PERFORMANCE OF CONTAINMENT VESSEL UNDER SEVERE ACCIDENT CONDITIONS

SPE analysis meeting #2

April 13-14, 2011, Washington DC

SUMMARY

Model 1 : **Sensitivity analyses & findings**

Model 2 : **Methodology & difficulties**

necs
Numerical Engineering & Consulting Services

Juan-José GAYETE

Charles GHAVAMIAN

Thibault MARTIN

Mahsa MOZAYAN KHARAZI

EDF

Sylvie MICHEL-PONNELLE

Etienne GALLITRE

Model 1

SUMMARY

Sensitivity analyses

- **Mesh disrectisation**
- **Mesh element type**
- **Concrete constitutive law**
- **Concrete constitutive law parameters**
- **Tendon / Duct interaction**

Modelling technique

Concrete

Solid element

Linear and quadratic configurations

Mesh size: described in another section

Liner

Shell elements

Thickness 1.6mm

Liner perfectly bonded with concrete

Hoop tendons

Truss elements

Tendon / concrete interface: 3 configurations

1- Grouted ducts: perfectly bonded

2- Slippery ducts (perfectly bonded in Z and R direction, free along tendon direction)

3- Ungrouted ducts (perfectly bonded in Z and R direction, friction along tendon direction)

