SPE-meeting Phase 1, Washington DC 2011-04-13

Scanscot Studies

STANDARD PROBLEM EXERCISE (SPE)

PERFORMANCE OF CONTAINMENT VESSEL UNDER SEVERE ACCIDENT CODITION

Project

- Scanscot organization

Patrick Anderson	Co-ordination, etc.
Björn Svärd	Model 1, tendon study
Oskar Elison	Model 2 and 3, liner study
Torulf Nilsson	Failure criteria
Ola Jovall	Initial planning, reviewing
Jan-Anders Larsson	Advising

- Financiers
  - Swedish Radiation Safety Authority (SSM) and Swedish / Finnish nuclear power industry

Overview

- Scope
- Scanscot SPE studies
  - General
  - Prestressing tendon behavior
  - Global containment response
  - Liner behavior near equipment hatch
  - Influence of structural parameter variation
- Conclusions

Scope

- Four different studies

Study 1 Explain the interaction between horizontal tendons and the containment structure. FE-model describing a horizontal slice of containment wall. (*Model 1*)

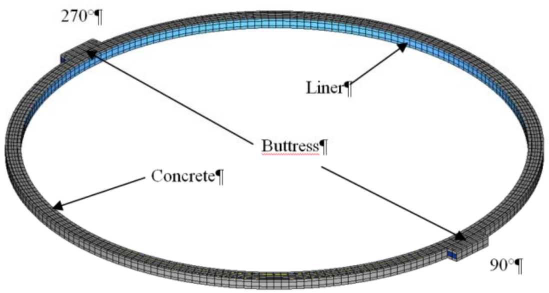
Study 2 Global structural response with focus on the behavior near the equipment hatch (penetration E/H). FE-model describing the whole containment model, refined in E/H region. (*Model 2 and 3*)

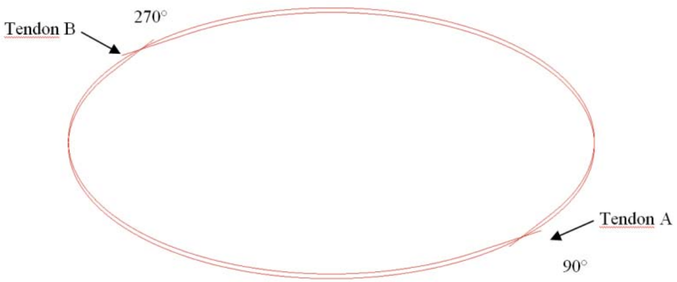
Study 3 Detailed behavior of the steel liner near the equipment hatch. FE-model describing the steel liner and the interaction with the concrete structure. (*Model 2*)

Study 4 Variation in input data and influence on containment structural behavior. Focus is on the global expansion of the containment. (*SPE 1.5*)

SPE studies
General

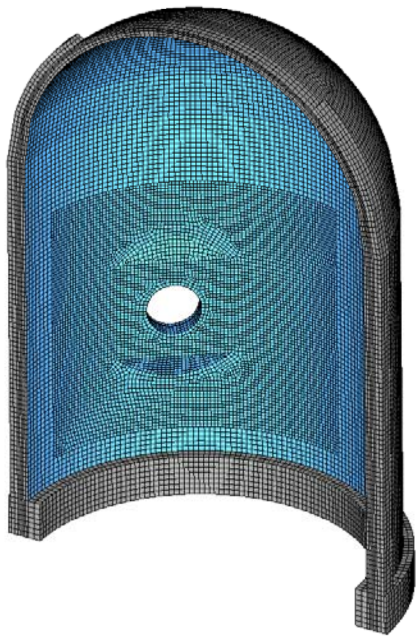
- Model 1



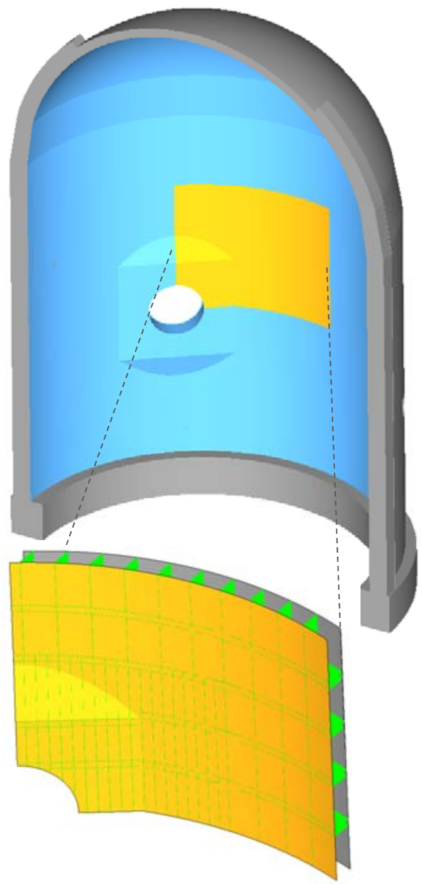


Midheigth horizontal slize model

- Model 2 and 3



Global model, refined in E/H region



Liner submodel, restrained by global model

SPE studies

General

- FE-program
  - Global model: Abaqus Explicit
  - Liner model: Abaqus Standard
- Material models
  - Concrete: Brittle cracking (linear compression, non-linear tension)
  - Steel: Plastic with hardening
- FE-models
  - Concrete: Solid elements
  - Reinforcement: Shell elements, orthotropic, embedded
  - Liner: Shell elements
  - Tendons: Bar elements (one by one)
- Input
  - ”best estimate”

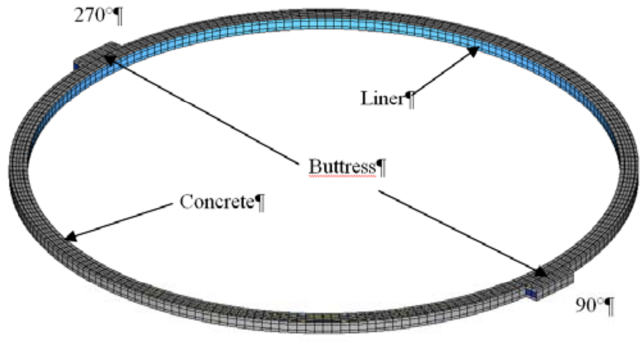
SPE studies

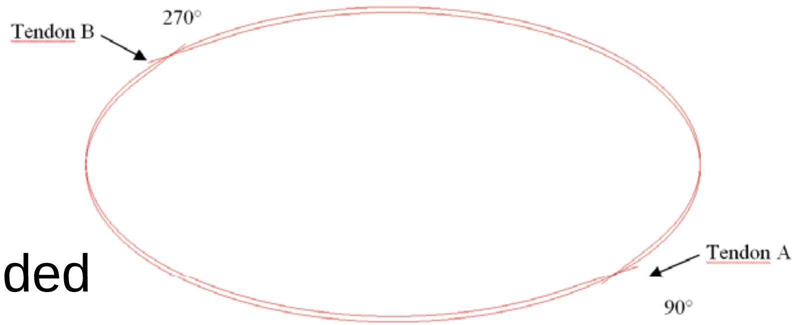
Prestressing tendon behavior (Model 1)

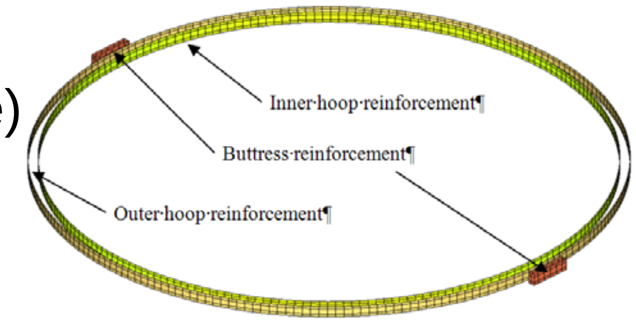
SPE studies

Prestressing tendon behavior (Model 1)

- FE-program
  - Abaqus Explicit
- Material models
  - Concrete: Brittle cracking
  - Steel: Plastic with hardening
- FE-model
  - Concrete: Solid elements
  - Reinforcement: rebar layer, embedded
  - Liner: Shell elements
  - Tendons: Truss elements (one by one)
- Input
  - ”best estimate” from material test



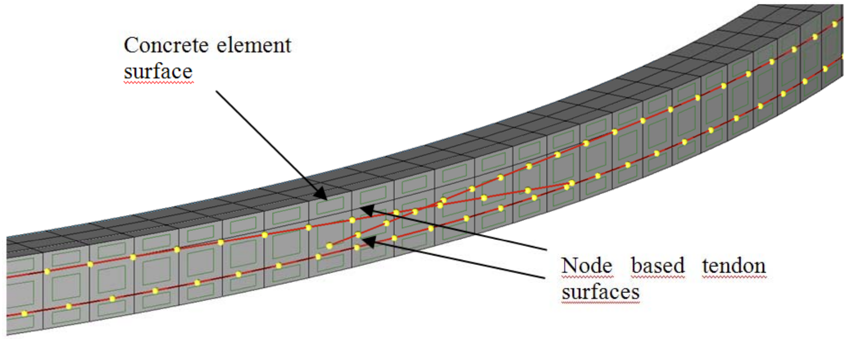


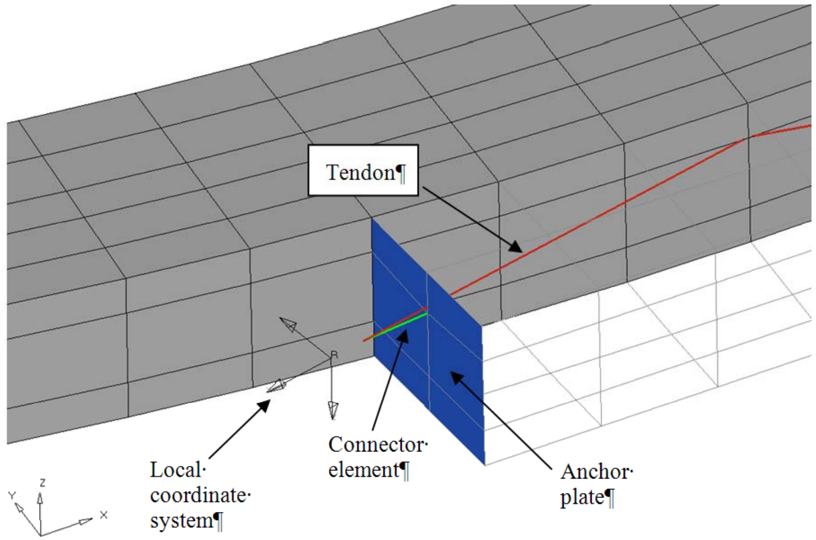


SPE studies

Prestressing tendon behavior (Model 1)

