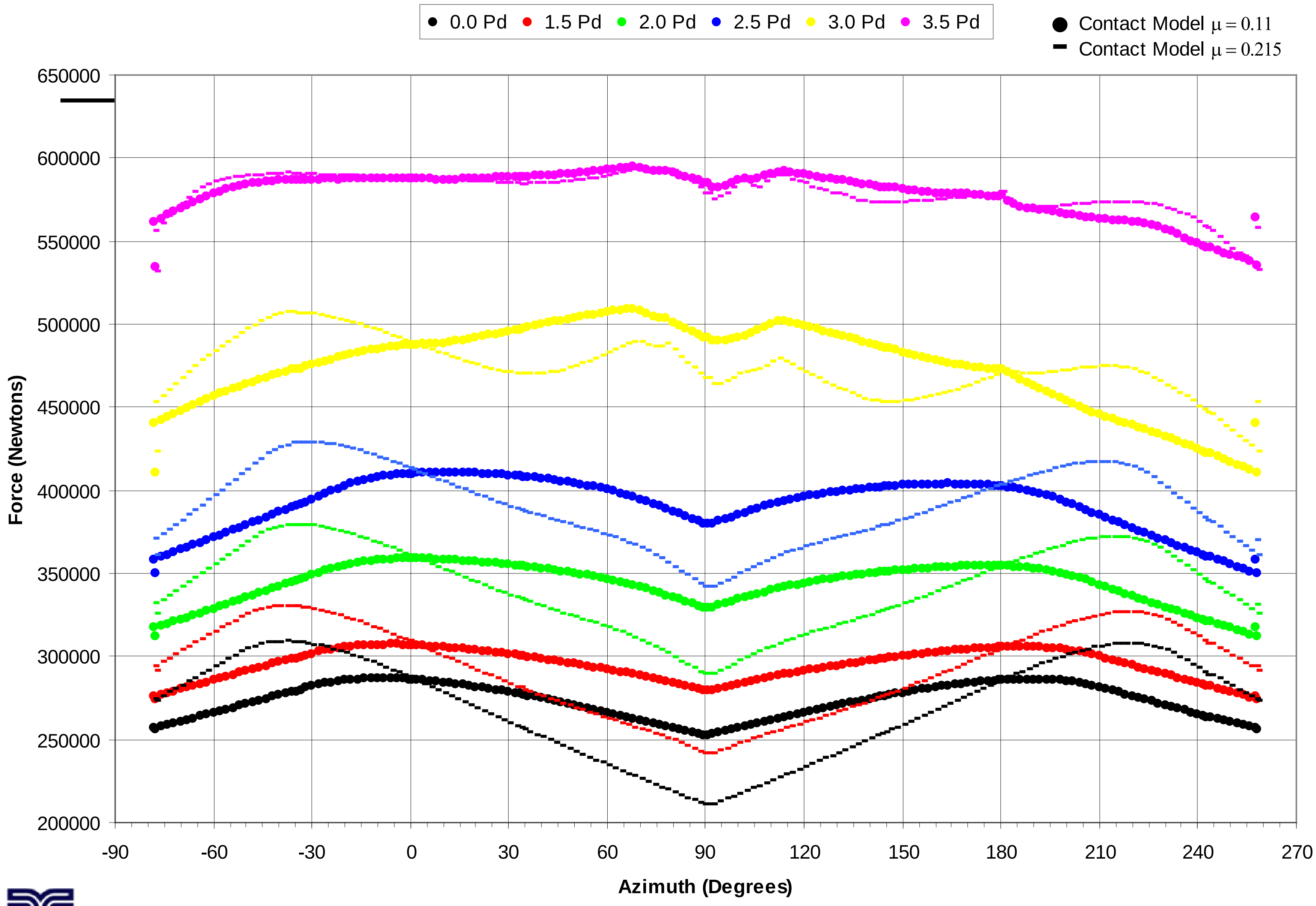
Tendon Force Distr. Comparing Full to 1 / 4 Scale Friction