steel reinforcement

Grid elements

Shell element with uniaxial behaviour

Linear

Rebar / concrete interface: perfectly bonded

Placed on inner and outer surfaces of concrete mesh

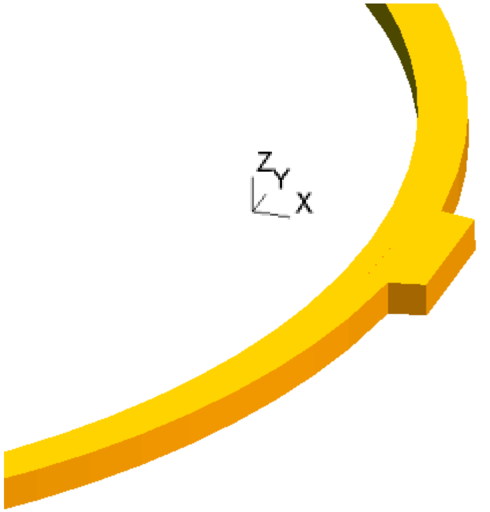
Model geometry

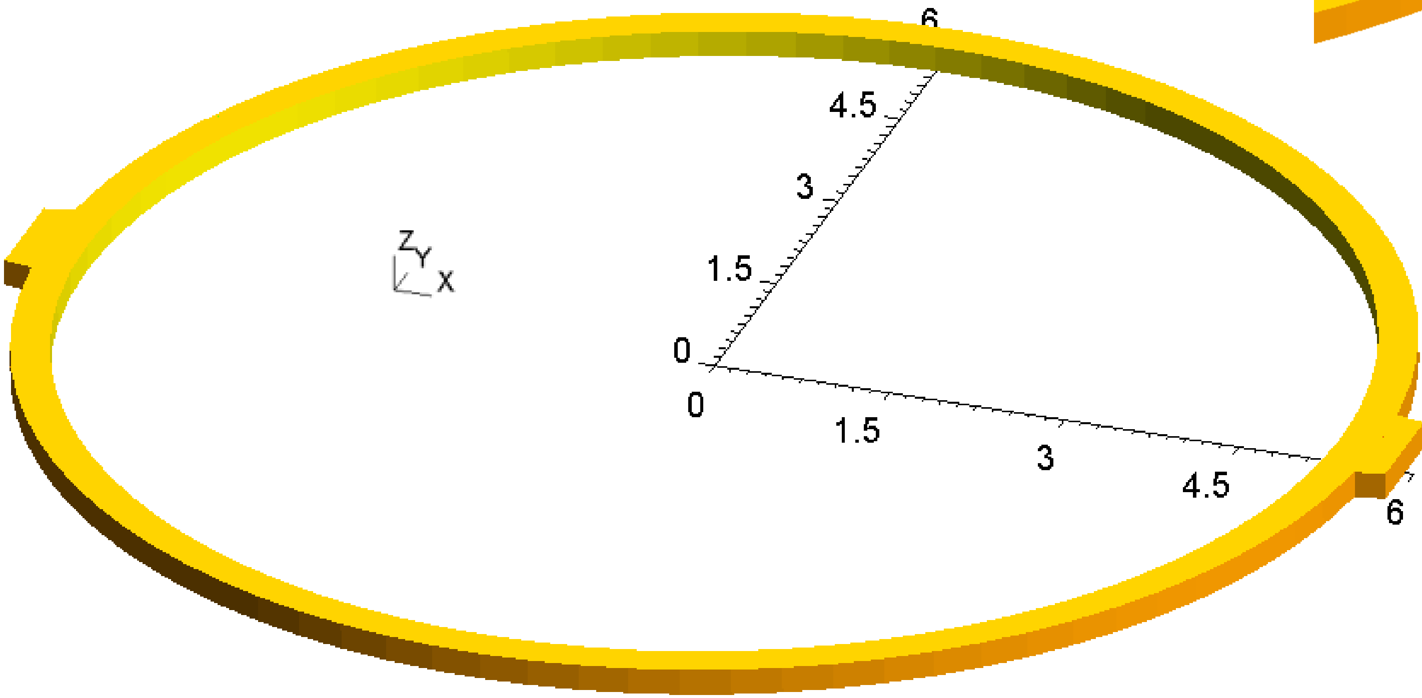
Internal radius = 5.7 m

External radius = 5.375 m

Vertical thickness = 22.5 cm

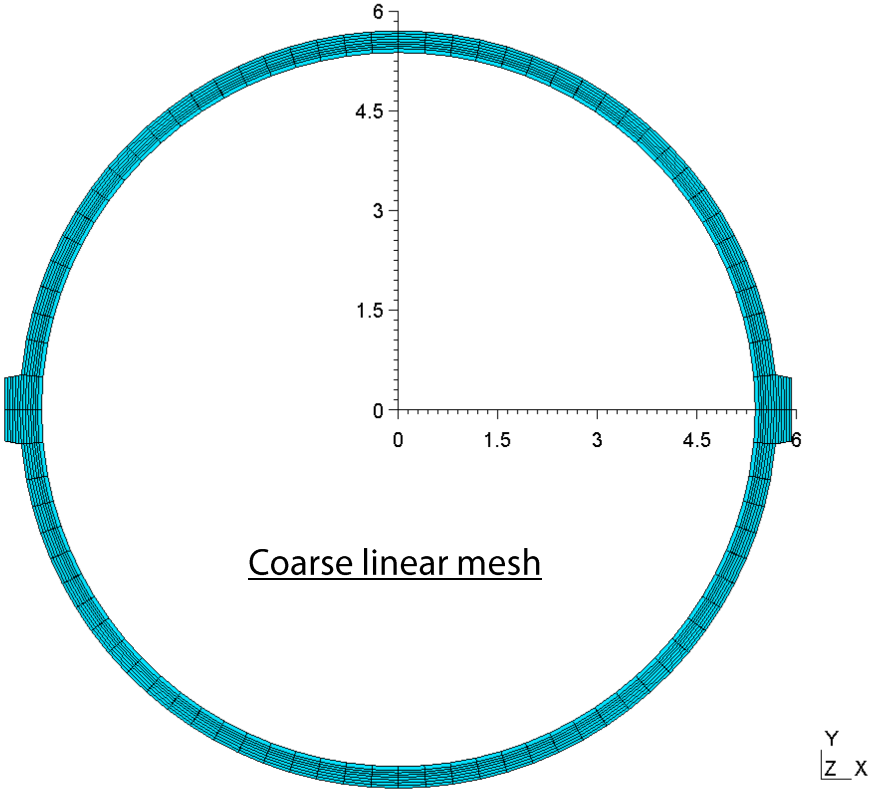
Horizontal thickness = 32.5 m



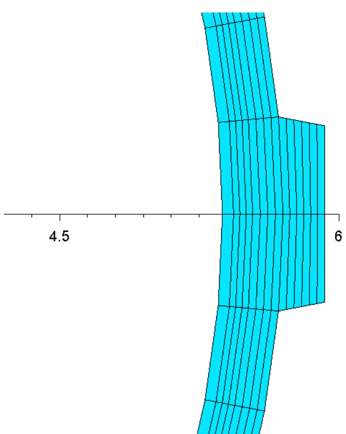


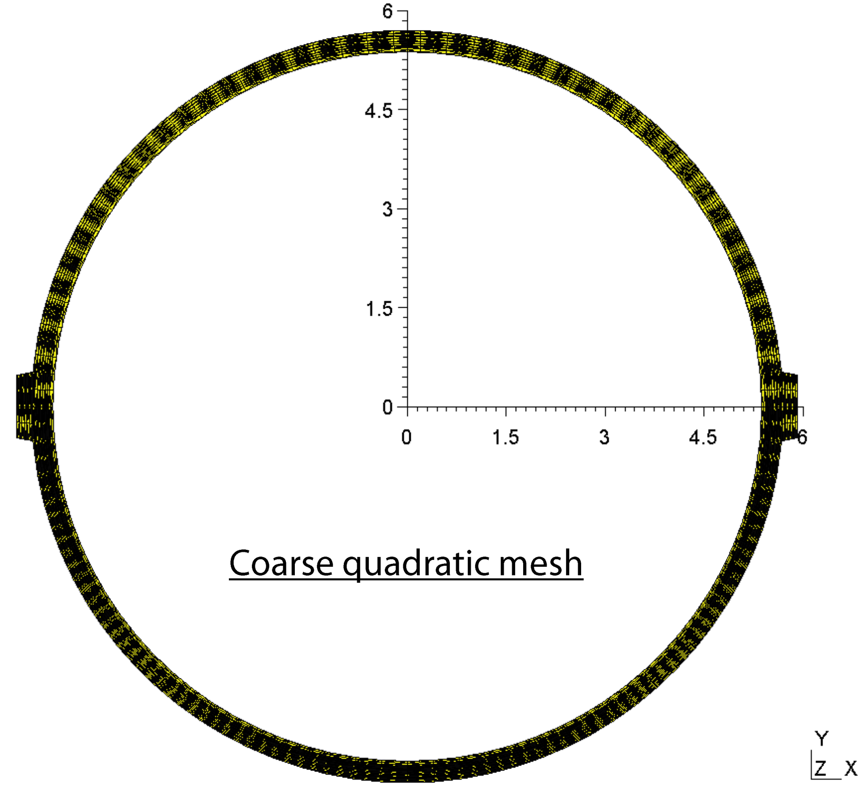
Mesh discretisation

3 situations

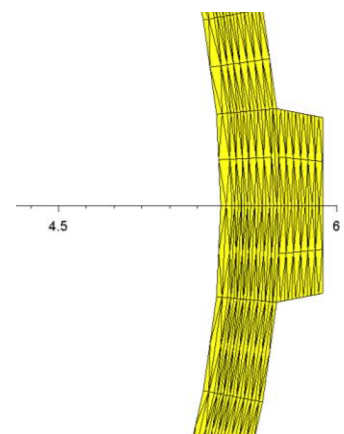


Coarse linear mesh

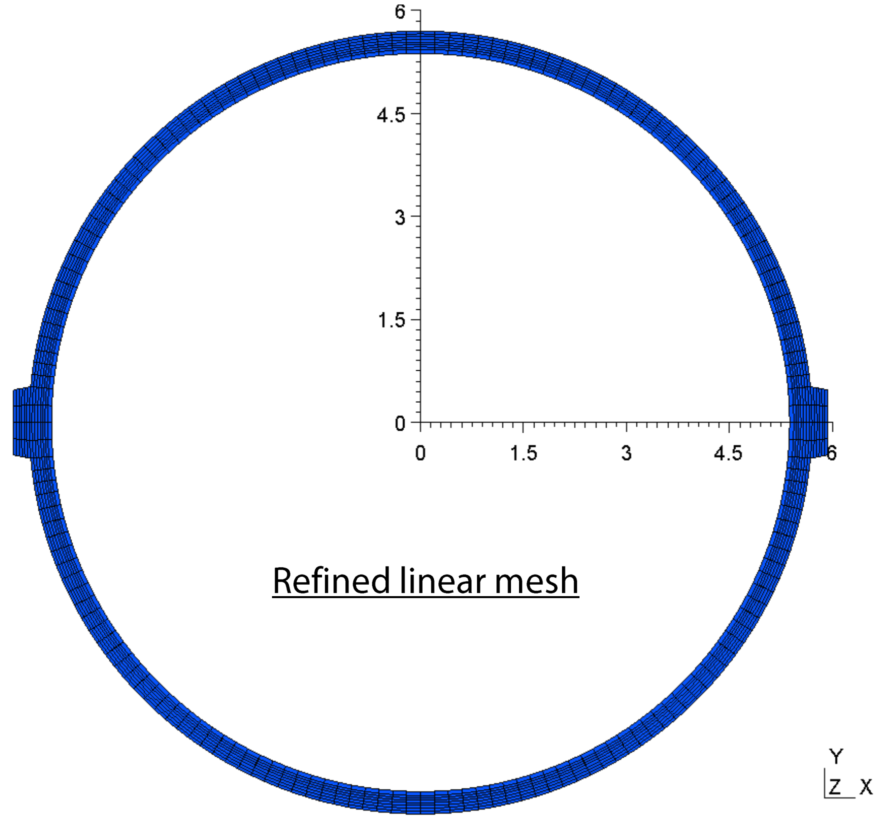




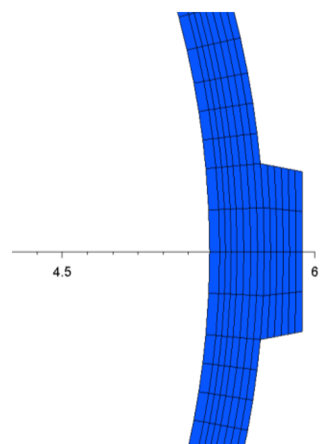
Coarse quadratic mesh



Mesh discretisation



Refined linear mesh

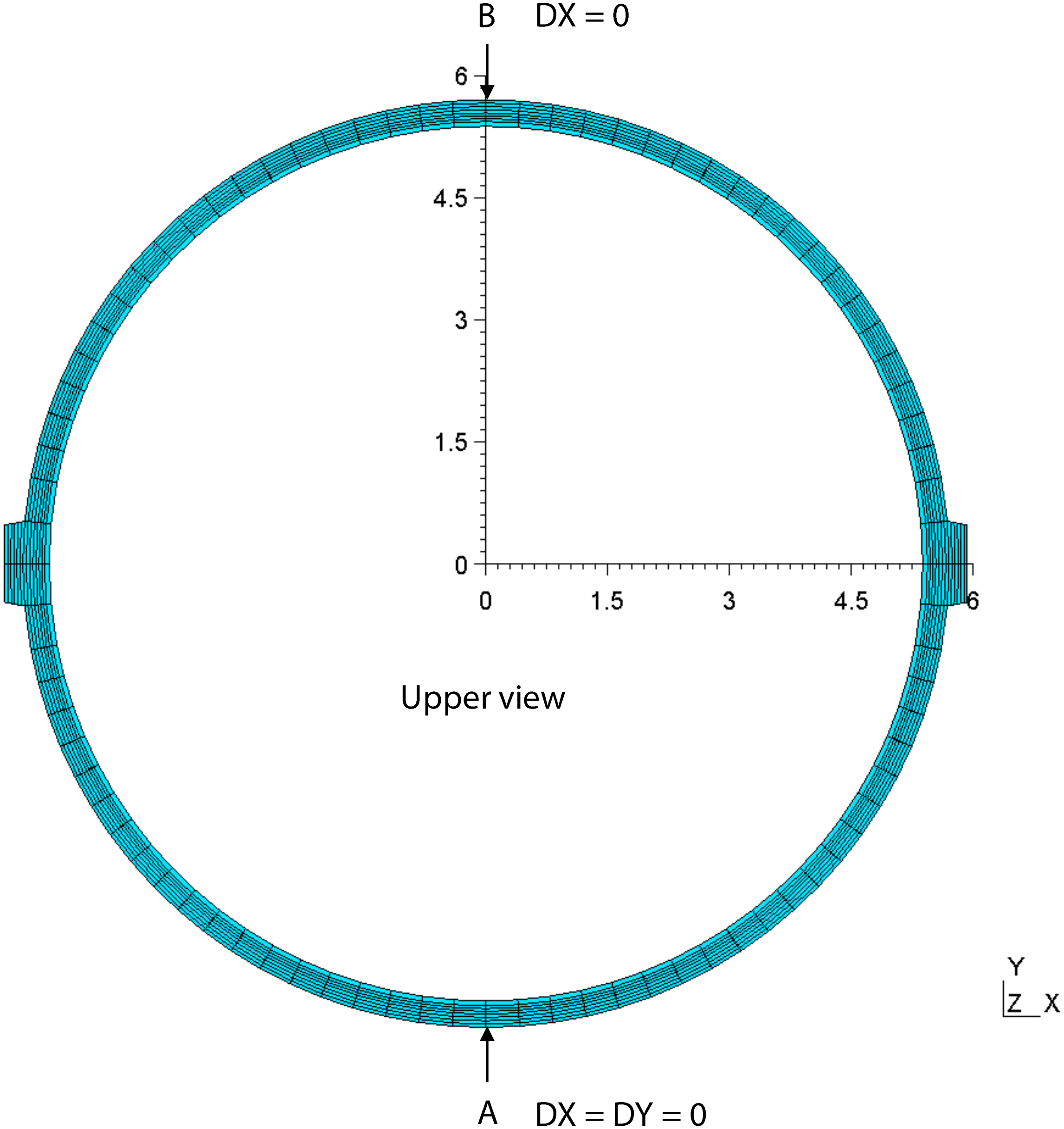


Boundary conditions

Upper face: Z DOF follow the same value

Lower face: DZ=0

See figure for the others



Concrete constitutive model

Known as "Mazars"

Features :

- Based on damage mechanics
- Unilateral behaviour (tension / compression distinction)
- Isotropic damage effect (single scalar damage index D)
- No crack reclosure (not suitable for cyclic loading)

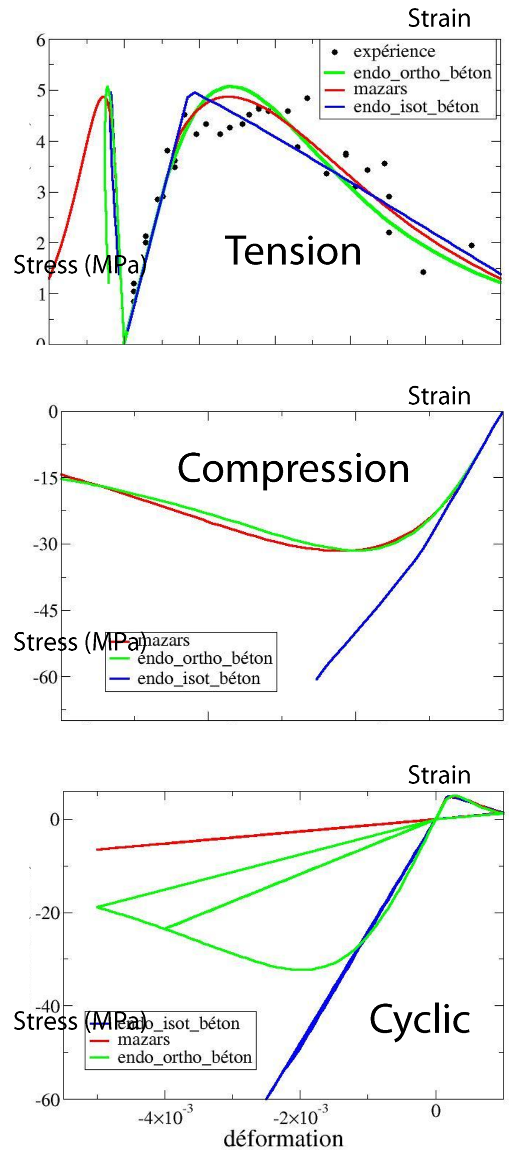
$$\sigma_{ij} = (1 - D) C_{ijkl}\, \varepsilon_{kl}$$

$$D = \alpha_t D_t + \alpha_c D_c$$

$$\alpha_{t,c} = \left(\sum_{i=1}^{3} \frac{<\varepsilon_i^{t,c}><\varepsilon_i>_+}{\varepsilon_{eq}^2} \right)^{\beta} \qquad D_{t,c} = 1 - \frac{\varepsilon_{eq\,0}(1 - A_{t,c})}{\varepsilon_{eq}} - \frac{A_{t,c}}{\exp[B_{t,c}(\varepsilon_{eq} - \varepsilon_{eq\,0})]}$$

$$\varepsilon_{eq} = \sqrt{\sum_{i=1}^{3} (<\varepsilon_i>_+)^2}$$

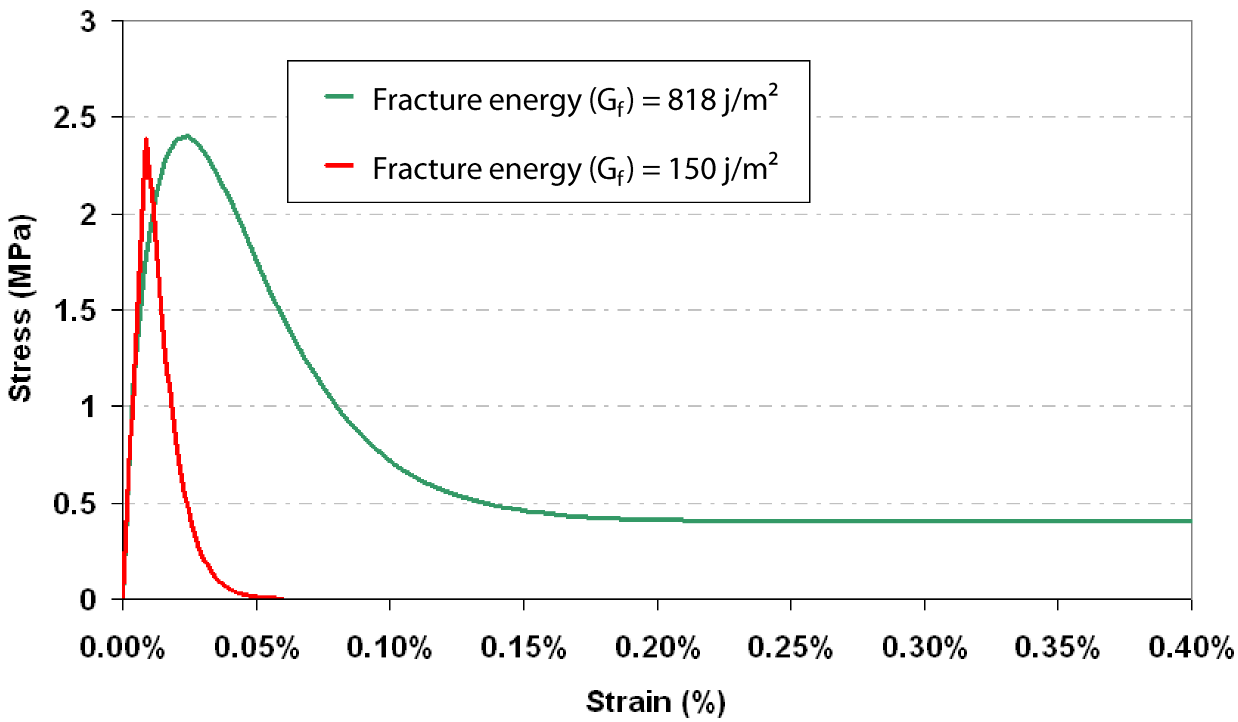
Mazars : red curves

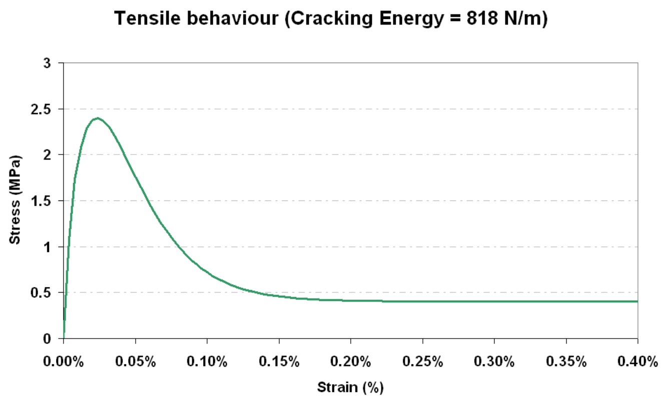


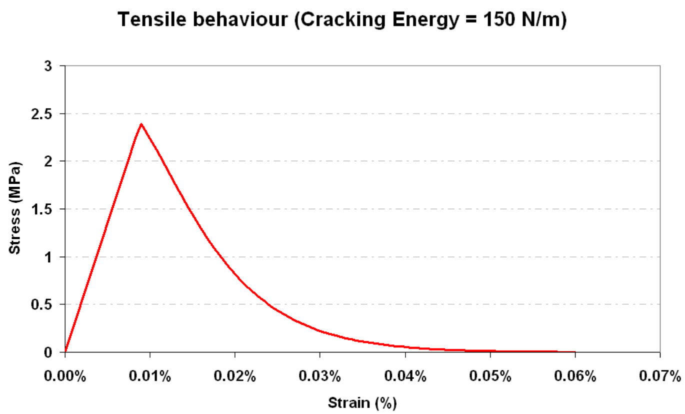
Concrete constitutive model

Material parameter set	M818	M150
Fracture energy (G_f) Mesh size	818 j/m^2 43 cm	150 j/m^2 43 cm
Young's Modulus (E)	26 900 MPa	26 900 MPa
Poisson's ratio (ν)	0.21	0.21
Density (ρ)	2 176 kg/m^3	2 176 kg/m^3
Tensile Strength (f_t) Strain	2.4 MPa 0.024%	2.4 MPa 0.009%
Compressive Strength (f_c) Strain	61 MPa 0.54%	62 MPa 0.54%

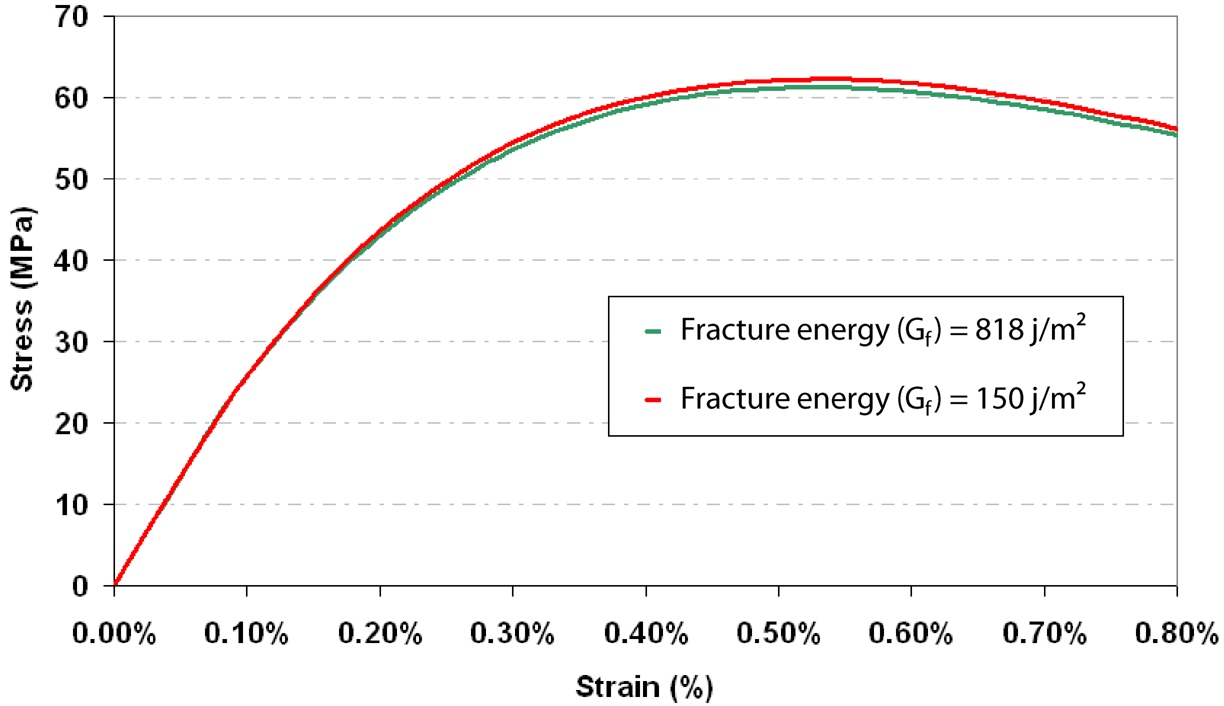
Concrete constitutive model

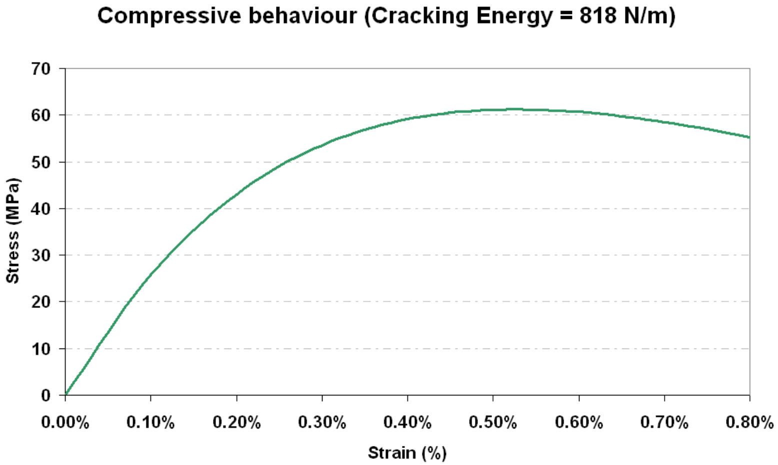


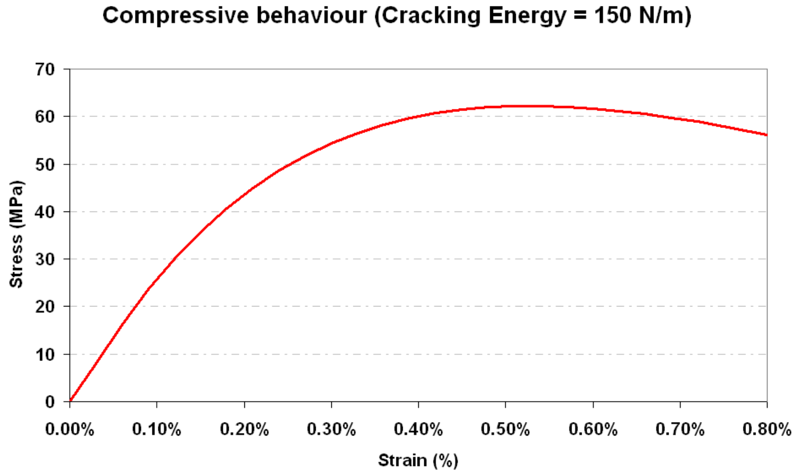




Concrete constitutive model







Liner steel constitutive model

Elastoplastic

Parameters:

Young's Modulus (E) = 210 000 MPa

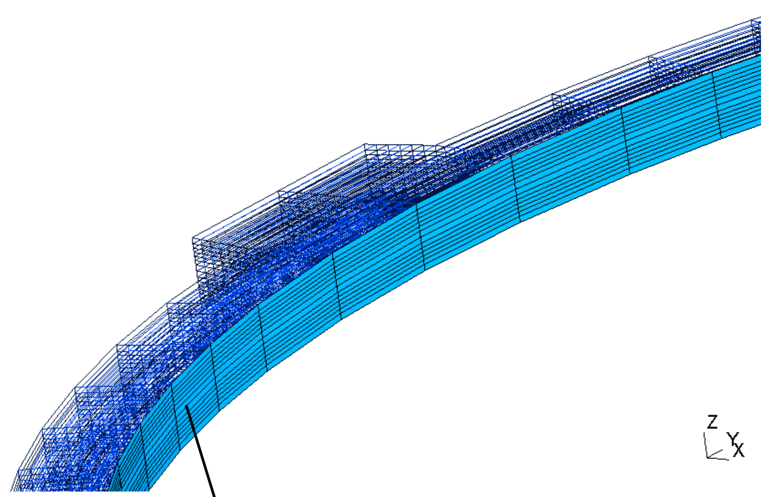
Young Modulus in plastic phase (E) = 927 MPa

Poisson's ratio (ν) = 0.3

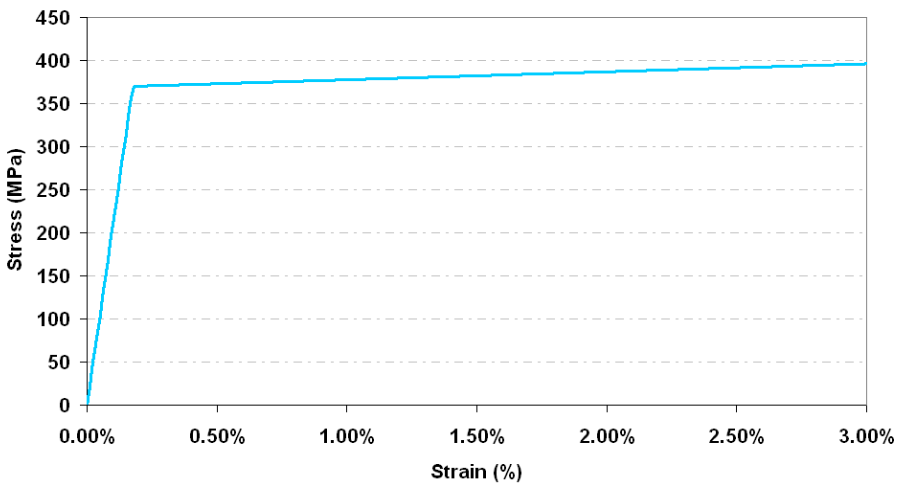
Density (ρ) = 7850 kg/m3

Yield Strength (Y_s) = 370 MPa

Density (ρ) = 7 850 kg/m^3



Liner thickness = 1.6 mm



Tendon steel constitutive model

Elastoplastic

Parameters:

Young Modulus in elastic phase (E) = 191 000 MPa

Young Modulus in plastic phase (E) = 5 894 MPa

Poisson's ratio (ν) = 0.3

Density (ρ) = 7850 kg/m3

Yield Strength (Y_s) = 1 679MPa

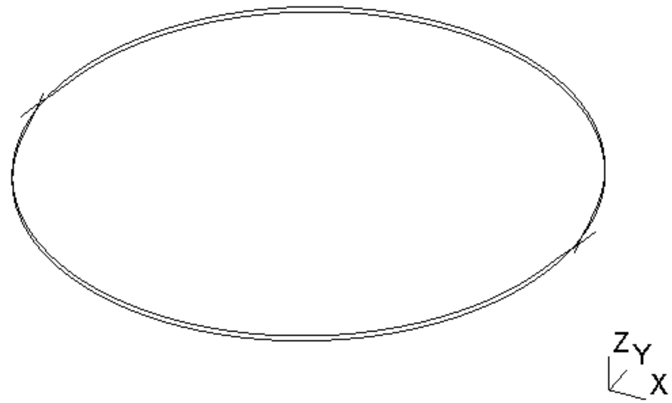
Tensile Strength (XXX) = 1 856.76 MPa

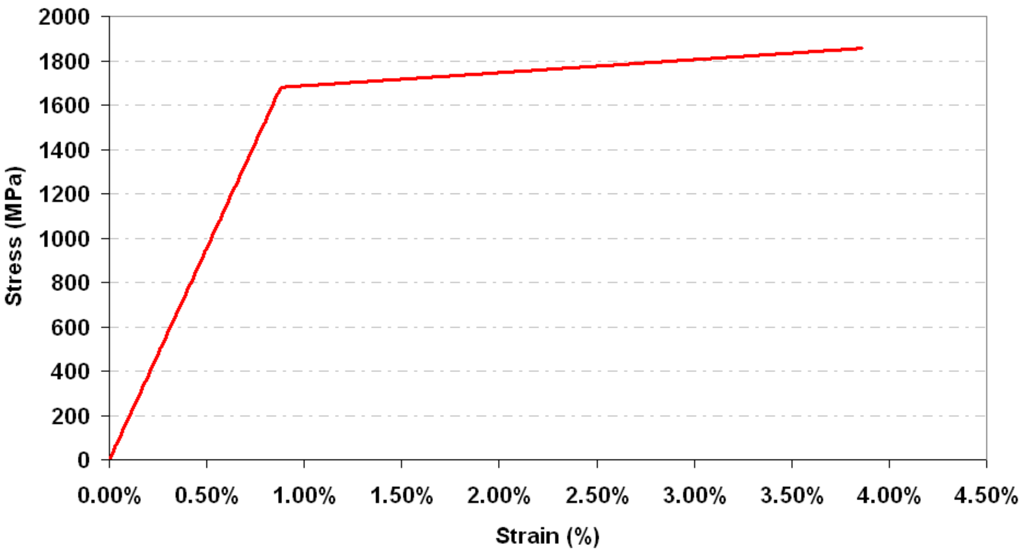
Density (ρ) = 7850 kg/m^3

Setting Losses = 3.95 mm

Angular and wobble friction: μ =0.21; λ = 0.001

Tendons section = 3.393 cm^2 (each tendon)





Tendon steel constitutive model

Elastoplastic

Parameters:

Young Modulus in elastic phase (E) = 185 000 MPa

Young Modulus in plastic phase (E) = 927 MPa

Poisson's ratio (ν) = 0.3

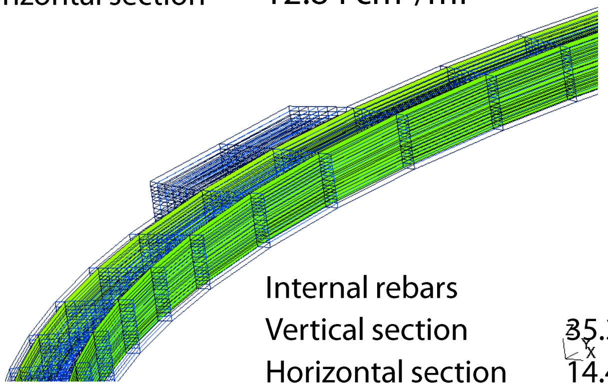
Density (ρ) = 7 850 kg/m3

Yield Strength (Y_s) = 408 MPa

External rebars

Vertical section 35.3 cm^2/ml

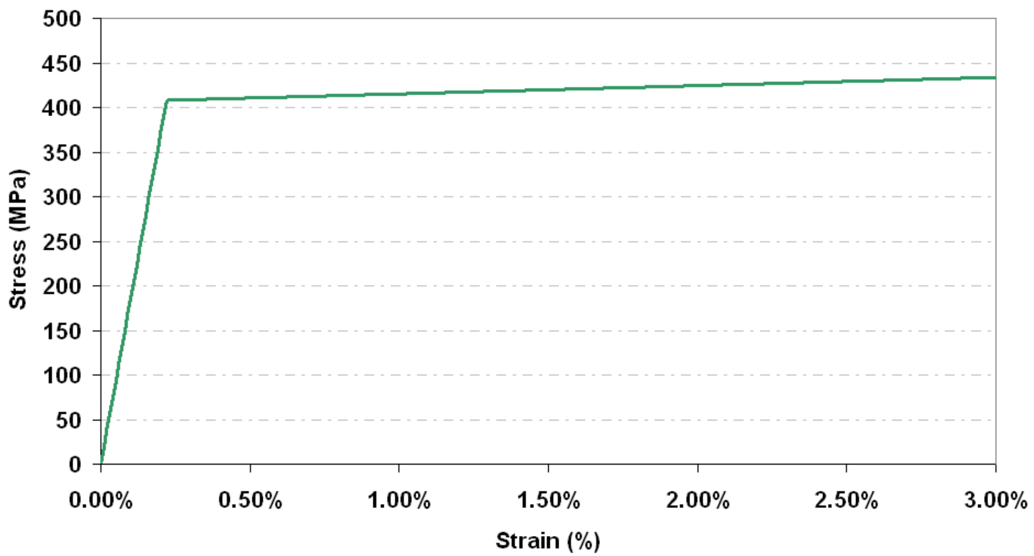
Horizontal section 12.84 cm^2/ml



Internal rebars

Vertical section 35.3 cm2/ml

Horizontal section 14.41 cm2/ml



Loading

Initial condition:

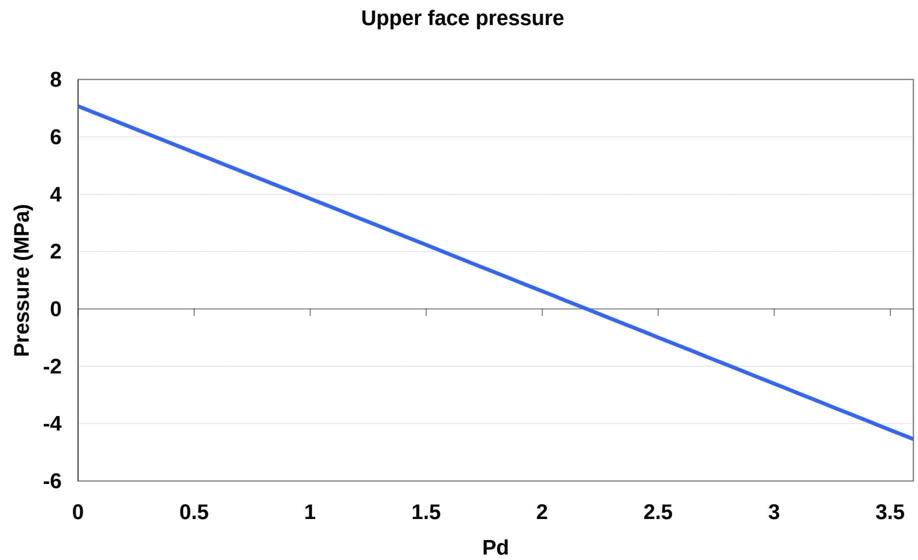
Hoop prestressing of 444 kN

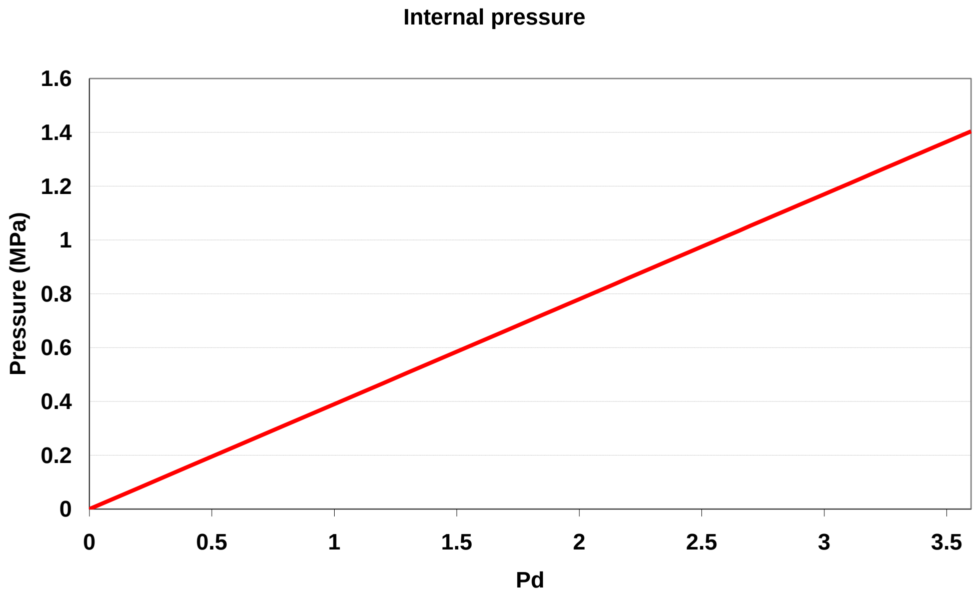
Downward pressure on top surface of 7.02 MPa

followed by:

Internal pressure P

Upward pressure on top surface of 8.27 x P MPa





Sensitivity analyses

Case study	Mesh	Tendon type	Concrete	Liner	Tendon	Rebar
Tendon type effect (TTE)	GROL	GD	M818	NL	NL	NL
		SD				
		NGD				
Mesh Type Effect (MTE)	GROL	GD	LE	LE	LE	LE
	FINL					
	GROQ					
Cracking energy effect (CEE)	GROL	SD	M818	NL	NL	NL
			M150			

Rebar behaviour
Linear LE
Non-linear NL

Tendon type
Grouted duct GD
Slippery duct SD
Ungrouted duct UGD

Concrete behaviour
Linear LE
EDF_2005 MEDF
Mazars (818 j/m^2, L=0.43 m) M818
Mazars (150 j/m^2, L=0.43 m) M150

Meshing
Coarse - linear GROL
Refined - linear FINL
Coarse quadratic GROQ

Tendon behaviour
Linear LE
Non-linear NL

Liner behaviour
Linear LE
Non-linear NL

Sensitivity analyses: tendon/duct interaction

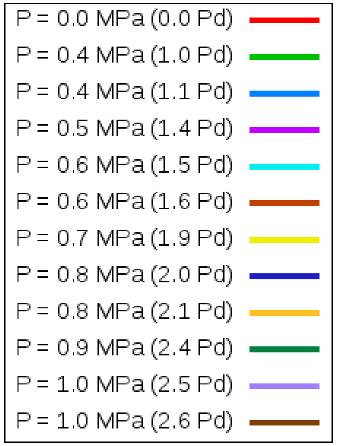
Nonlinear analysis

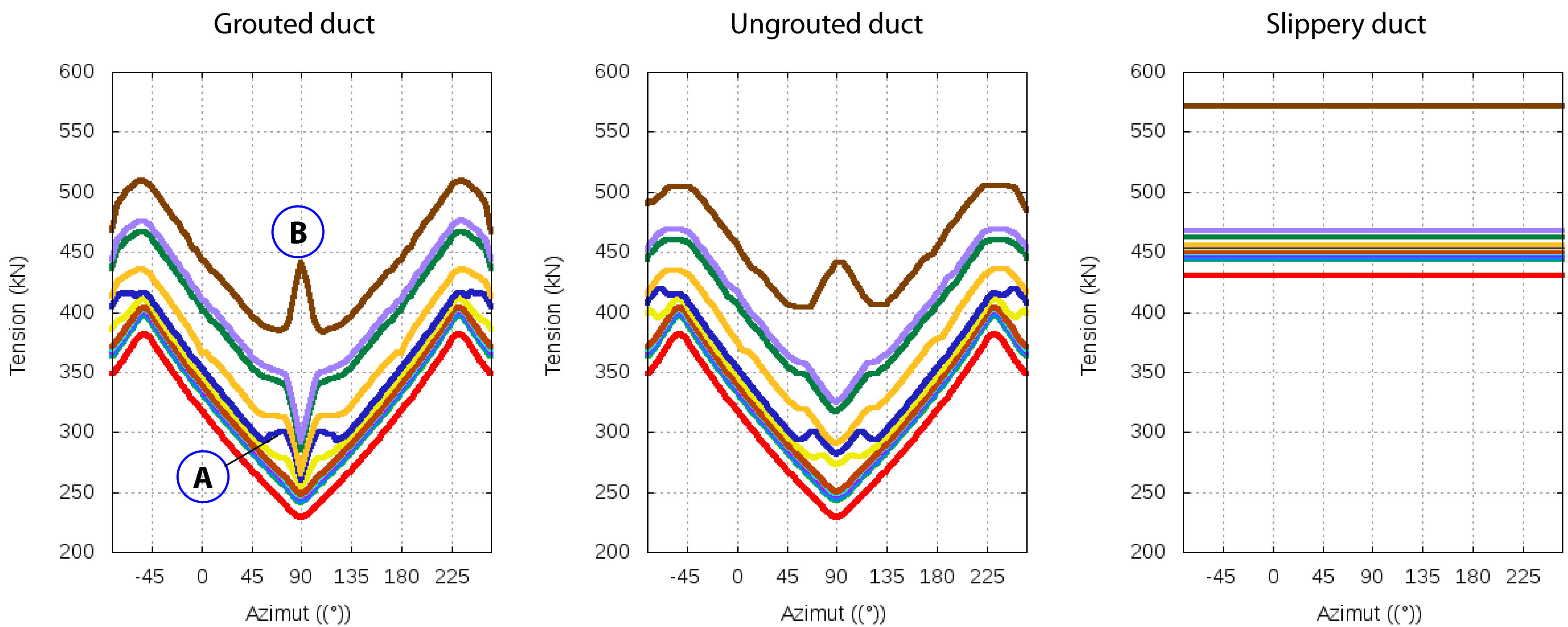
With grouted duct, high strain localisation appear where concrete cracks (modelling simplification).

When ducts are ungrouted, localisation is less strong (representative of Sandia test).

Fully slippery ducts produce uniform tendon tension. The initial prestressing should have been lowered to encounter for losses.

Tendon H-67 tension distribution





Sensitivity analyses: tendon/duct interaction

Nonlinear analysis

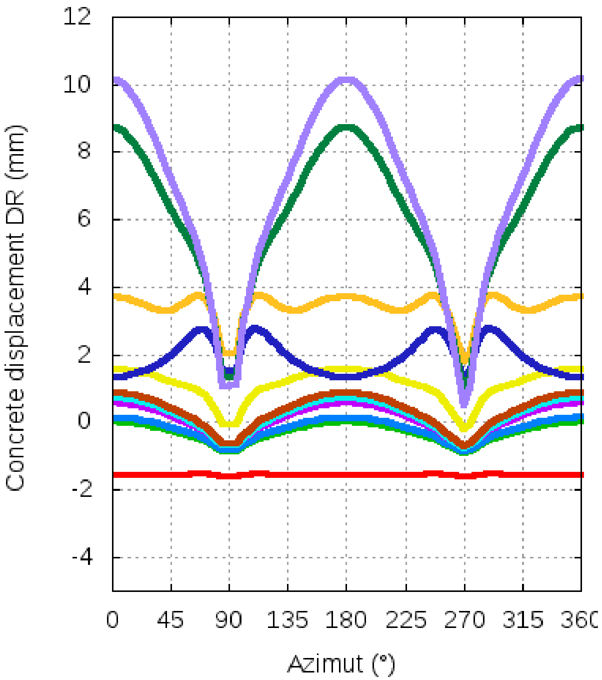
Grouted and ungrouted tendons exhibit the same radial displacements during linear elastic range of behaviour. This is also the case at high internal pressure loading with strong concrete damage. In between, results are significantly different.

For fully slippery duct, deflections are uniform, and lower, due to stronger prestressing.

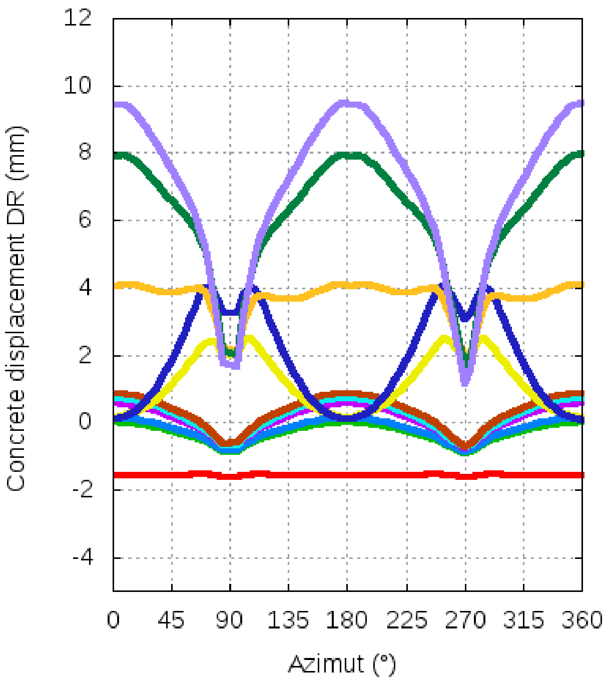
Radial displacement (z = H/2, external face)

- P = 0.0 MPa (0.0 Pd)
- P = 0.4 MPa (1.0 Pd)
- P = 0.4 MPa (1.1 Pd)
- P = 0.5 MPa (1.4 Pd)
- P = 0.6 MPa (1.5 Pd)
- P = 0.6 MPa (1.6 Pd)
- P = 0.7 MPa (1.9 Pd)
- P = 0.8 MPa (2.0 Pd)
- P = 0.8 MPa (2.1 Pd)
- P = 0.9 MPa (2.4 Pd)
- P = 1.0 MPa (2.5 Pd)

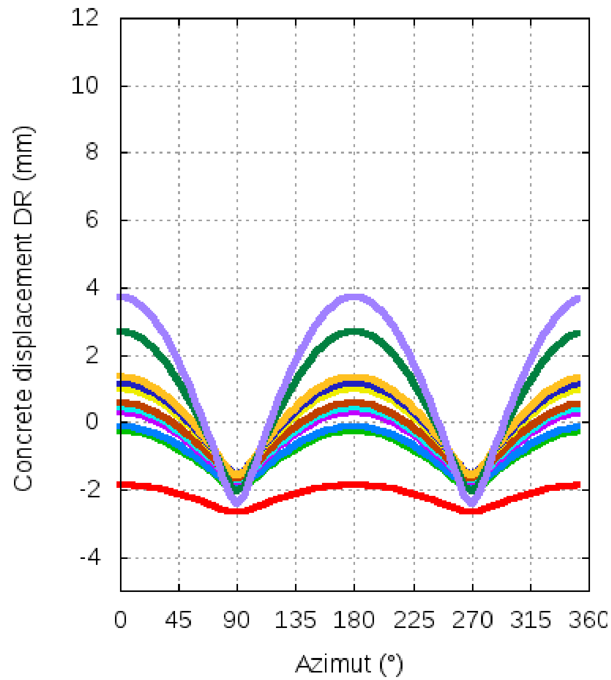
Grouted duct



Ungrouted duct



Slippery duct

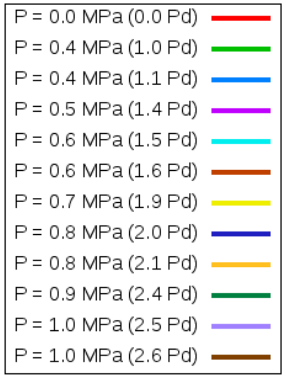


Sensitivity analyses: tendon/duct interaction

Nonlinear analysis

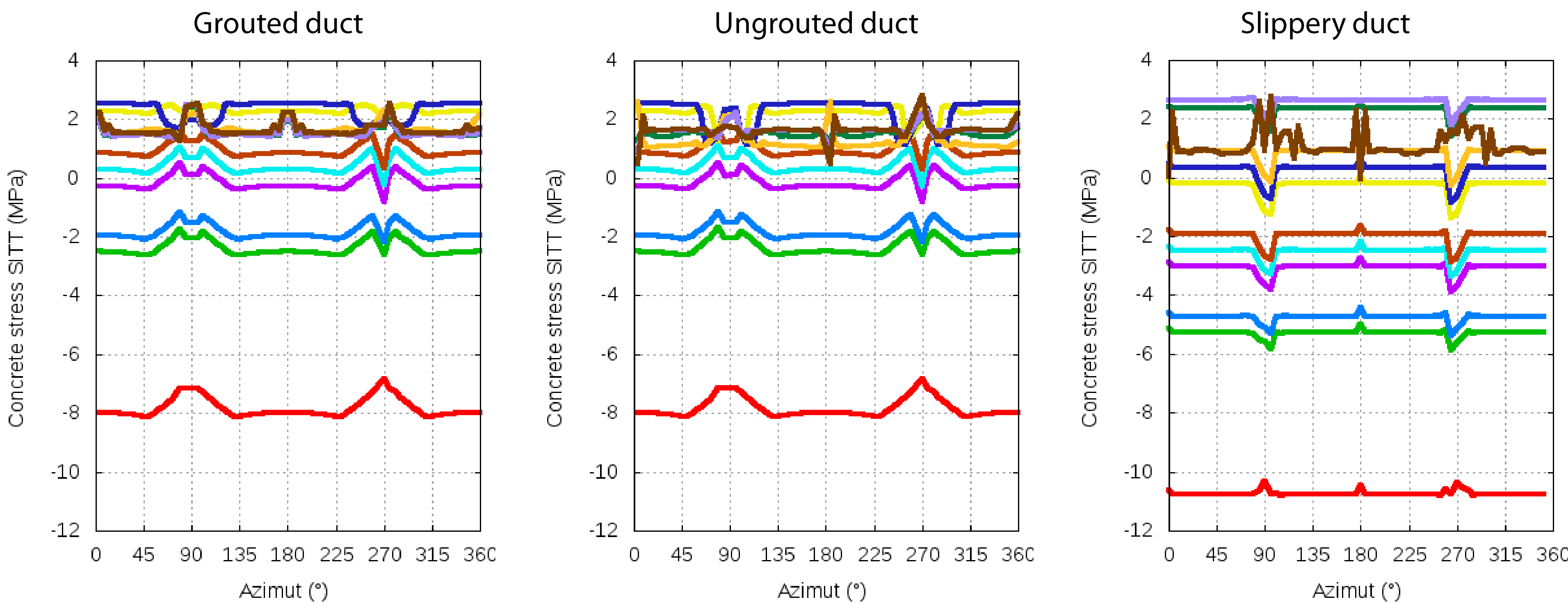
Concrete hoop stress

(z = H/2, mid-section)