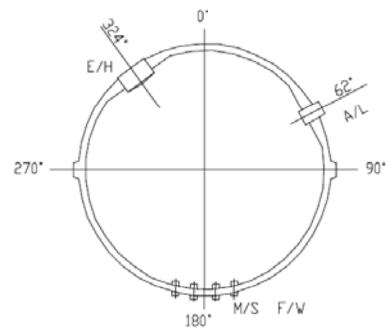
- FE-model, tensioning
  - Interaction: Contact definition (μ=0.22)
  - Prestressing: Connector force (F_o = 427 kN)
  - Seating: Connector motion (u_1 = 3.95 mm)
  - Long-term effects: Temperature load (tendon relaxation 85E-6, concrete creep -170E-6)



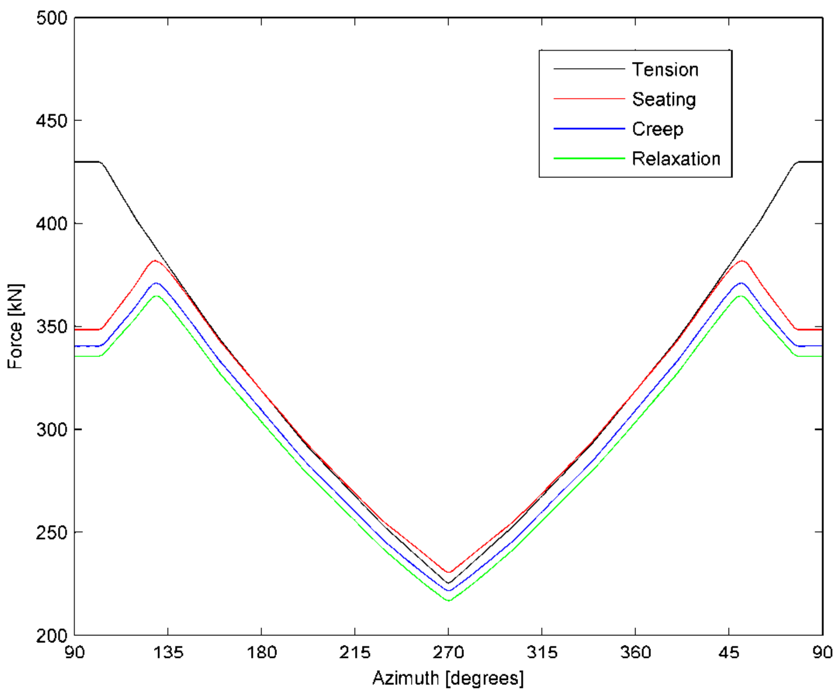


SPE studies

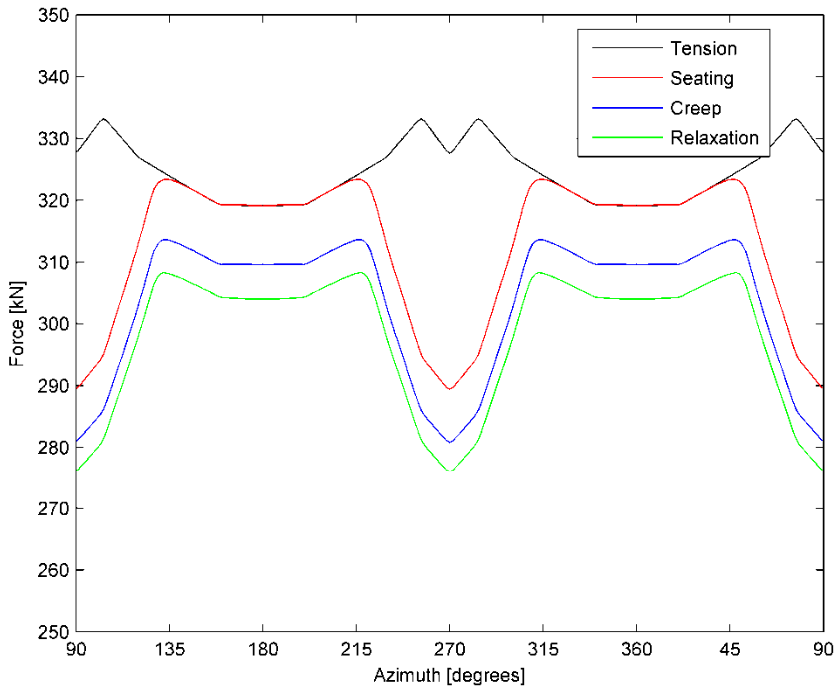
Prestressing tendon behavior (Model 1)



- Results, tendon force after prestressing



Force in tendon A

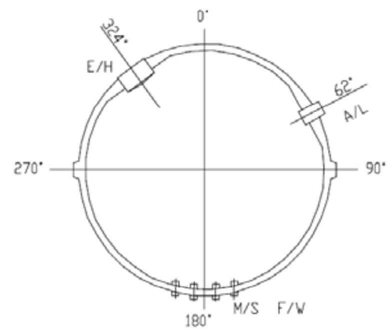


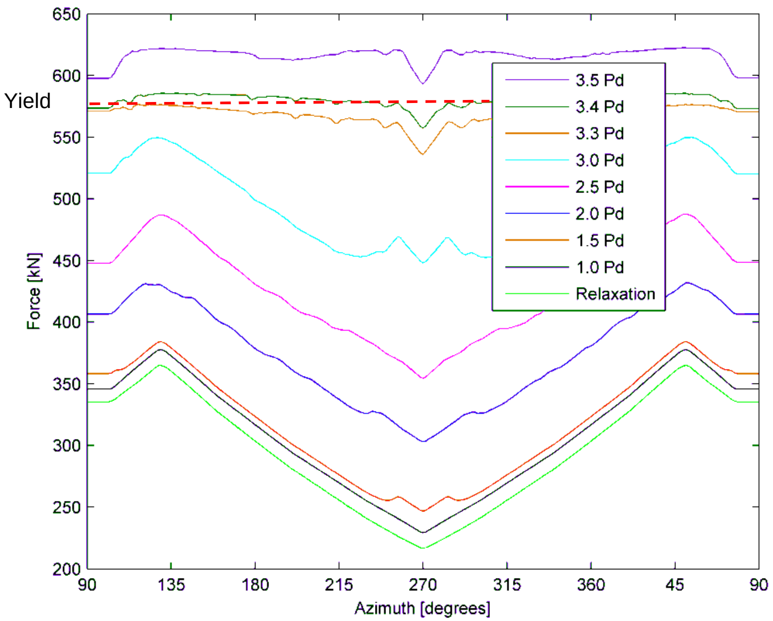
A spännkabel A och B

SPE studies

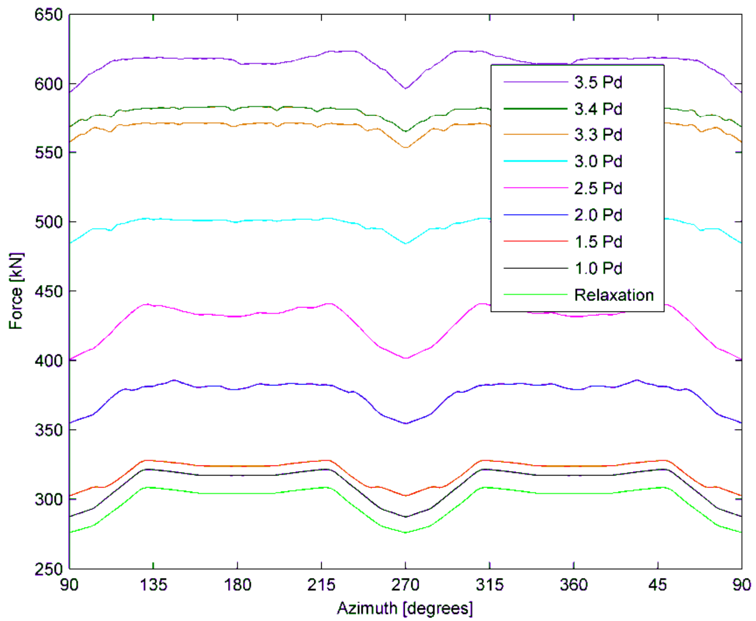
Prestressing tendon behavior (Model 1)