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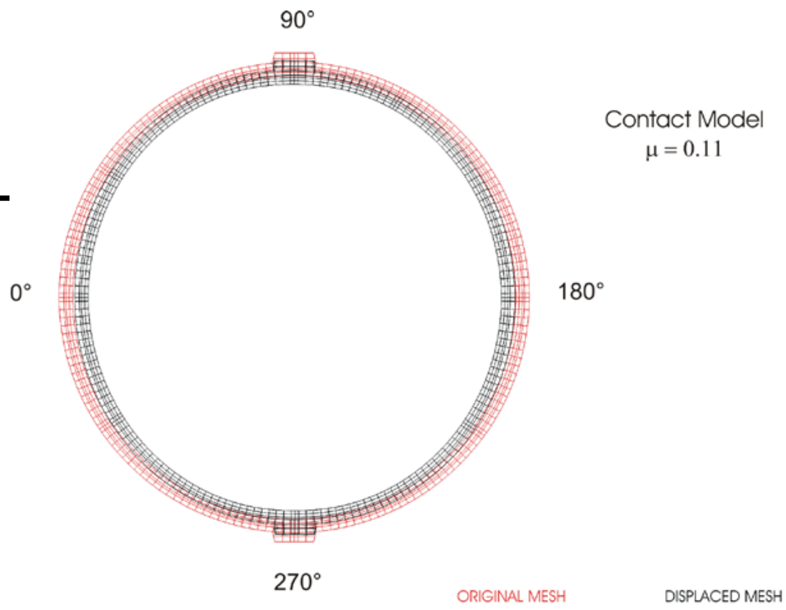
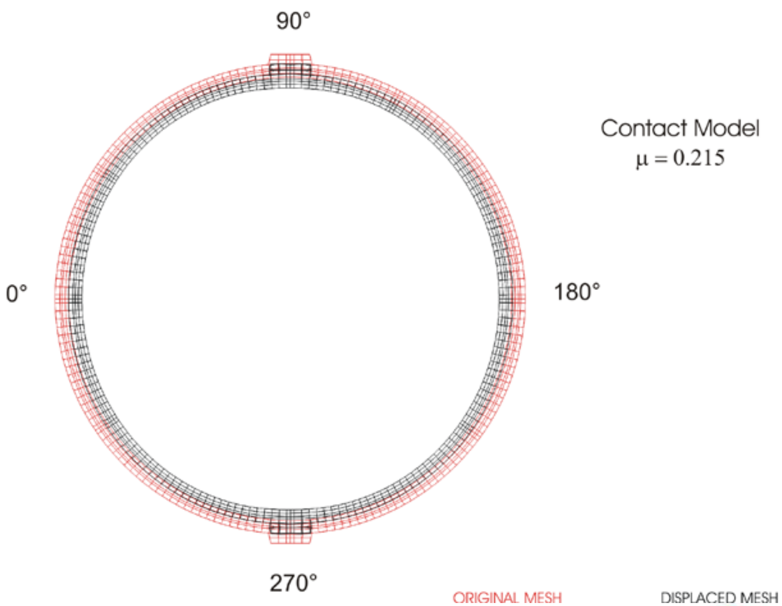
Comparing Full to 1/4 Scale Friction - Deformed Shape After Prestress (x200)