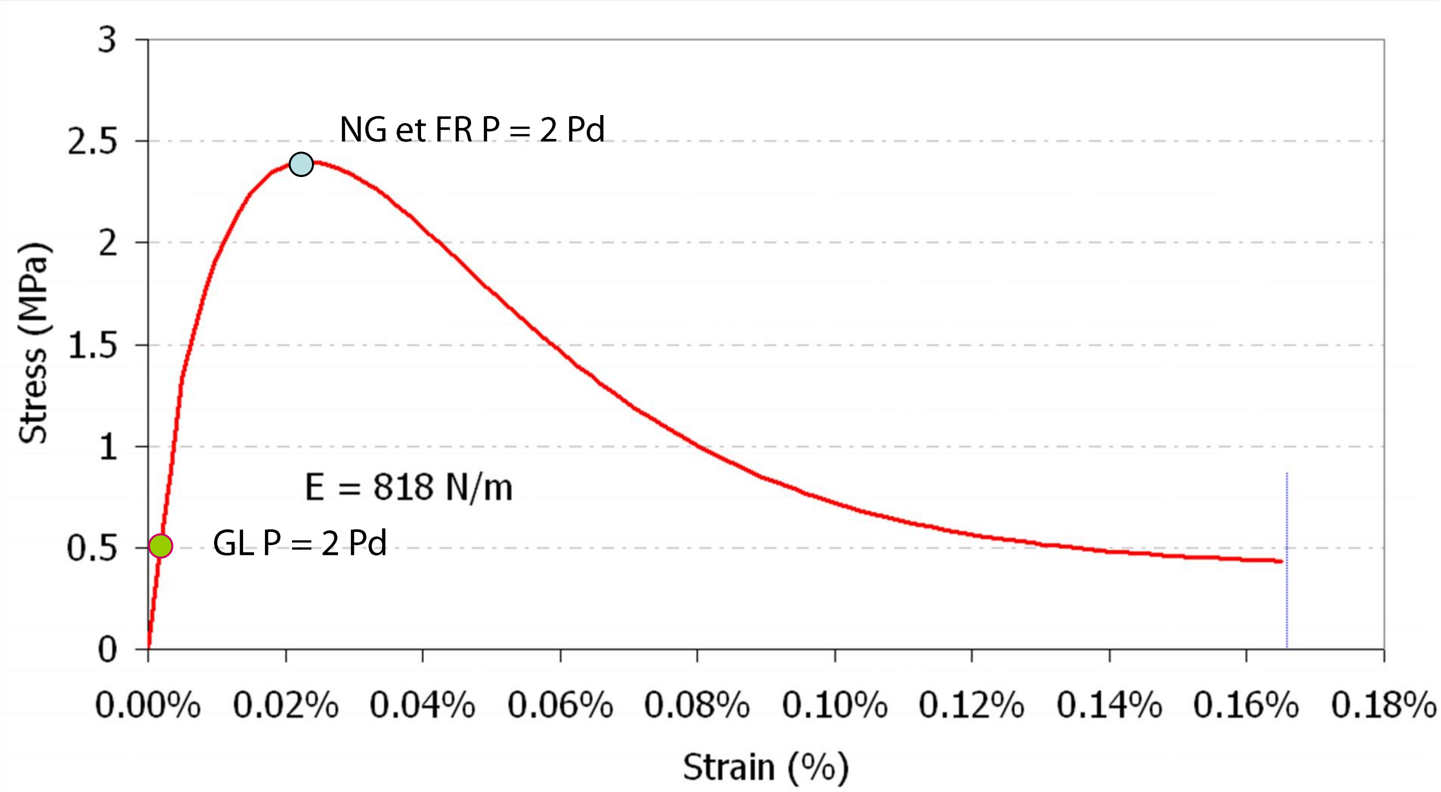


Concrete hoop stresses are quite similar between both grouted an ungrouted tendons.

Slippery ducts lead to late cracking



Sensitivity analyses



Sensitivity analyses: mesh element type

Grouted ducts – Linear elastic analysis

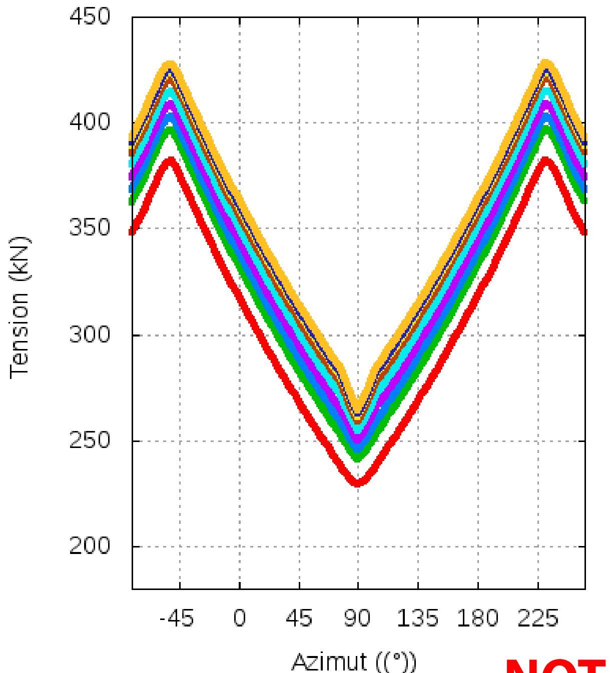
Tendon 67 tension

- P = 0.0 MPa (0.0 Pd)
- P = 0.4 MPa (1.0 Pd)
- P = 0.6 MPa (1.5 Pd)
- P = 0.8 MPa (2.0 Pd)
- P = 1.0 MPa (2.5 Pd)
- P = 1.2 MPa (3.0 Pd)
- P = 1.3 MPa (3.3 Pd)
- P = 1.3 MPa (3.4 Pd)
- P = 1.4 MPa (3.6 Pd)

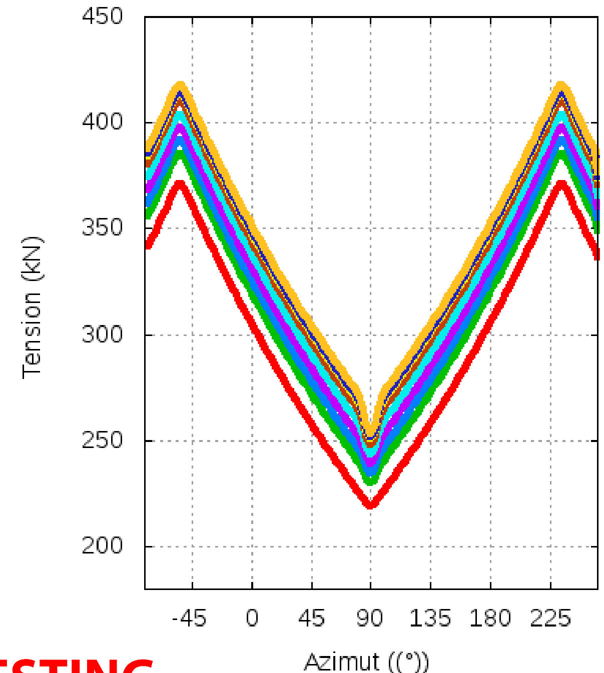
Very slight differences on tendon tensile forces (higher values for linear elements).

Variations are more emphasised with quadratic elements.

Coarse linear meshing



Coarse quadratic meshing



NOT VERY INTERESTING

Sensitivity analyses: mesh element type

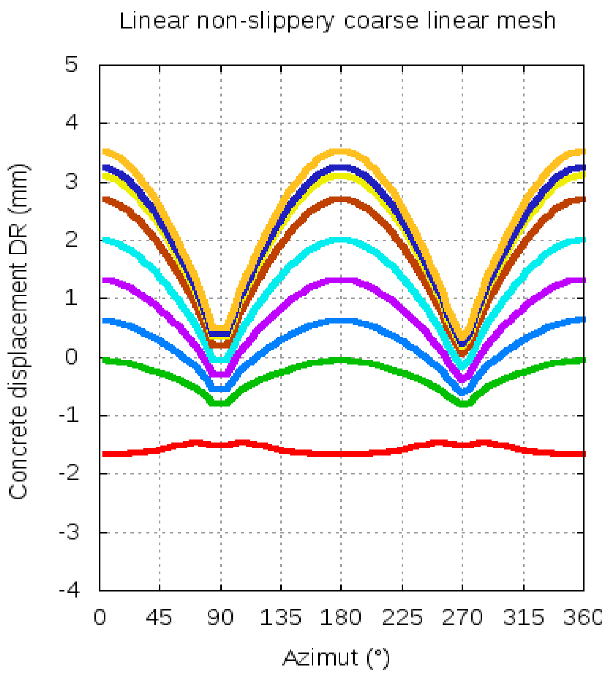
Grouted ducts – Linear elastic analysis

Radial displacement
(z = H/2, external face)

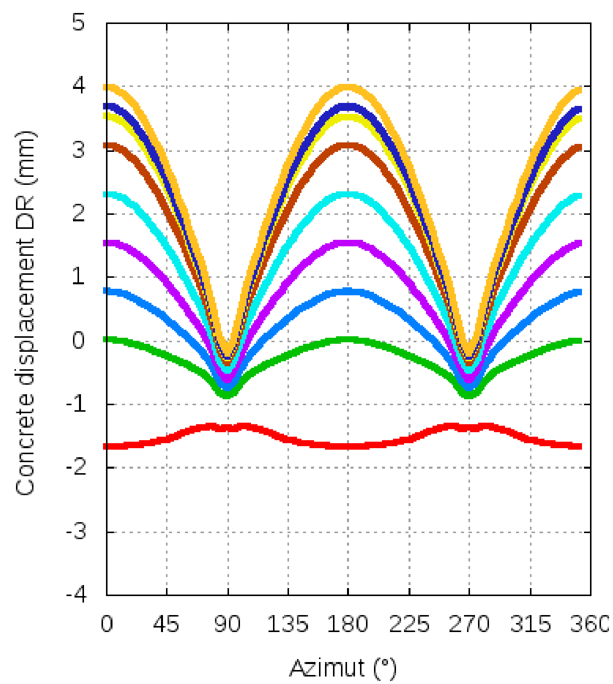
- P = 0.0 MPa (0.0 Pd)
- P = 0.4 MPa (1.0 Pd)
- P = 0.6 MPa (1.5 Pd)
- P = 0.8 MPa (2.0 Pd)
- P = 1.0 MPa (2.5 Pd)
- P = 1.2 MPa (3.0 Pd)
- P = 1.3 MPa (3.3 Pd)
- P = 1.3 MPa (3.4 Pd)
- P = 1.4 MPa (3.6 Pd)

Refined and quadratic meshing produce larger displacement. This is due to the presence of flexural deflection of the model

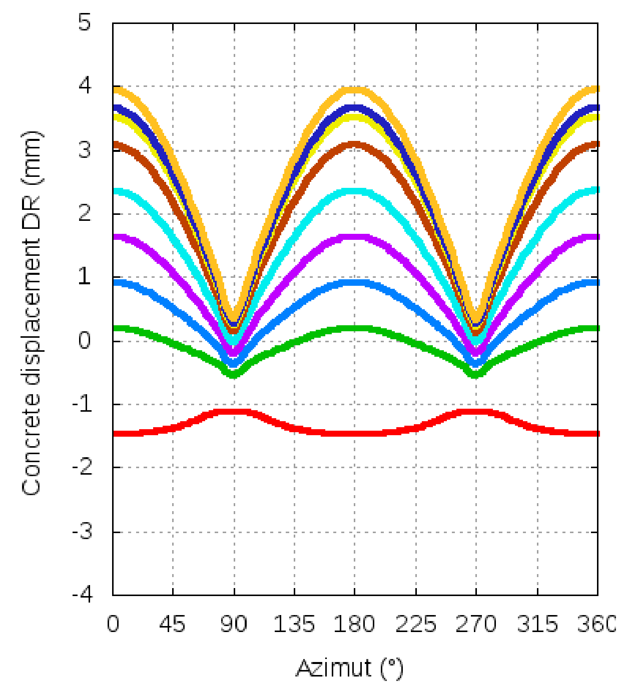
Coarse linear meshing



Coarse quadratic meshing



Refined linear meshing



Sensitivity analyses: mesh element type

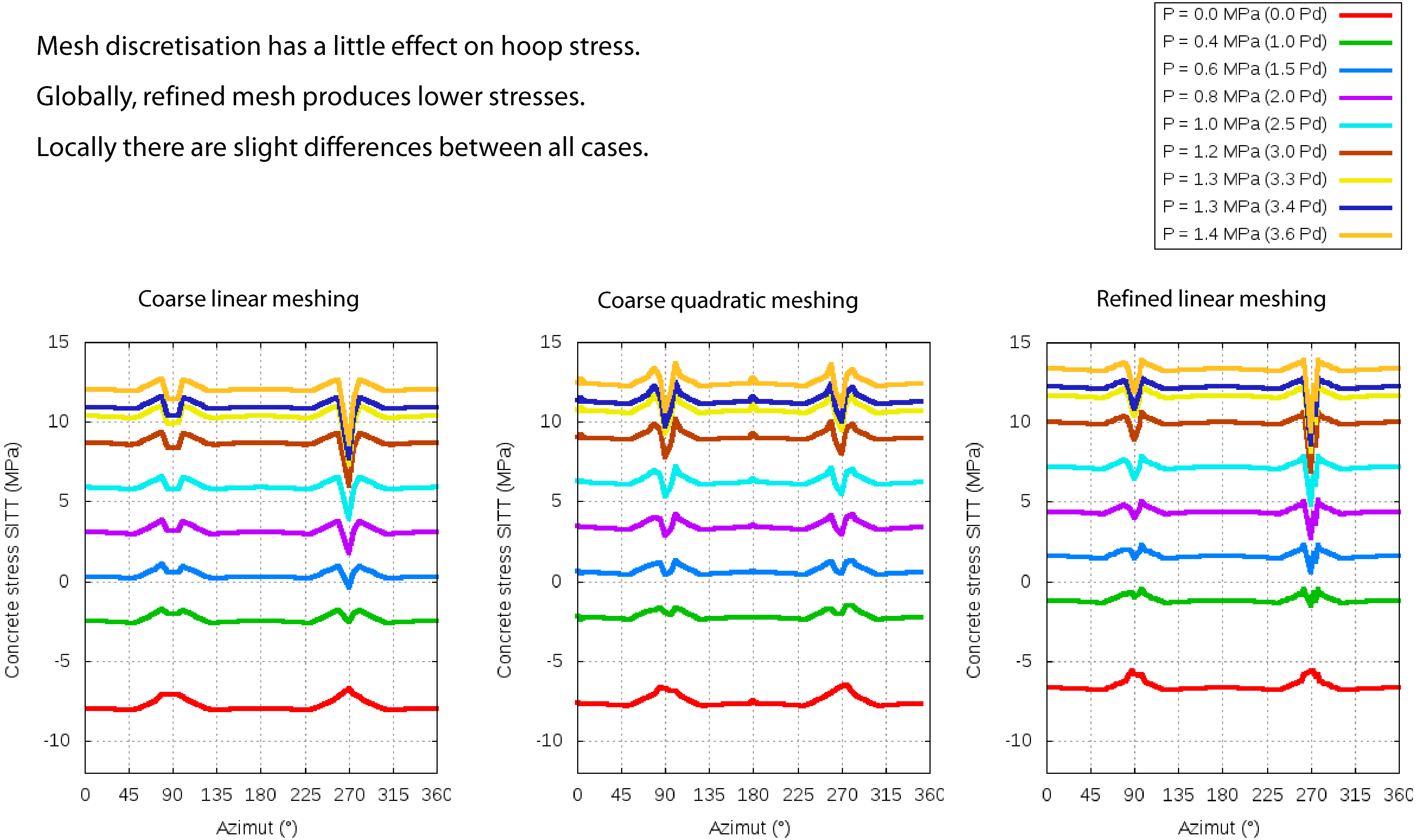
Grouted ducts – Linear elastic analysis

Mesh discretisation has a little effect on hoop stress.

Globally, refined mesh produces lower stresses.