- Results, tendon force at increasing pressure





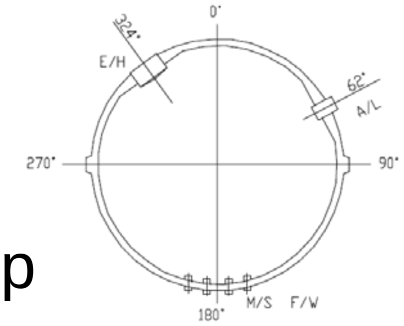
Force in tendon A



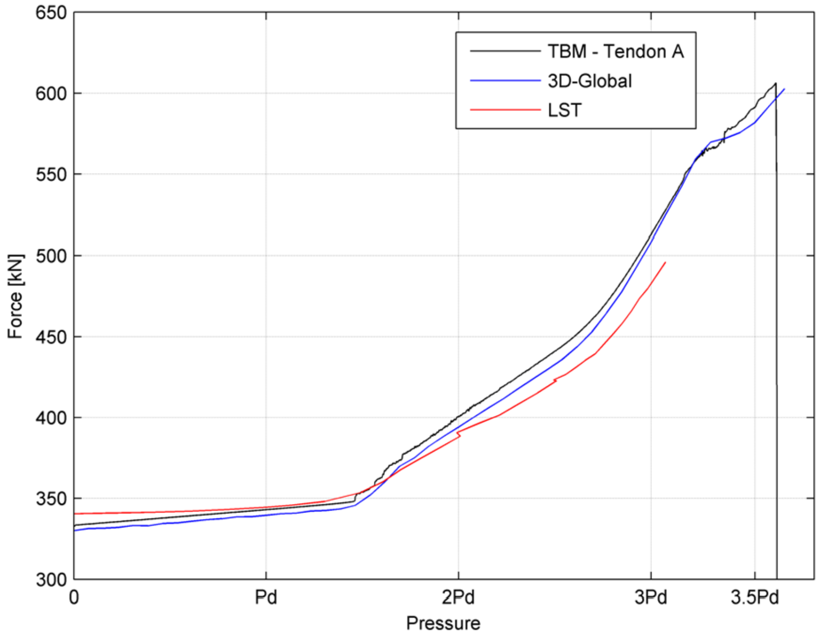
Average force tendon A and B

SPE studies

Prestressing tendon behavior (Model 1)

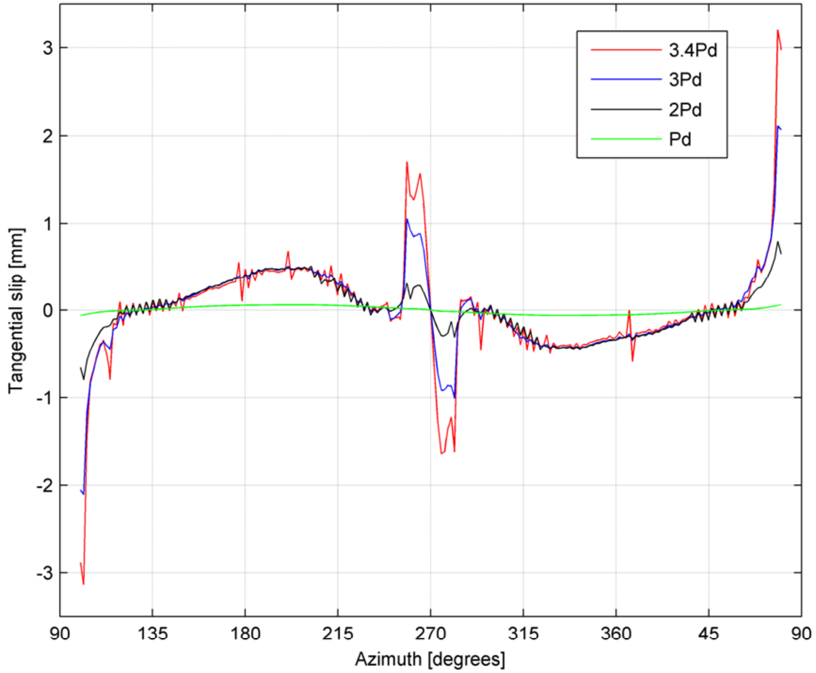


- Results, tendon anchor force and tangential slip



Force in tendon at anchorage

3D-model: Average tendon 52 to 68
Measurments: Average 53,58,63 and 67



Tangential slip

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Liner near equipment hatch (Model 2)

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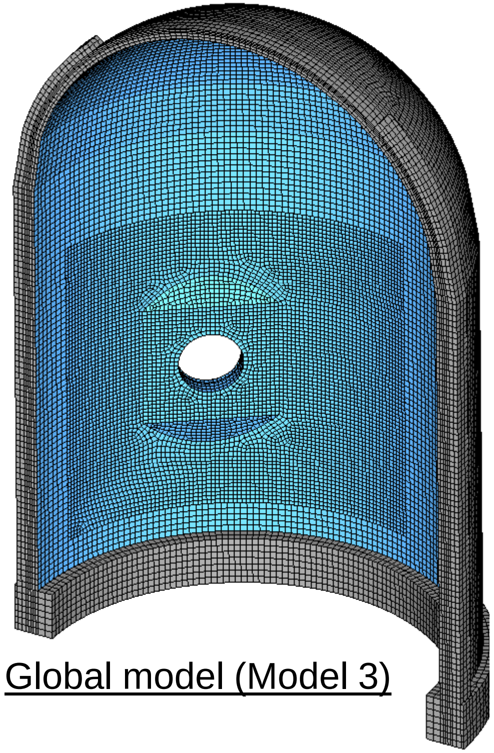
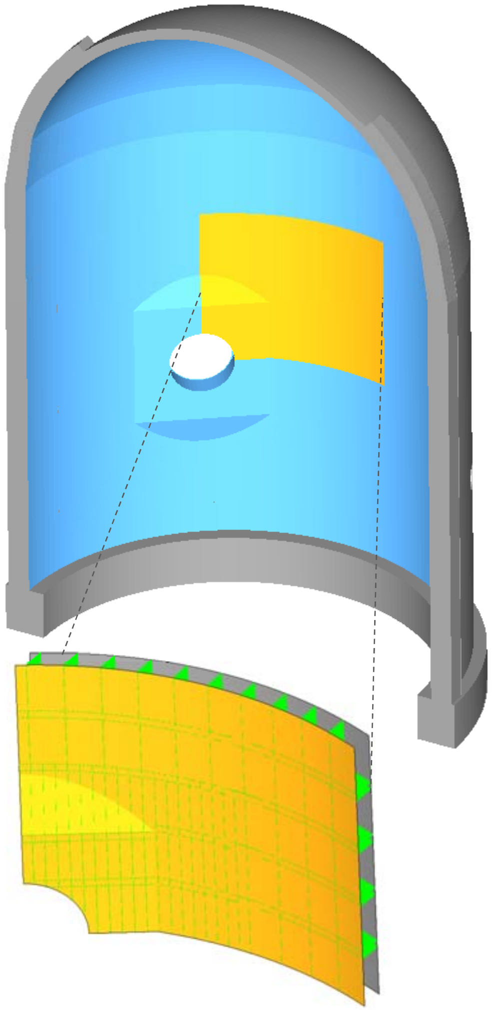
Liner near equipment hatch (Model 2)

- FE-model, general
  - Concrete structure described by global model, refined in E/H region (tie)
  - Steel liner described by submodel guided by displacement in global model
- FE-program
  - Global model: Abaqus Explicit
  - Liner model: Abaqus Standard



Global model (Model 3)



Liner submodel (Model 2)

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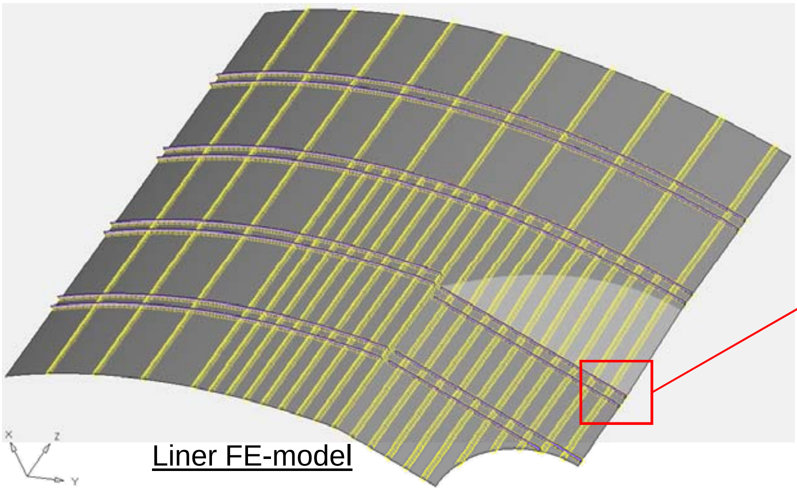
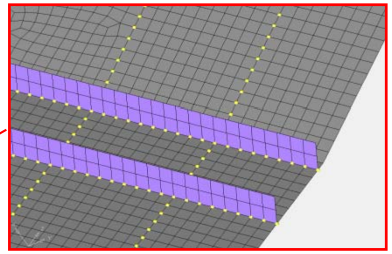
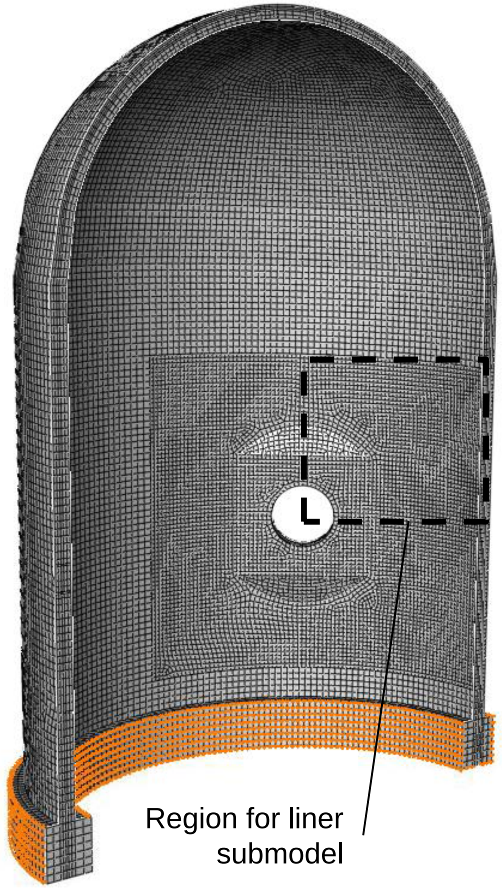
Liner near equipment hatch (Model 2)

- FE-model, interaction
  - Vertical anchors: Connector elements, in-plane shear stiffness, normal-plan rigid
  - Horizontal stiffeners: Connector and shell elements, in-plane shear stiffness, normal-plan ”free”
  - Contact definition between liner and concrete