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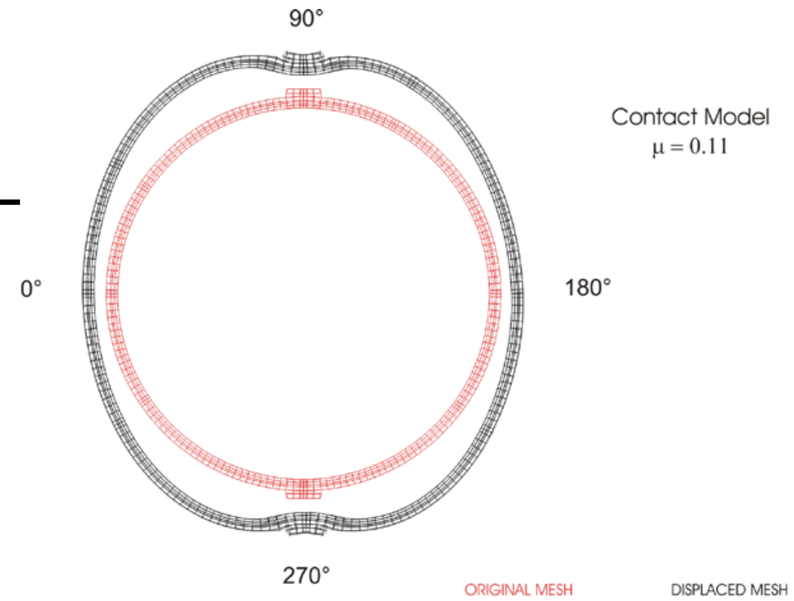
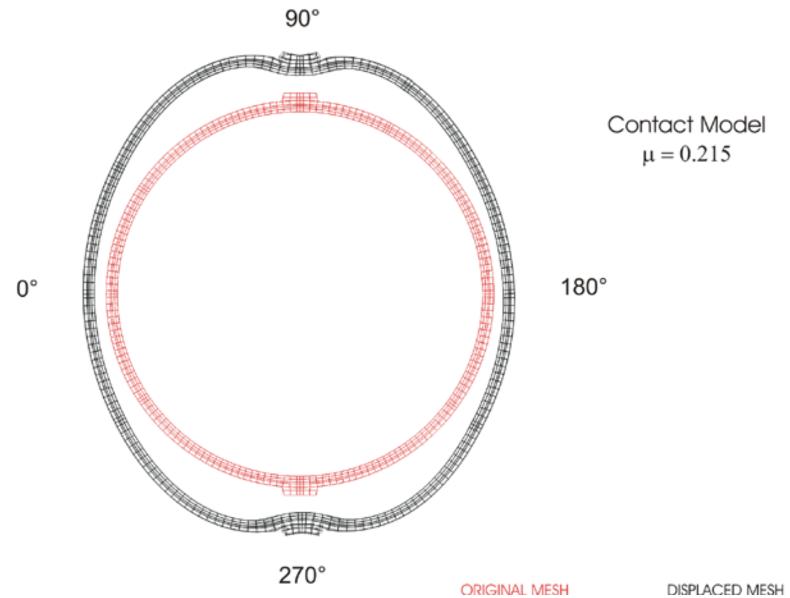
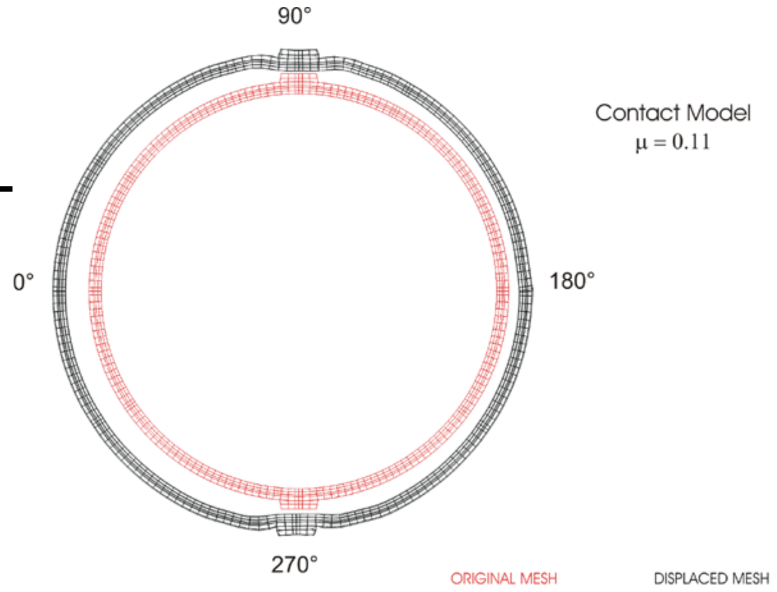
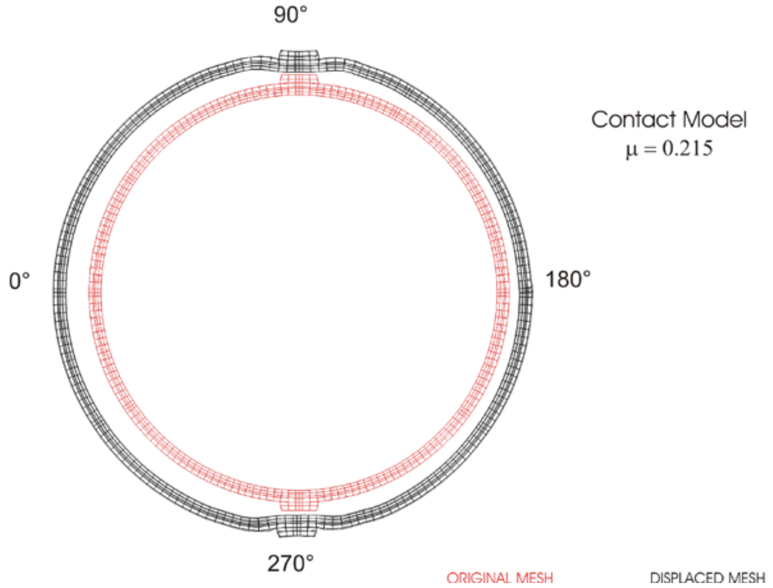
Comparing Full to 1/4 Scale Friction - Deformed Shape At P=2Pd (x200)