Locally there are slight differences between all cases.

Concrete hoop stress
(z = H/2, mid section)



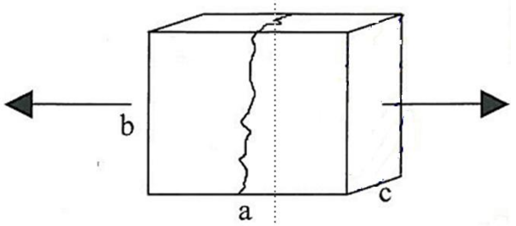
NOT VERY INTERESTING

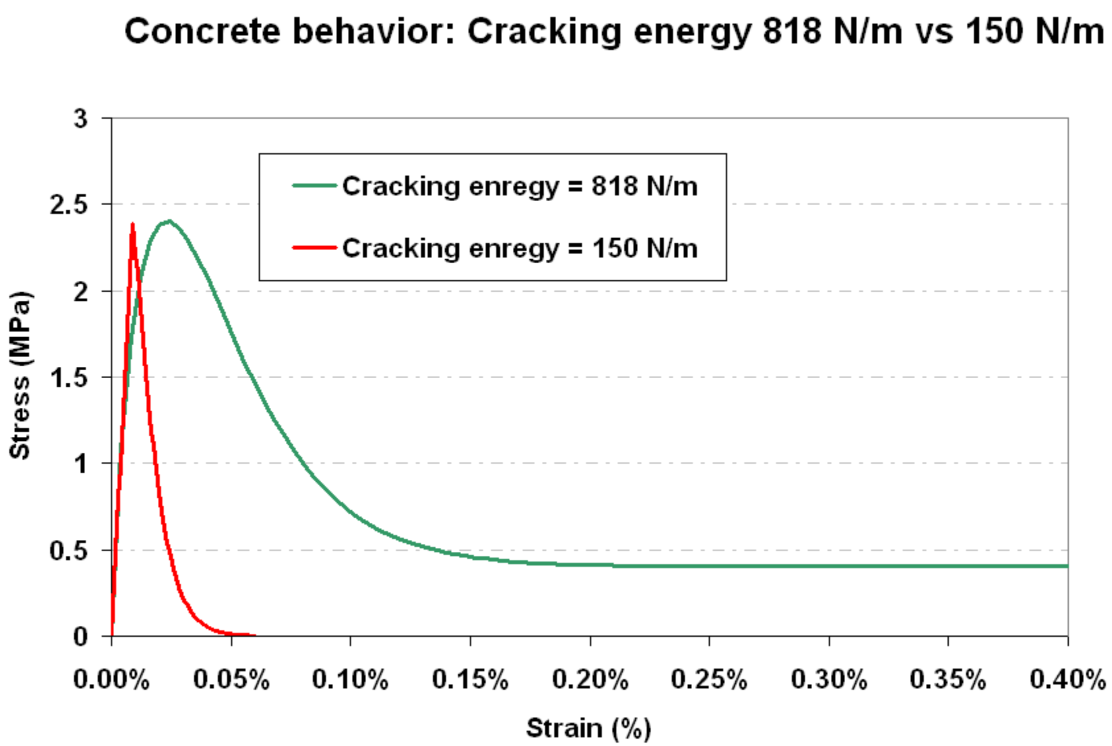
Sensitivity analyses: G_f fracture energy

Ungrouted ducts

Cracking energy effect (CEE): Cracking energy. Non-Grouted duct

Energy needed to fracture a concrete bloc= G_f x b x c





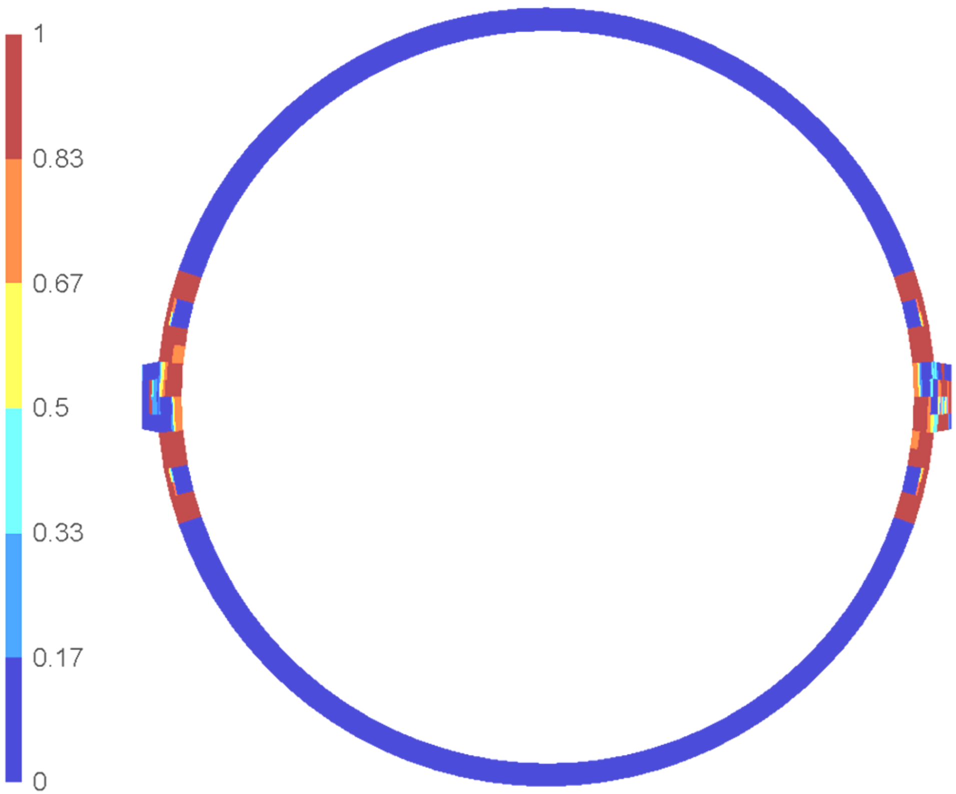
Sensitivity analyses: G_f fracture energy

Ungrounted ducts

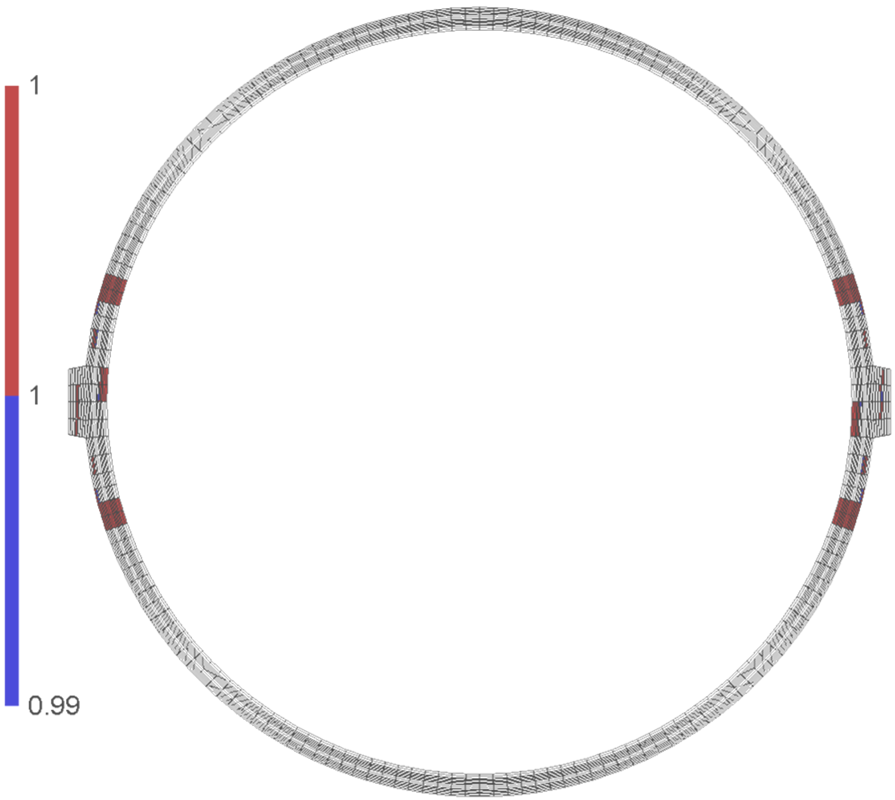
Cracking energy effect (CEE): Cracking energy. Non-Grouted duct

Damage index D at 1.7 x Pd (Gf = 150 j/m^2)

At P = 1.7 Pd full thickness is damaged (D =1) so it can not be loaded any more



0 < D < 1



ZOOM :
0.99 < D < 1

Sensitivity analyses: fracture energy effect

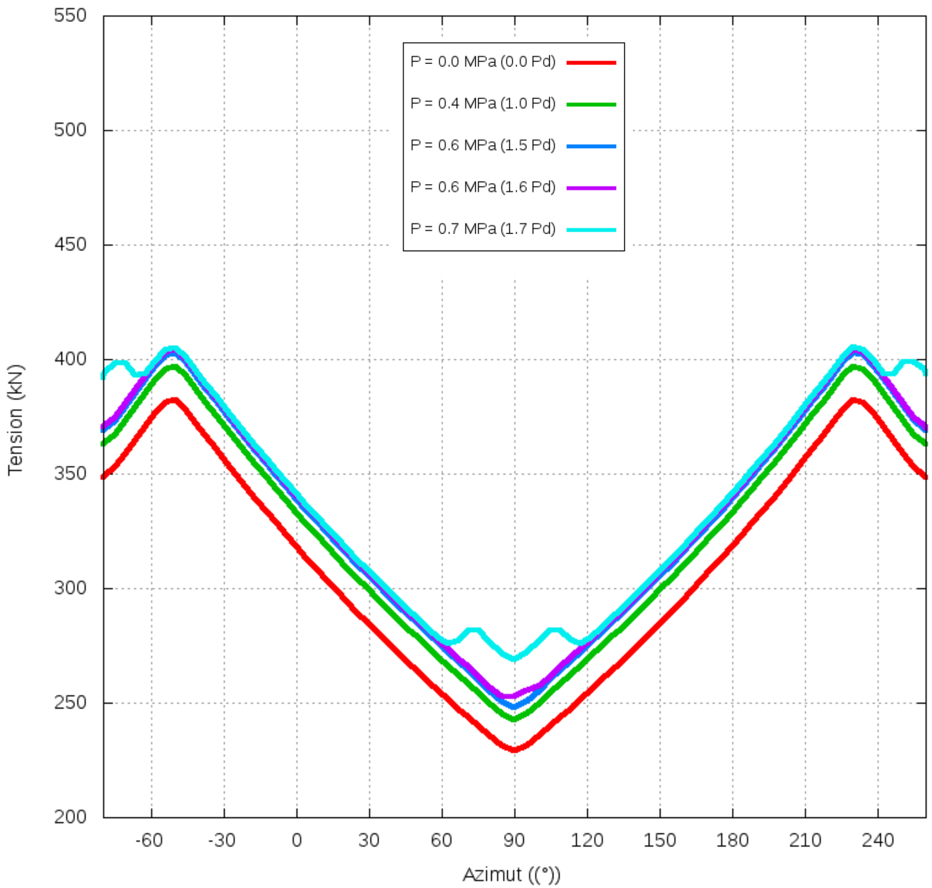
Ungrouted ducts – Nonlinear analysis

Tendon tension

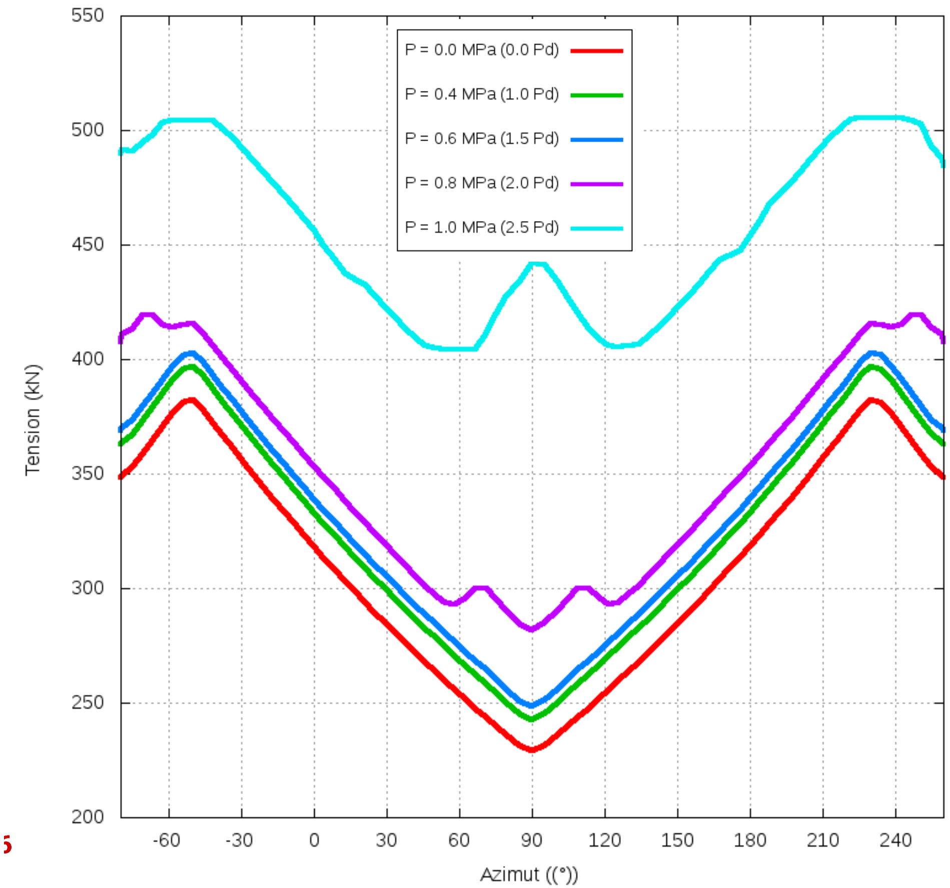
Low G_f produces early damaging. Thus early stress concentration in tendons.

Low Gf raised more difficulties to pursuit calculation (reasons are under investigation). While high Gf allow to reach higher values.