*connectors highlighted in yellow



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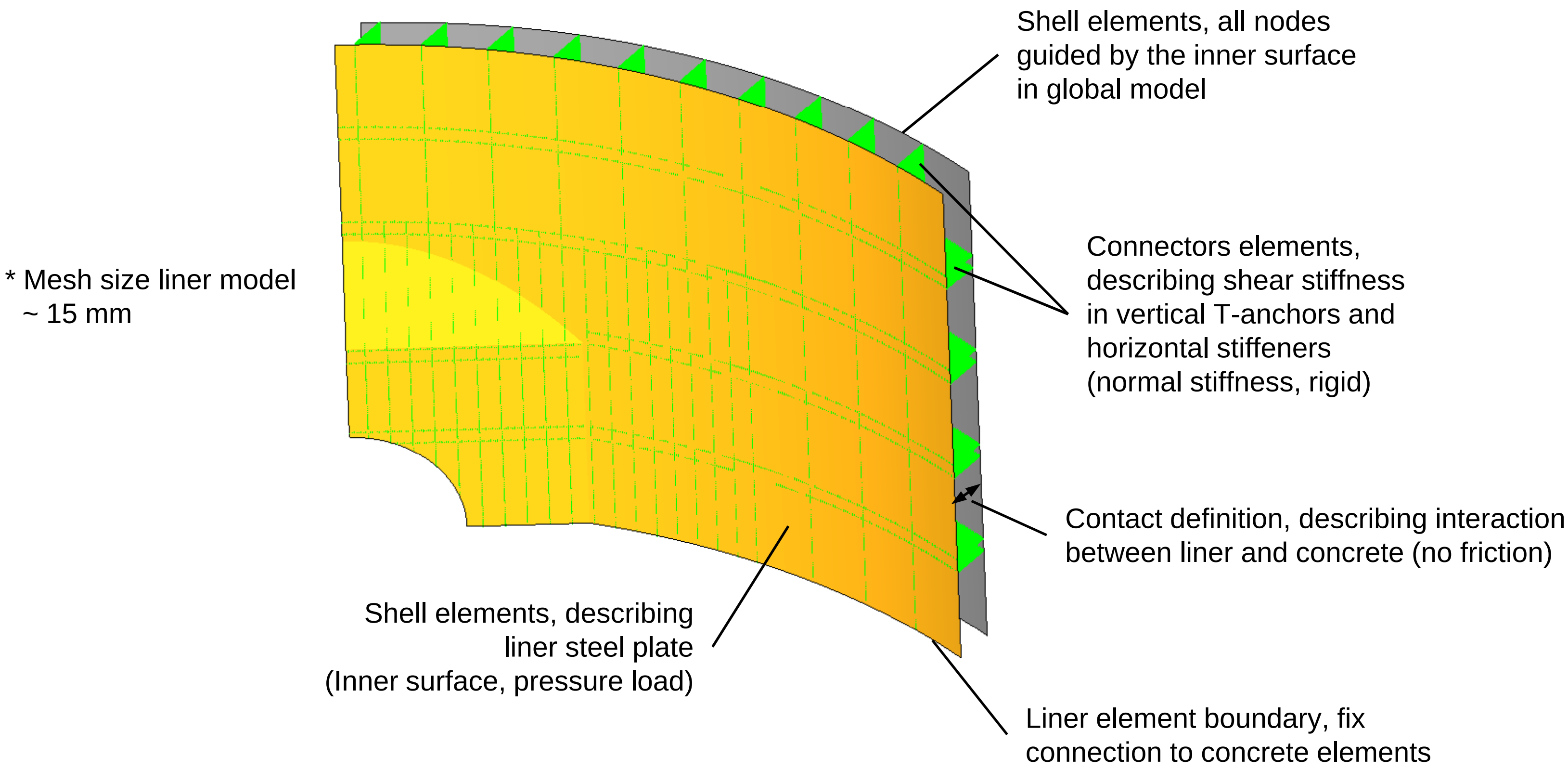
Liner near equipment hatch (Model 2)

- FE-model, interaction



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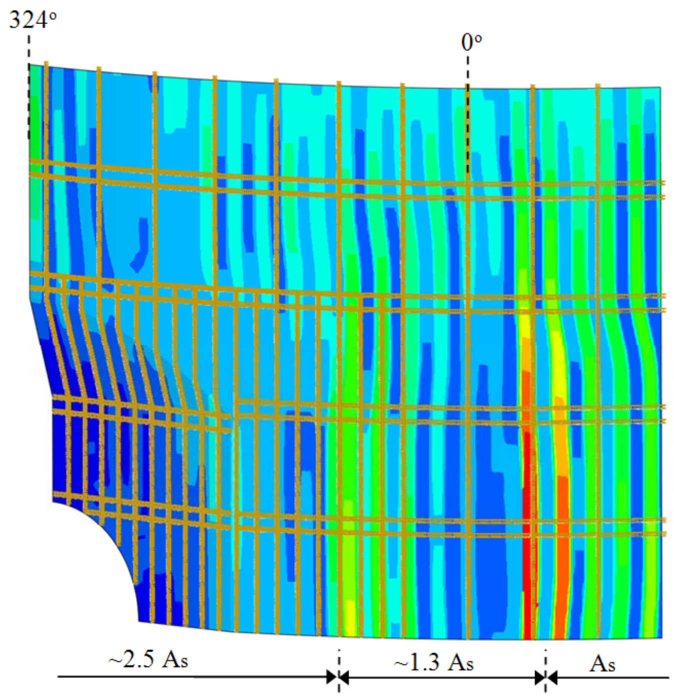
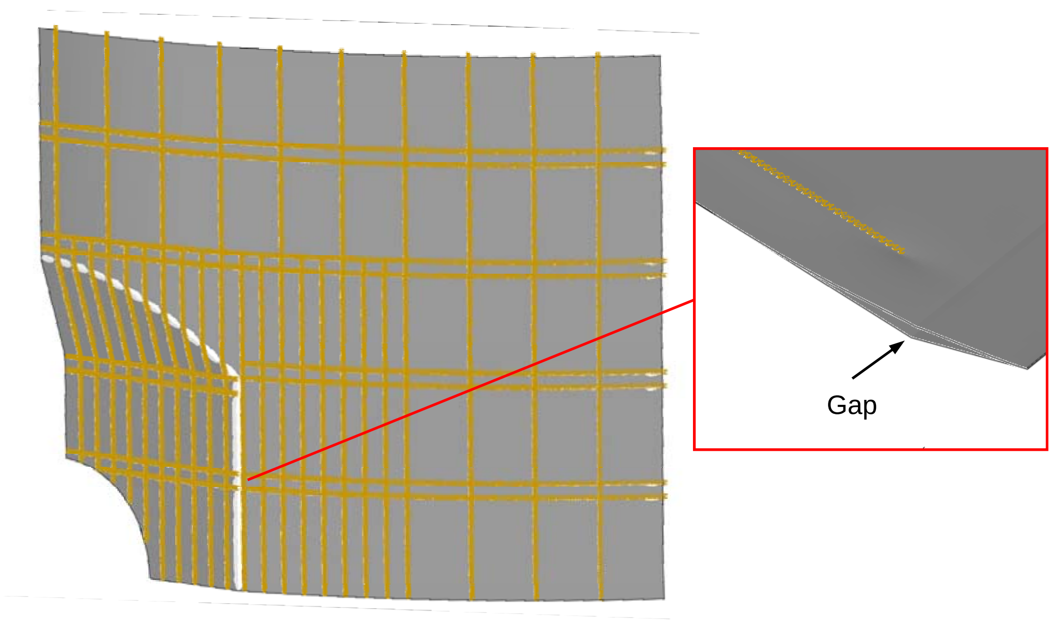
Liner near equipment hatch (Model 2)

- Results, concrete strain and contact



Concrete hoop strain at 3.3 p_d (1.29 MPa).

As = general hoop reinforcement



Contact opening between liner and concrete at 3.3 p_d (1.29 MPa)
*White color, separation between liner and concrete

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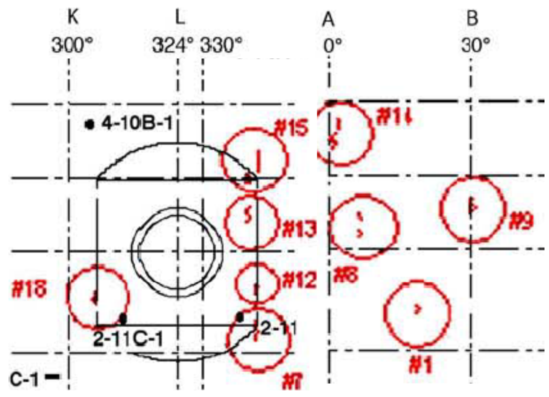
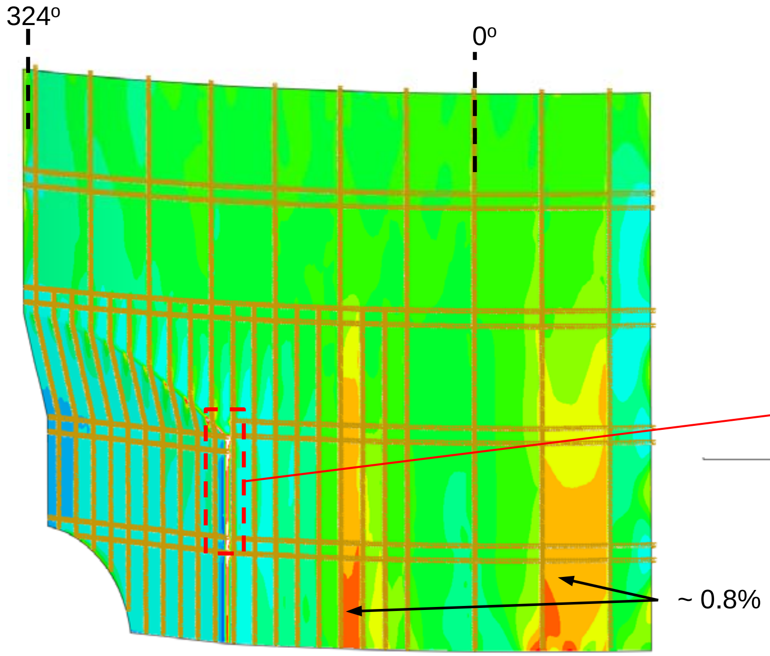
Liner near equipment hatch (Model 2)