Comparing Full to 1/4 Scale Friction - Deformed Shape At P=3.5Pd (x200)





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CONCL. - TENDON BEHAVIOR STUDIES

- **With 6mm anchor set, largest radial displacements occur near buttress, which creates elliptical displaced shape. With 2mm anchor set, displacement more uniform over entire circumference and smallest displacements occur at buttresses. This is more the trend that occurred in the test.**

- **Tendon Contact Surface Model also compared effects of changing friction coefficients and changing zones of anchor set - important since friction is substantially different at full scale (0.11 vs. 0.21).**

- **Overall conclusions: contact surface approach provides much improved simulation of cylinder response and tendon behavior at intermediate pressures (1.5 Pd to 3Pd), but near the tendon limit state of ~3.5Pd, all methods provide a reasonable prediction. Further, the low and intermediate pressure response is sensitive to anchor set and friction coefficient (scaling) assumptions, but high pressure response is not.**

Some General Containment Analysis Conclusions / Guidelines

Global vs. Local Response Prediction

- Bi-symmetric about one plane or Quarter-symmetry about two orthogonal planes?
- Wedge or Sector symmetry, i.e. can a 'slice' or repeating sector (e.g. 30º) of the structure represent the response of the entire structure
- Axisymmetric? Sources of non-axisymmetric behavior include
  - Major openings (usually the Equipment Hatch and Personnel Airlocks)
  - Hoop tendon buttresses ("Ribs"),
  - Dome tendon layout (part of which is rectilinear)
  - Basemat rebar layout (part of which is rectilinear)
- Apparent geometric symmetries can mask underlying asymmetries in the structure, such as changes in stiffness associated with variations in reinforcing.

Level of Detail and Mesh Densities

- Need to anticipate types of behavior:
  - Membrane action
  - Flexure
  - shear
- General FE modeling guidelines apply
  - Use “reasonable” aspect ratios on element shapes
- Specific for PCCVs:
  - Increased refinement at base of wall, wall-base-juncture
  - Use enough solid elements through thickness to characterize bending and shear (probably a minimum of 6 linear elements through thickness)
  - Increase refinement at wall-dome juncture
  - Increase refinement wherever steep gradients in stress/strain occur
- Most reliable approach – conduct a model exercise of a similar structure using a known solution or a scale test model to validate meshing decisions, assumptions and software

Modeling Reinforcement

- “Subelements” are recommended where
  - Plain concrete and steel are “two separate materials joined together”
- Some form of automated mesh generation is generally required
- For small, local models, rebar can be simulated as “truss” elements, but this requires nodal points for every element. Can be very cumbersome.