Concrete M150



Concrete M818

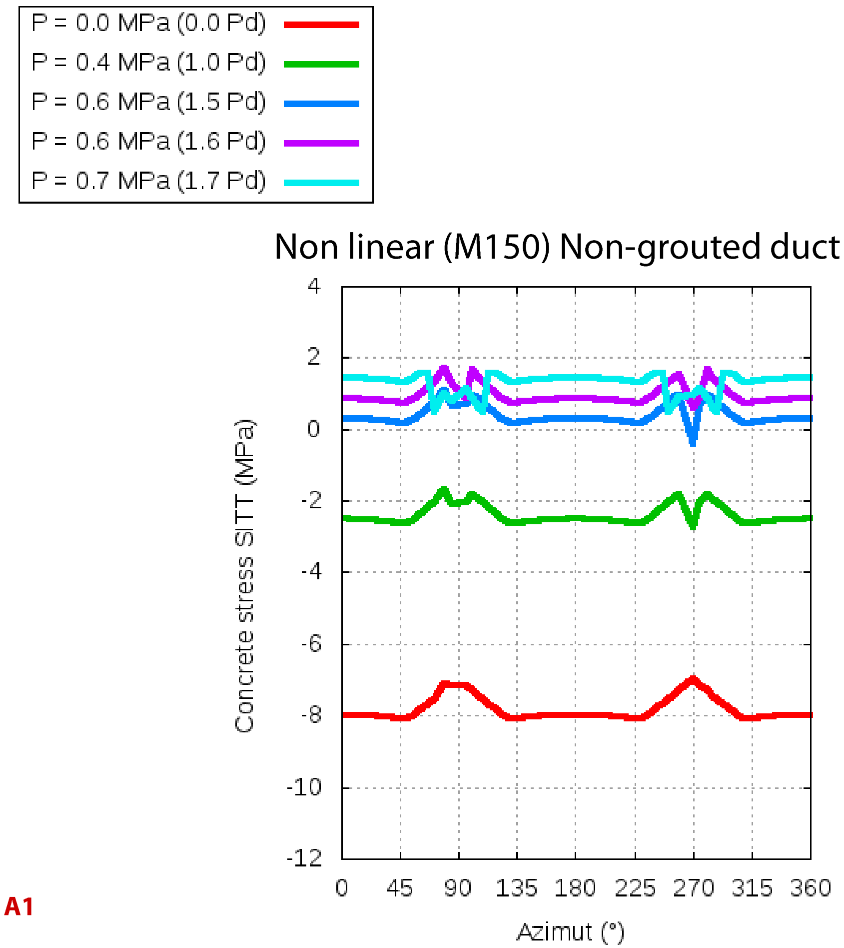


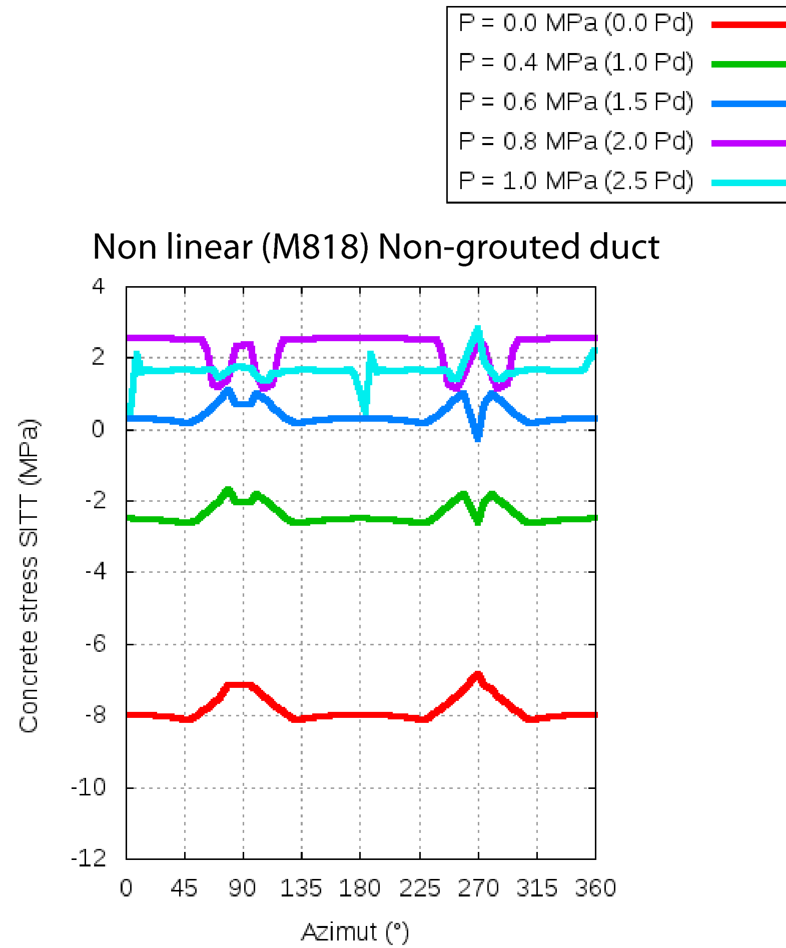
Cracking energy effect (CEE): Concrete hoop stress (z = H/2, half thickness). Non-Grouted duct

1. Avec l'énergie de fissuration plus basse (150 N/m) à P = 1.5 Pd on est proche du pic de contrainte en traction (2.4 MPa) et la partie post-pic de la loi de comportement a une descente brutale ce qui fait que à partir de cette pression l'anneau s'endommage brutalement et le calcul ne converge plus .

2. Avec l'énergie de fissuration plus élevée, à P = 1.5 Pd on est loin du pic en traction.

3. Avec l'énergie de fissuration de (150 N/m) on a un comportement plus réaliste mais le fait de n'avoir pas un résidu de résistance au béton complique la convergence du calcul

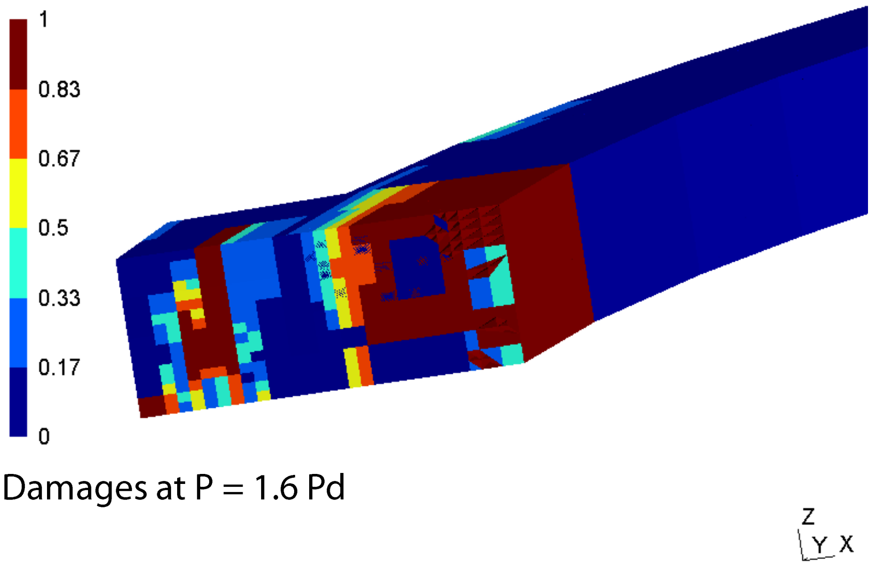




Cracking energy effect (CEE): Concrete damage. Non-Grouted duct

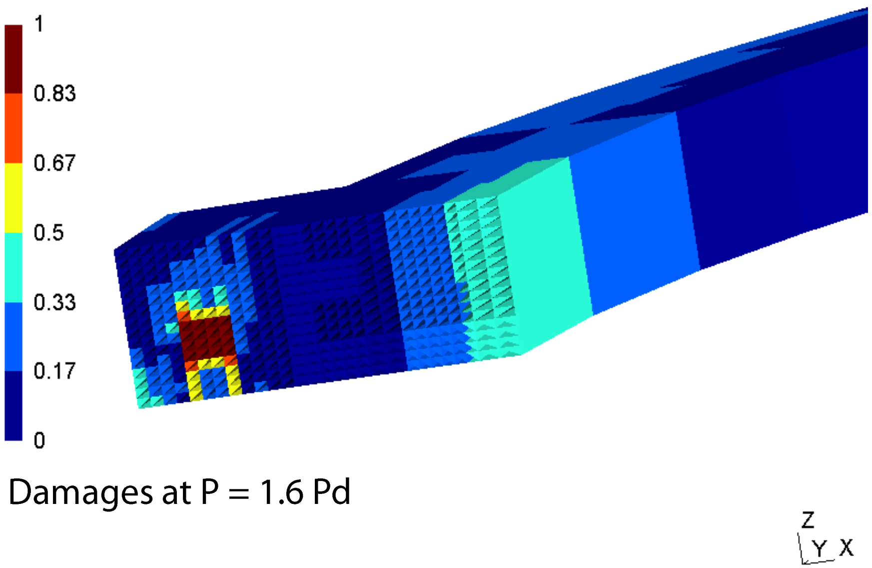
1. Quand l'énergie de fissuration es plus basse (gauche), l'anneau commence à endommager plus tôt (pour la même pression P = 1.6Pd on voit un endommagement plus élevé pour MM150)

Non linear (M150) Non-grouted duct



Damages at P = 1.6 Pd

Non linear (M818) Non-grouted duct



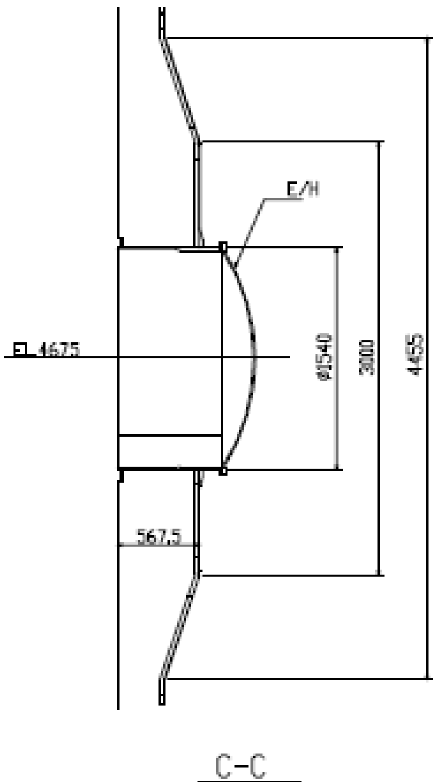
Damages at P = 1.6 Pd

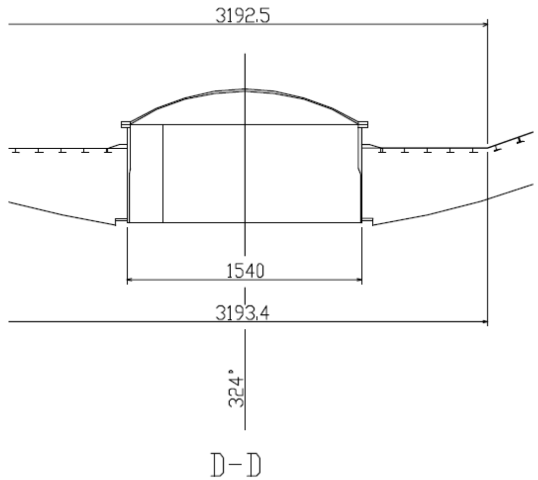
Model 2

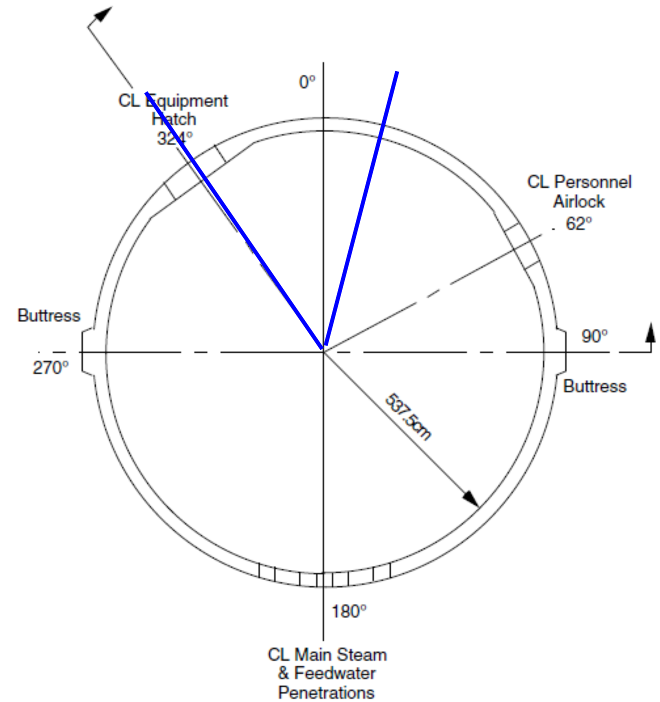
SUMMARY

- Description of equipment hatch geometry
- Modeling assumptions and phenomenological models
- Description of liner tearing criteria used
- Deformed shape
- Liner seals state at p = 0 (prestress applied), p = 1.0 pd

Model geometrical description







From NUREG_CR-6810-appendices.pdf (A-28)