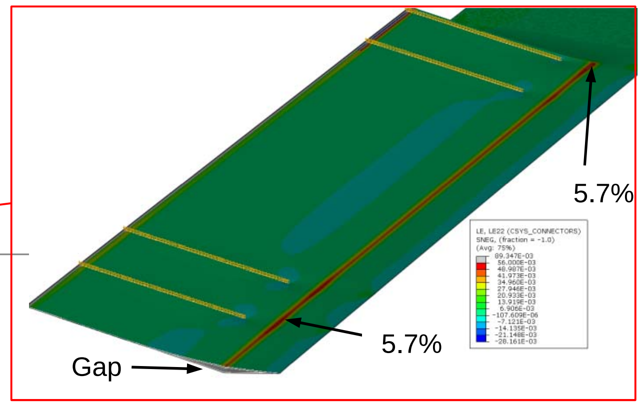
- Results, liner strain



Detected tears in liner after LST



Liner hoop strain in at 3.3 P_d (1.29 MPa)



Hoop strain at 3.3 P_d (1.29 MPa)
*High tensile strain on inside of bendline

- Elevated liner hoop strain
  - Vertical bend line, flexural
  - Regions where reinf. is reduced
- Non considered strain localisation
  - Grinding of welds, 50% of thickness
  - Discrete concrete cracks / friction

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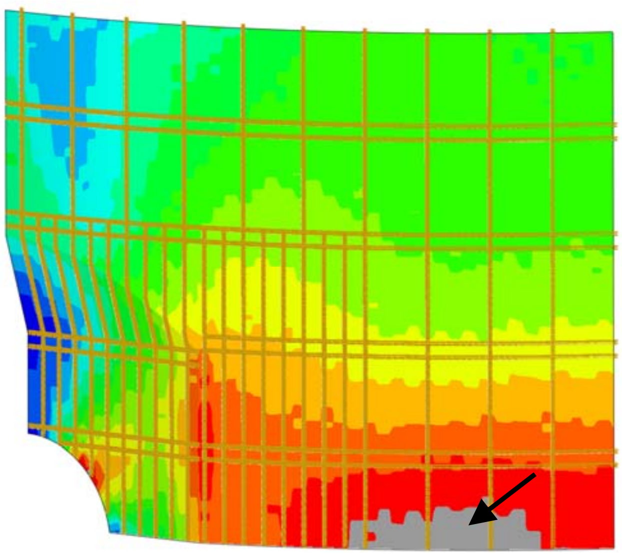
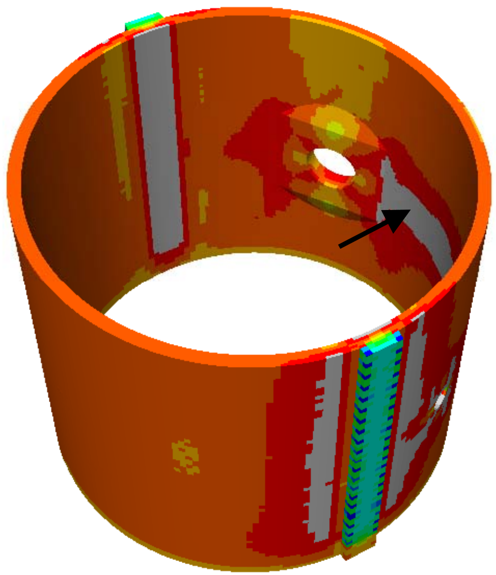
Liner near equipment hatch (Model 2)

- Results, concrete cracking



Initial cracking in E/H region at 1.33 P_d (0.52 Mpa)



Initial through-wall cracking 1.38 P_d (0.54 Mpa)

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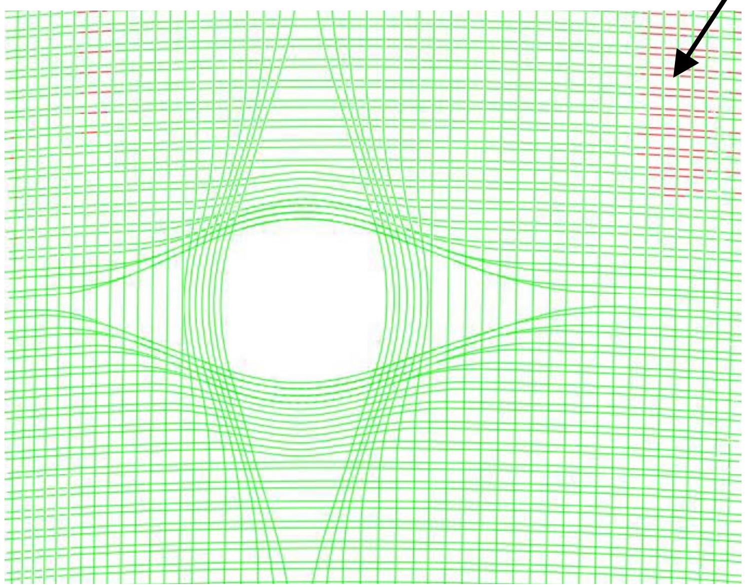
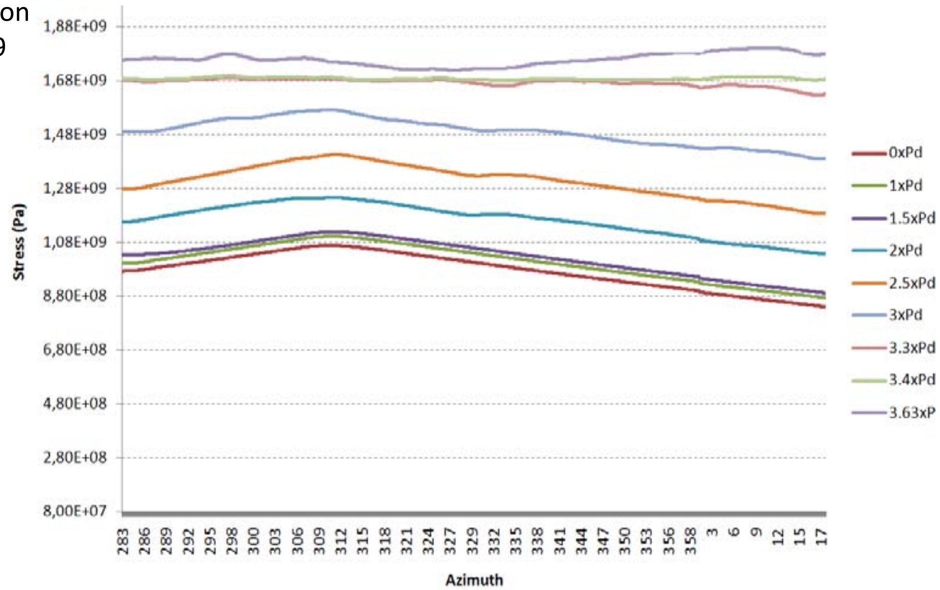
Liner near equipment hatch (Model 2)

- Results, tendon stress and strain



Tendon strain exceeding 1% at 3.4 p_d (1.32 MPa)



Tendon stress in E/H region for tendon no 69

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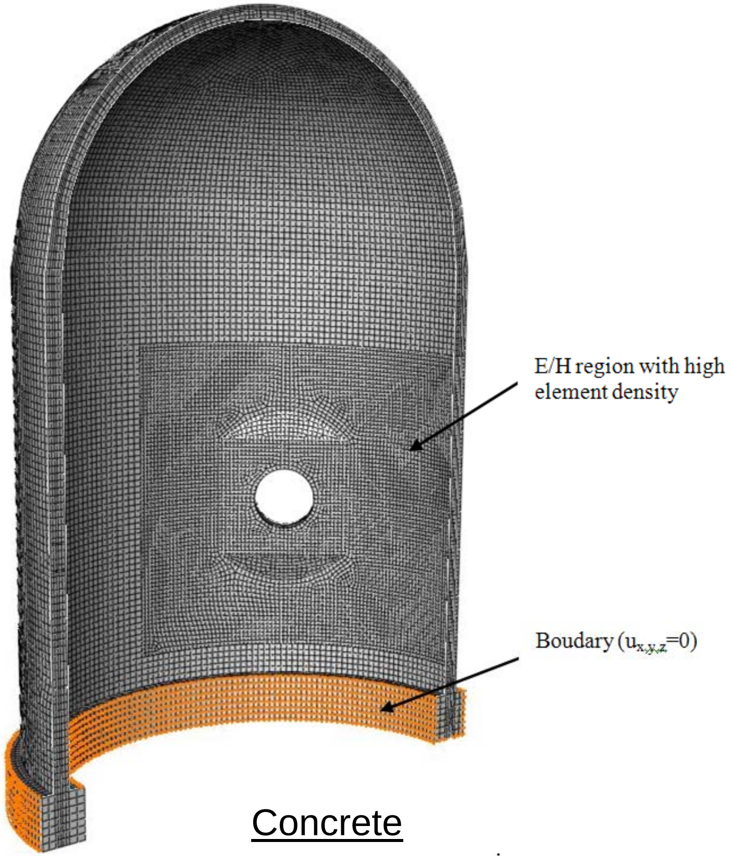
SPE studies

Global containment response (Model 3)