Modeling Prestressing

- Can be modeled as rebar because the tendons are grouted
  – In an axisymmetric model, horizontal tendons are "dots"
  – What azimuth is selected; what is initial tendon stress?
- Simulating Initial Conditions and Losses
  – Calculate best estimate "in service" values
  – Apply tendon stresses, and allow model to equilibrate; check tendon stress after equilibrium is reached; sometimes this is iterative
- Consider losses:
  – Elastic shortening
  – Steel relaxation
  – Shrinkage and creep
  – Anchor set
  – Angular friction (and wobble friction)
  – Others, e.g. temperature (for example $\alpha\Delta T$ causes loss of prestress)

Modeling the Liner

- Except for local sub-model studies, liner can be considered bonded to concrete
  - Model with shell elements
- Should consider
  - Variations in thickness (and mfg. tolerances)
  - Possible corrosion for consideration of 50-year-life evaluation
- Checks for temperature induced buckling should be performed with separate calculations

Material Modeling Best Practices

- **Minimum Suite of Material Property Inputs**
  - **Concrete**
    - **Young's Modulus, F_{ck}, F_{tk}, Poisson's ratio**
  - **Steel**
    - **Young's Modulus, F_{yk}**
  - **Multi-point stress-strain curves for all, if data is available, and the analysis objectives warrant it.**
- **Constitutive Modeling**
  - **Concrete: smeared cracking, crushing, post-cracking shear retention, confinement effects**
  - **Steel: yielding**
  - **Temperature dependence**
- **Steel Concrete Interaction**
  - **Liner slip/contact surface?, generally not found to be necessary**
  - **Tendon anchor zones-should be considered, especially where coincide with zones of high shear or cracking**
  - **Rebar anchor zones - generally not a candidate for explicit modeling unless there is anchorage detail located in a concrete high tension or shear zone**

Time-Dependent Effects

- EPR Approach considers drying creep and basic creep with
  - Changes to P/T stress levels
  - Changes to short-term vs. long-term Moduli
  - A linearized stiffness approach
- Probably ok for most aspects of the design check
- May want to consider a “Stage” analysis with step-by-step time dependence effects
  - Could provide greater accuracy (and possibly address lack of conservatism) for predicting rebar and concrete stresses in compressive zones (e.g. at outer base of cylinder wall)

Linear Approximations of Behavior

- **Sometimes used in PCCV analysis:**
  - **Reduced concrete Young's Modulus to account for cracking**
  - **Adjustments to stiffness to account for aging**
  - **Thermal Degradation adjustments**
  - **Development of linear formulation springs**
- **Can be a limitation on accuracy of deformation prediction**
  - **Deformation prediction; tangent stiffness or "secant stiffness" approaches are approximate, and sometimes require iterative analysis**
  - **Section force and moment prediction; e.g. at wall-base juncture, section forces are highly statically indeterminate**

Application of Loads and Suite of Analyses

- Boundary Conditions, Dead, and Pressure Loads
  - Ensure that BC's and point load applications occur "for enough" away from local area of interest
  - Ensure that local deformation state is compatible with the global one
  - For submodels, ensure that "rigid-body" displacements are adequately constrained
- Uniform Temperature Rise
- Hydrogen Deflagration
- Discussion of Temperature Analysis

Checks on Solution Quality

- General behavior (at important response milestones) of an "idealized" cylinder and dome can be checked by spreadsheet.
- Example: Simplified check Analysis (using the 1:4 scale PCCV model)

Seismic Evaluation

- Important considerations for Seismic Analysis
  - Structure masses
  - Structure stiffnesses (may need to consider what is desired/expected "performance" level)
  - Foundation stiffnesses
  - Section forces in wall are combined correctly
- Considerations of Ductility and Performance-Based Design