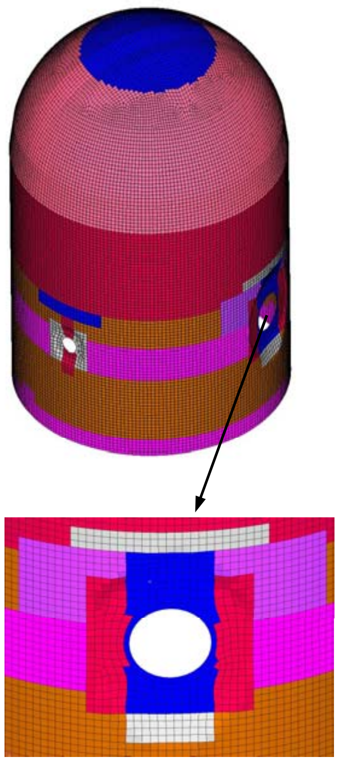
SPE studies

Global containment response (Model 3)

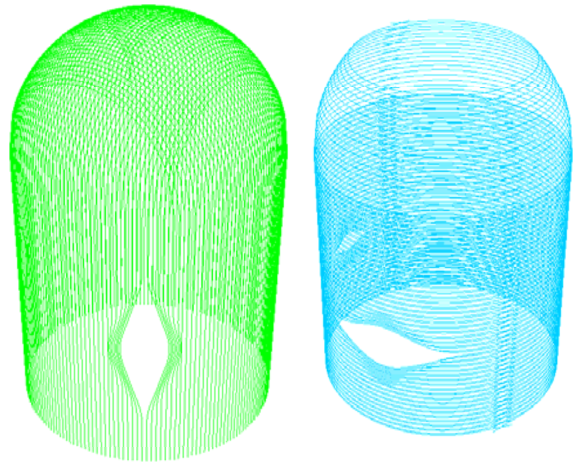
- FE-model



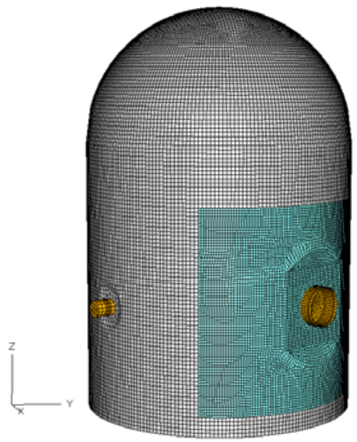
Concrete



Reinforcement



Tendons

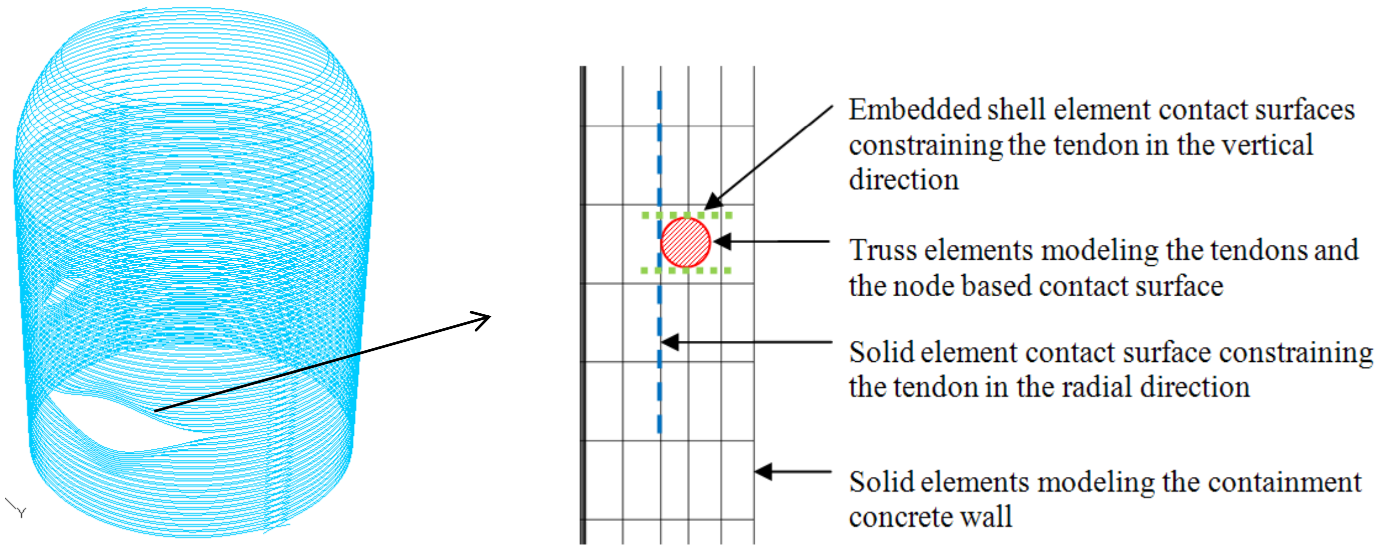


Liner

SPE studies

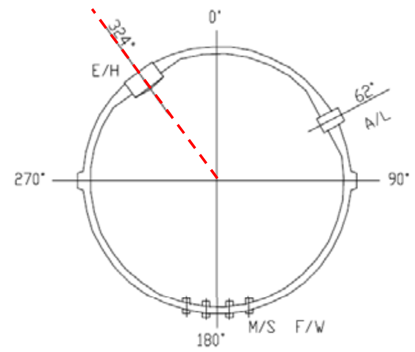
Global containment response (Model 3)

- FE-model, tendon interaction

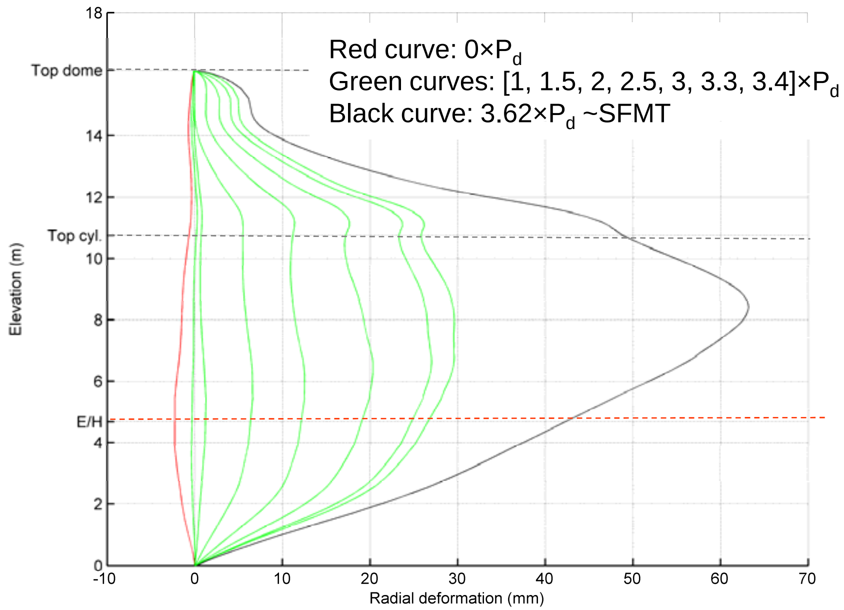


SPE studies

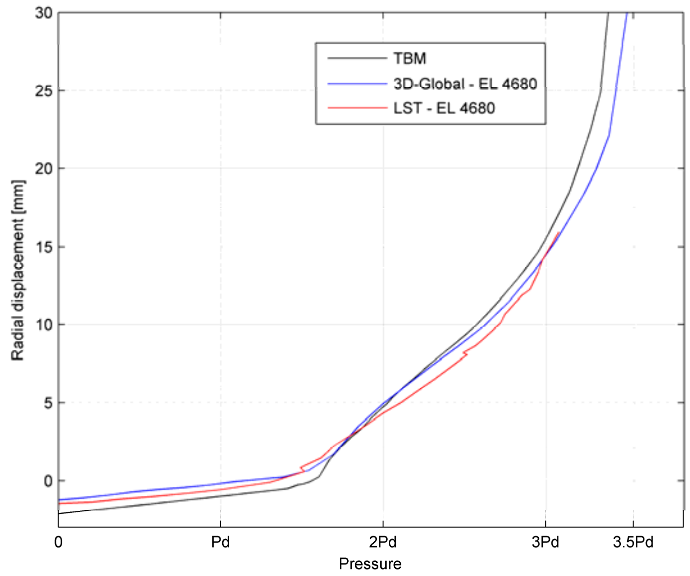
Global containment response (Model 3)



- Results, radial displacement



Displacemnt at 324º (E/H)

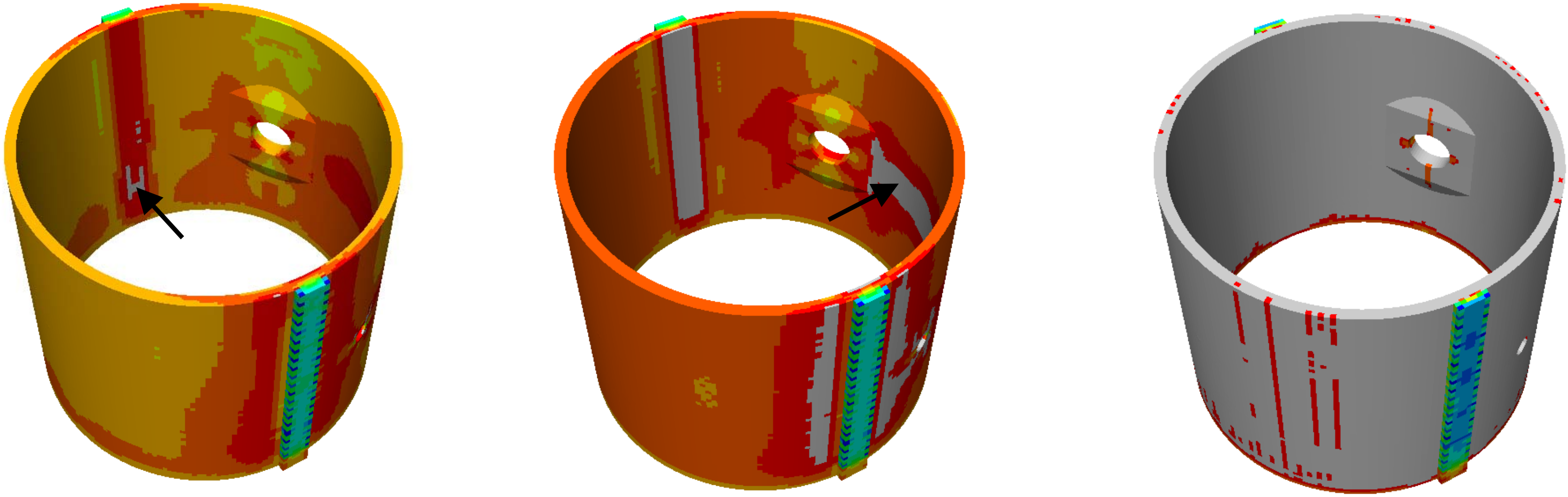


Average displacemnt at elevation 4.7 m (E/H)

SPE studies

Global containment response (Model 3)

- Results, concrete hoop cracking



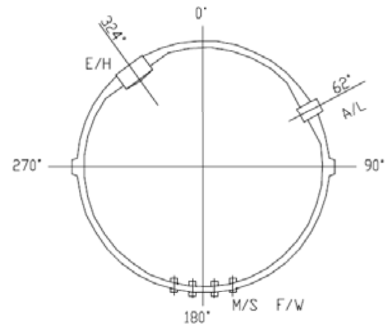
Initial cracking (1.23P_d , 0.48 MPa) | Initial through-wall cracking (1.38P_d , 0.54 MPa) | ~ All regions cracked (1.92P_d , 0.75 MPa)

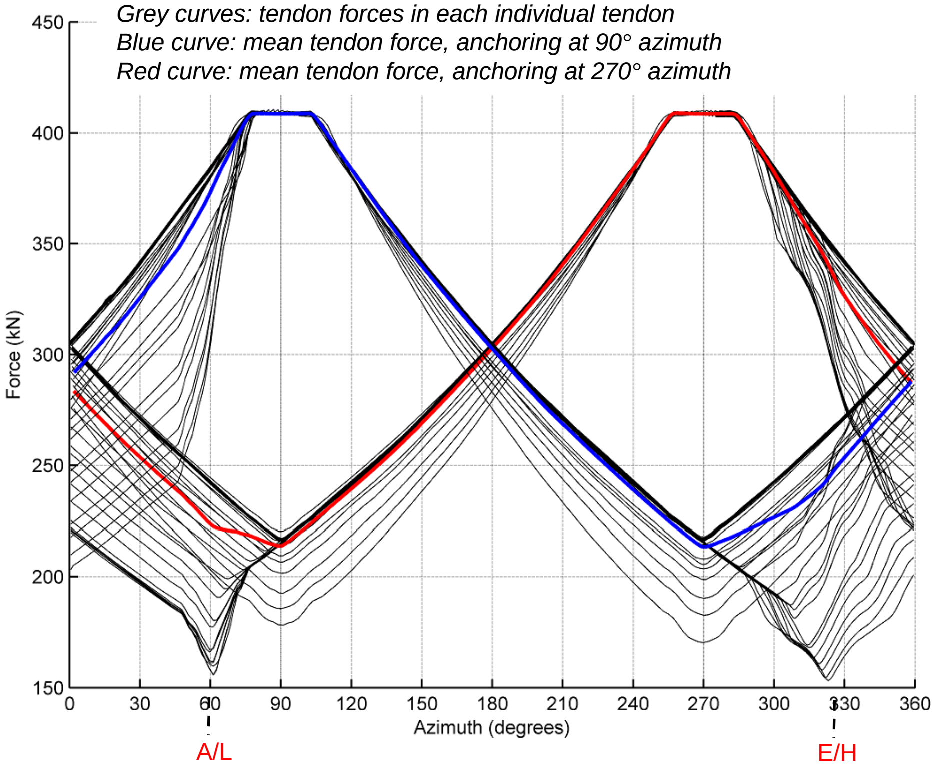
- Over 2P_d concrete stress ~ 0 in general parts of the cylinder wall

SPE studies

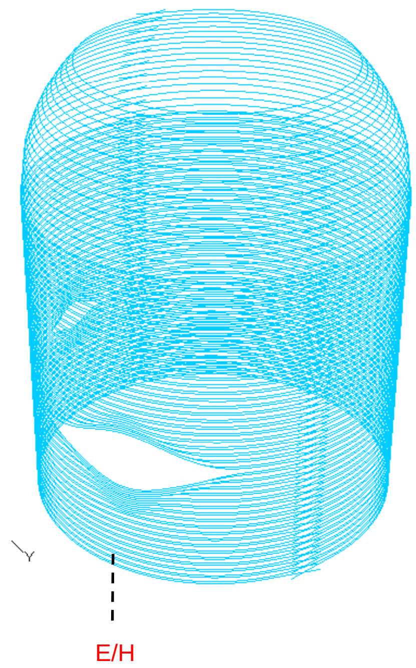
Global containment response (Model 3)

- Results, tendon force at <u>before</u> seating





Force in all hoop tendons in the cylinder wall

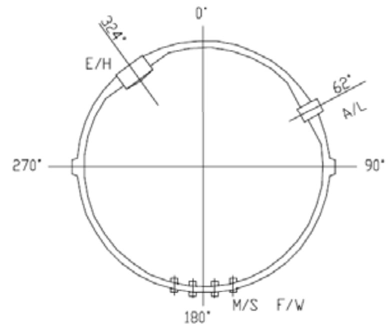


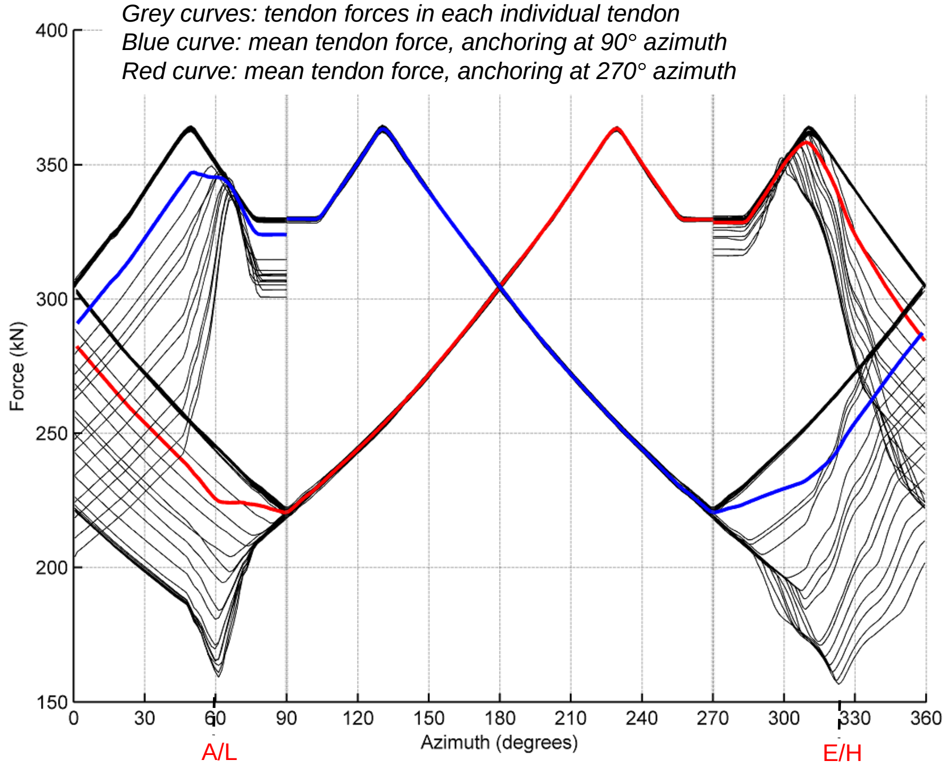
Side view, all hoop tendons

SPE studies

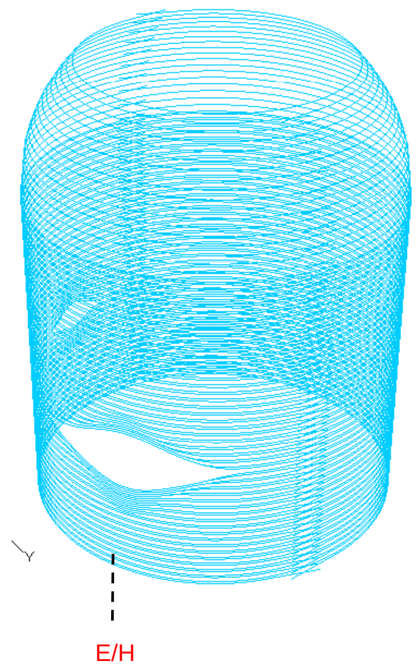
Global containment response (Model 3)

- Results, tendon force <u>after</u> seating





Force in all hoop tendons in the cylinder wall

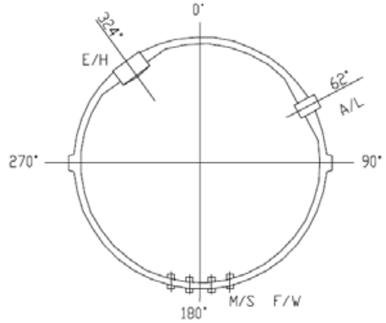


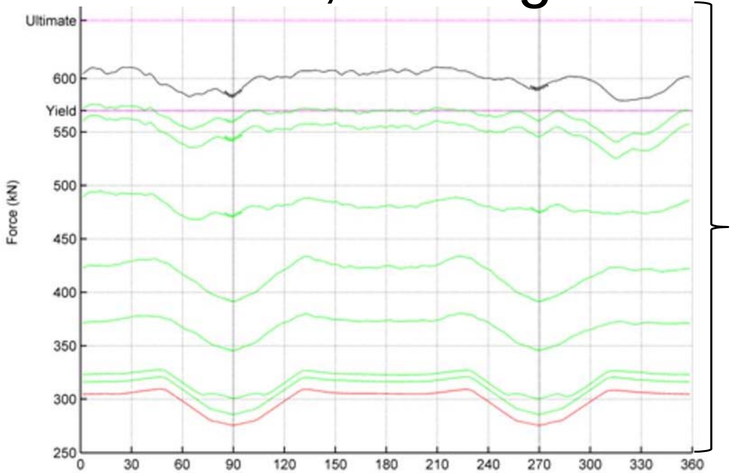
Side view, all hoop tendons

SPE studies

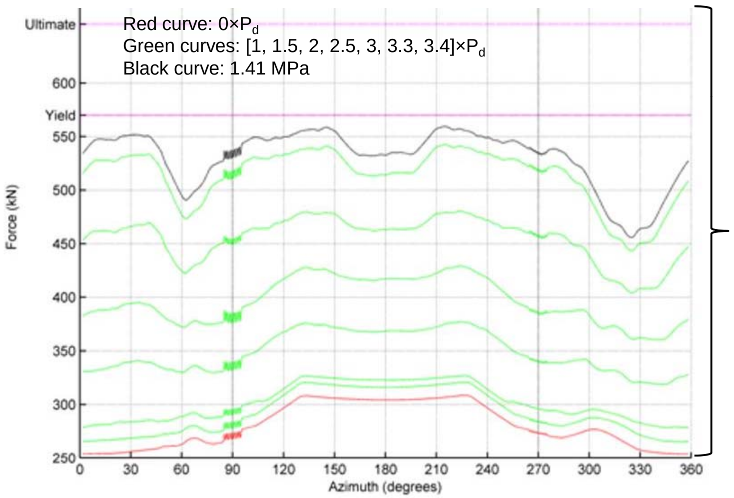
Global containment response (Model 3)

- Results, average force at increasing pressure

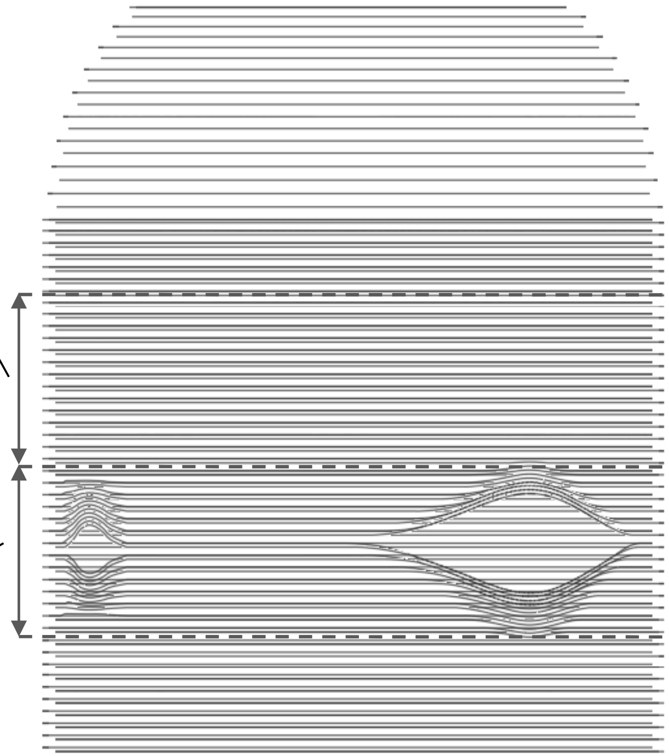




Average force level 6.4 to 9.9 m



Average force level 2.8 to 6.3 m



Side view, all hoop tendons

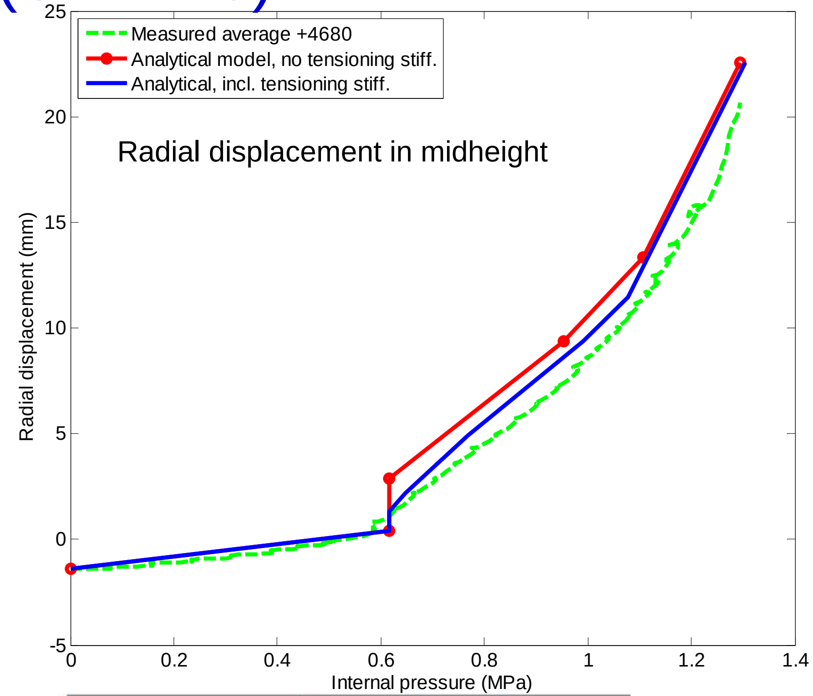
SPE studies

Influence of variation in output (SPE 1.5)

SPE studies

Influence of variation in output (SPE 1.5)

- **Objective**
  - Study the influence of variation in input data on the global expansion
  - Important for liner integrity
- **Model**
  - Simple structural model describing the radial deformation in midheigth
  - Variation in input data given from material tests and literature (JCSS)

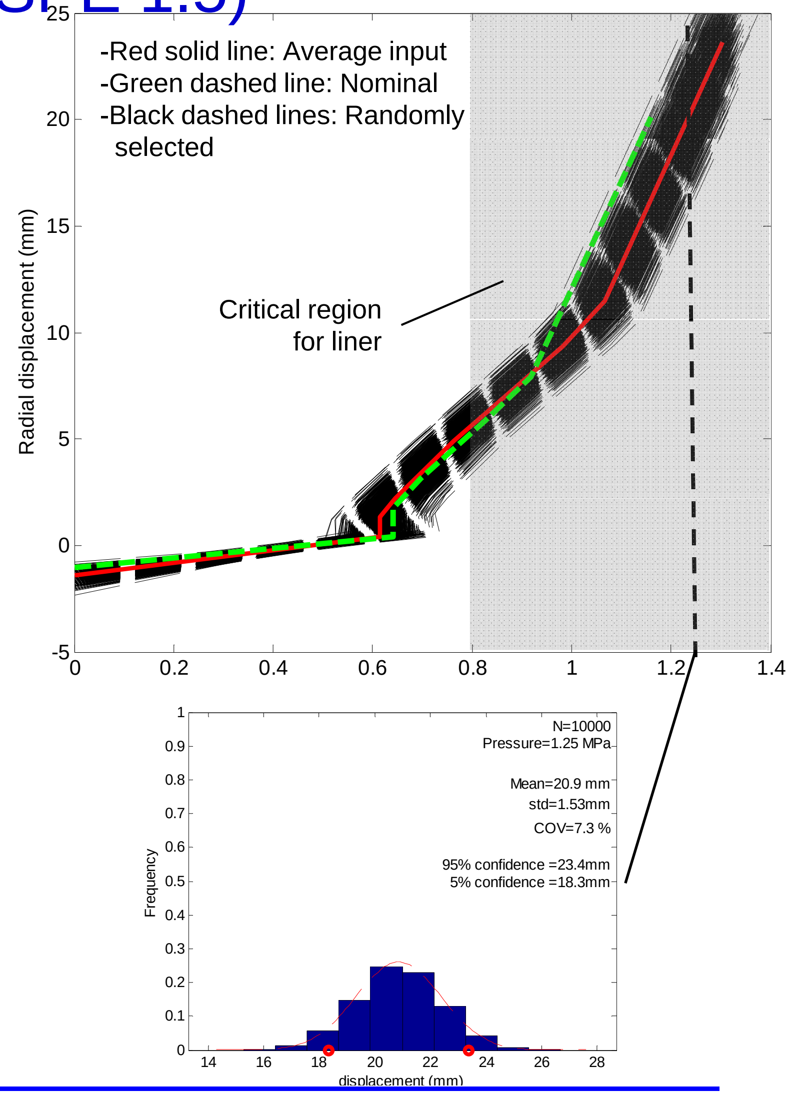


Input parameter		Average value	Coefficient of variation	Type of distribution
Concrete	Cross-section area	0.325 m²/m	-	Deterministic
	E-modulus	26.8 GPa	15% [1)]	Log-normal
	Tensile strength	2.1 MPa	15% [1)]	Log-normal
Liner	Cross-section area	1800 mm²/m	-	Deterministic
	E-modulus	220 GPa	-	Deterministic
	Yield strength	383 MPa	2%	Log-normal
Reinforcement	Cross-section area	2800 mm²/m [3)]	-	Deterministic
	E-modulus	185 GPa	2%	Deterministic
	Yield strength	460 MPa	2%	Normal
Tendon	Cross-section area	2950 mm²/m	-	Deterministic
	E-modulus	200 GPa	2%	Normal
	Yield strength	1690 MPa	2%	Normal
Prestress [2)]	Tendon initial stress	850 MPa	6%	Normal

SPE studies

Influence of variation in output (SPE 1.5)

- Results, statistical variation
  - Large number of analyses with randomly selected input (Monte Carlo simulation)
  - Nominal values differs mainly in steel yield limits
  - Load level critical for liner integrity, COV ~ 7.5%
  - Global displacement in midheigth fits to normal distribution



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Influence of variation in output (SPE 1.5)

- Results, statistical variation
  - Originates mainly from variation in prestress