And PCCV-QCON-01

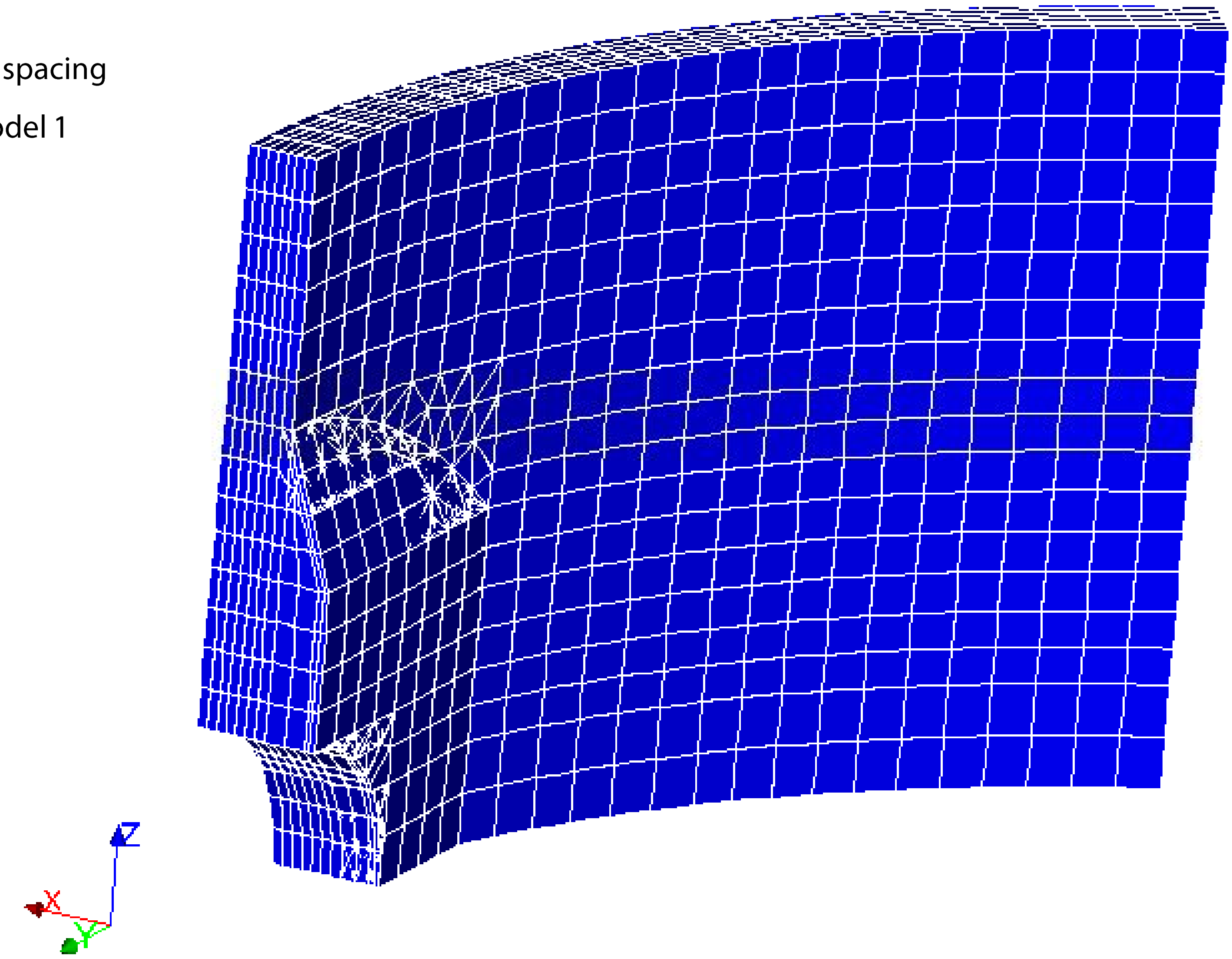
Meshing: concrete

Solid element

Quadratic

Average size = anchorage spacing

Properties: same as for model 1



Meshing: liner

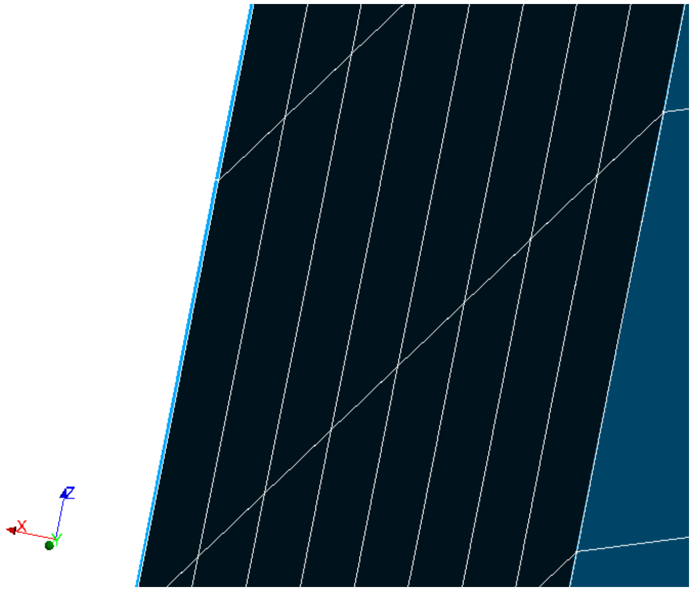
Solid element

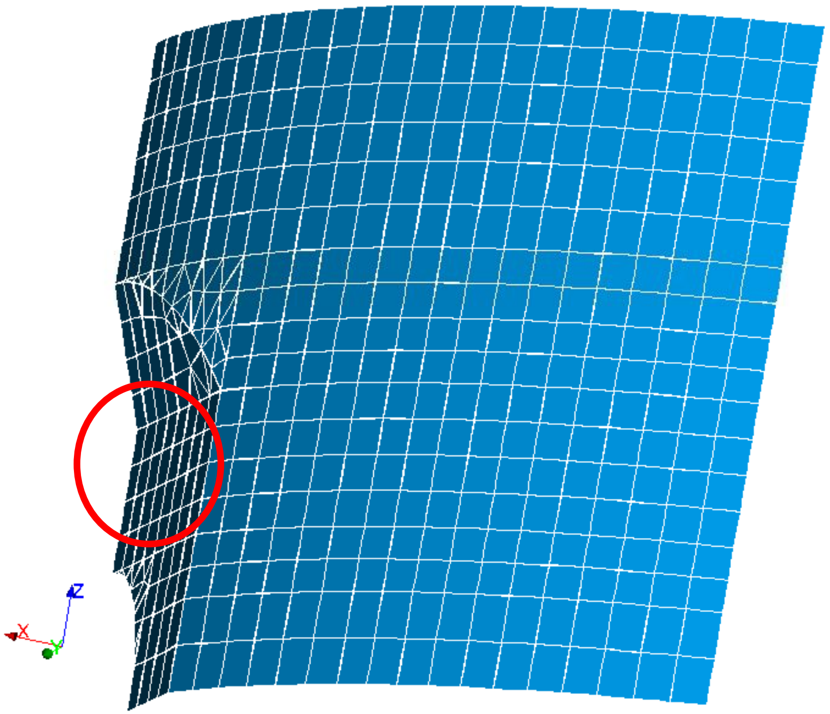
Quadratic

Thickness 1.6mm

Liner perfectly bonded with concrete at nodes except at seal lines (same Ur)

Properties: same as for model 1





Meshing: seal

Cohesive zone model elements

Hexa-CZE (zero volume element)

Quadratic number of nodes with special shape function

Liner / concrete interface: same radial displacement

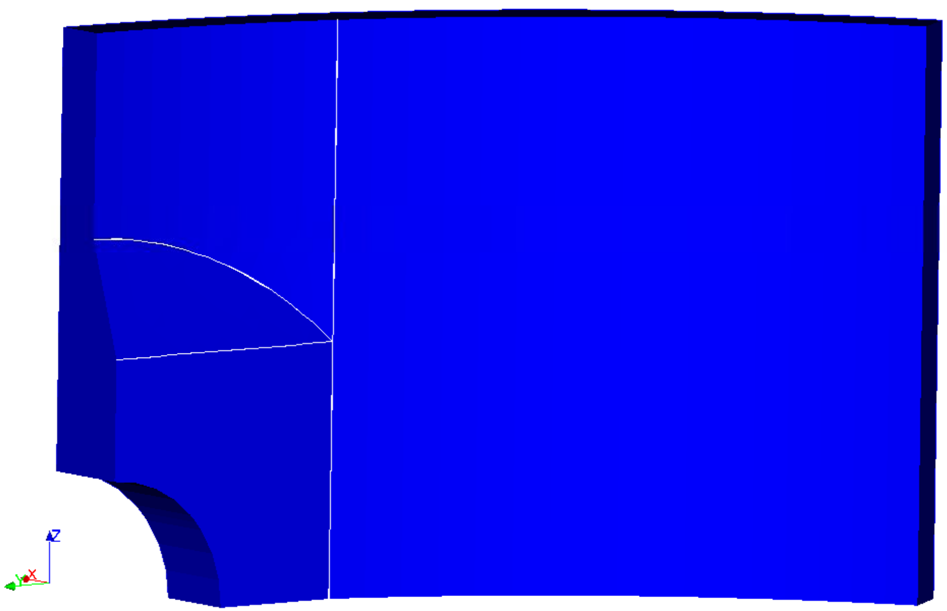
E= 223 GPa

ν= 0

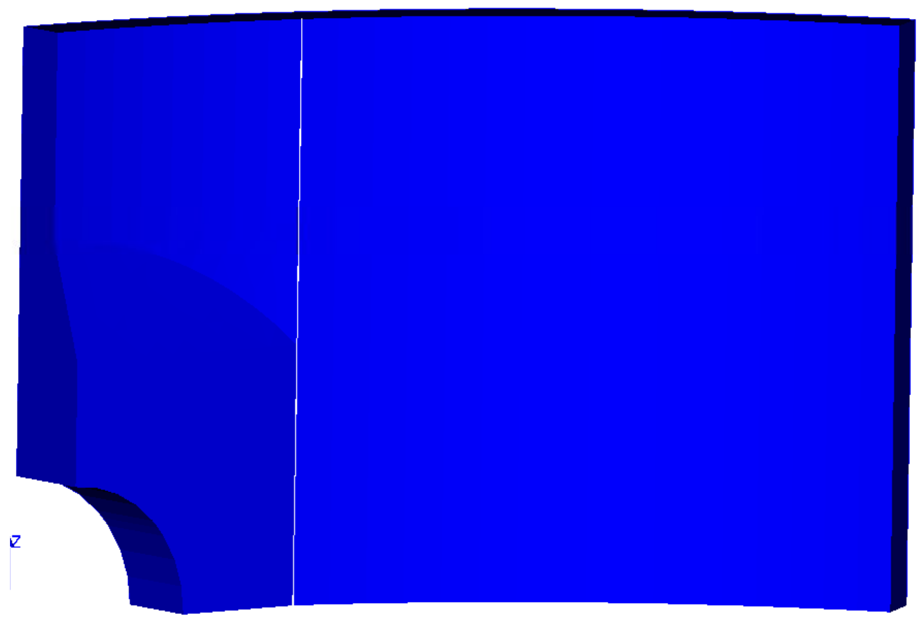
ρ= 7 850 kg/m^3

GC = 130 MPa.µm	Surface energy density
SIGM_C = 498 MPa	Failure stress
COEF_EXTR =0.	Shape of stress vs jump displacement curve - Mode I crack opening
COEF_PLAS = 0.5	

Seals surrounding the E/H



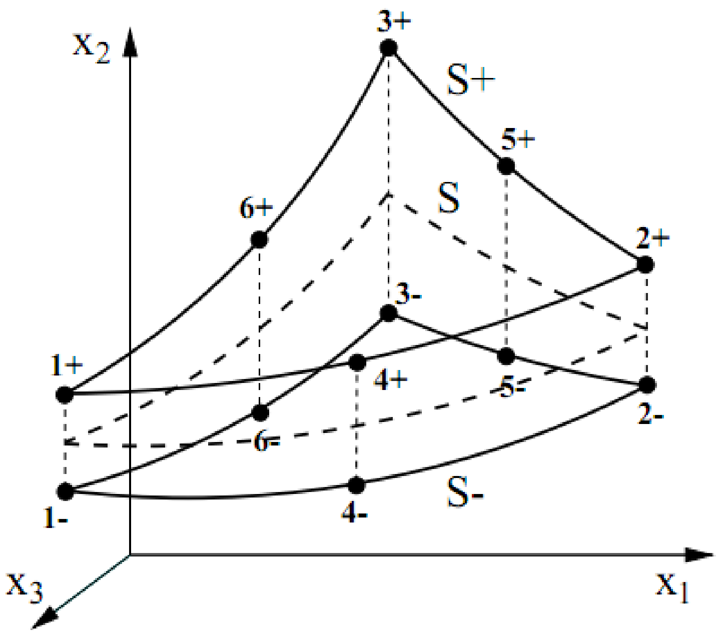
One vertical seal



Difficulties at intersections!

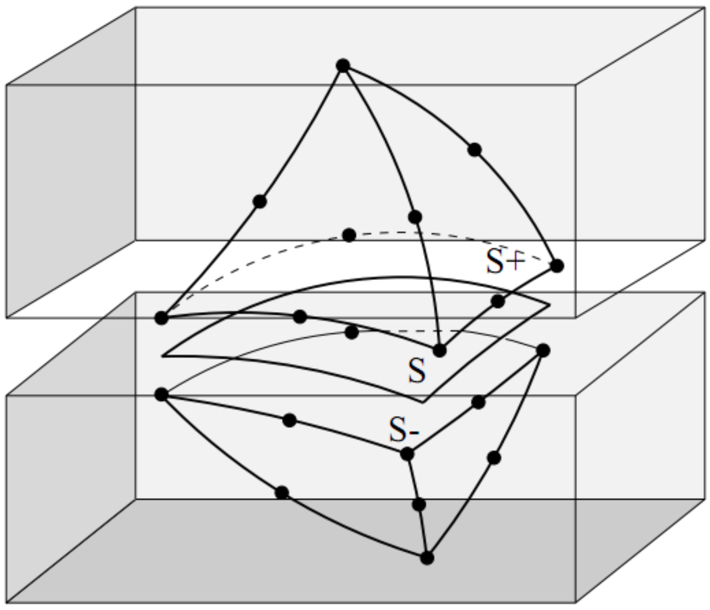
Cohesive zone model elements

Example of tetra-cohesive zone elements. In model 2 we use hexa-CZE.



Geometry of a cohesive element

S+ and S- are coincident in initial state



Assembly of a cohesive element with adjacent liner elements

Liner tearing constitutive model

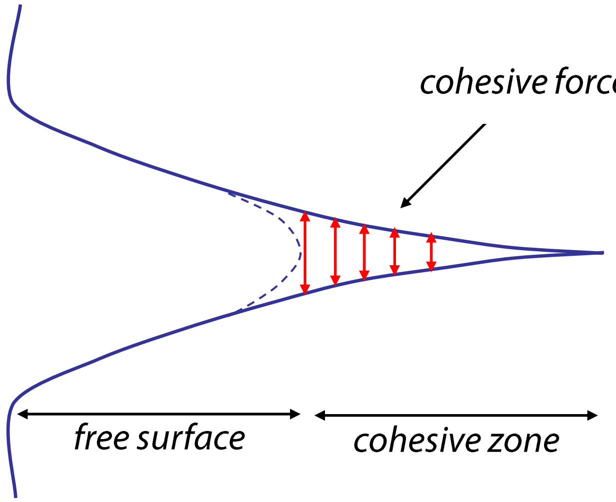
Known as "CZM", Cohesive zone model

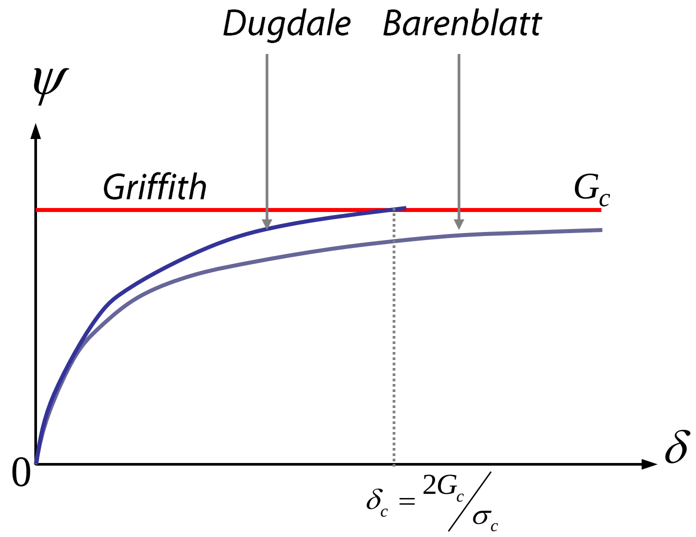
Features :

- Energy formulation for failure: minimization of the total energy

$$E_T = \Phi + \Psi - W^{ext}$$

(deformation, external forces, ***surface****)*



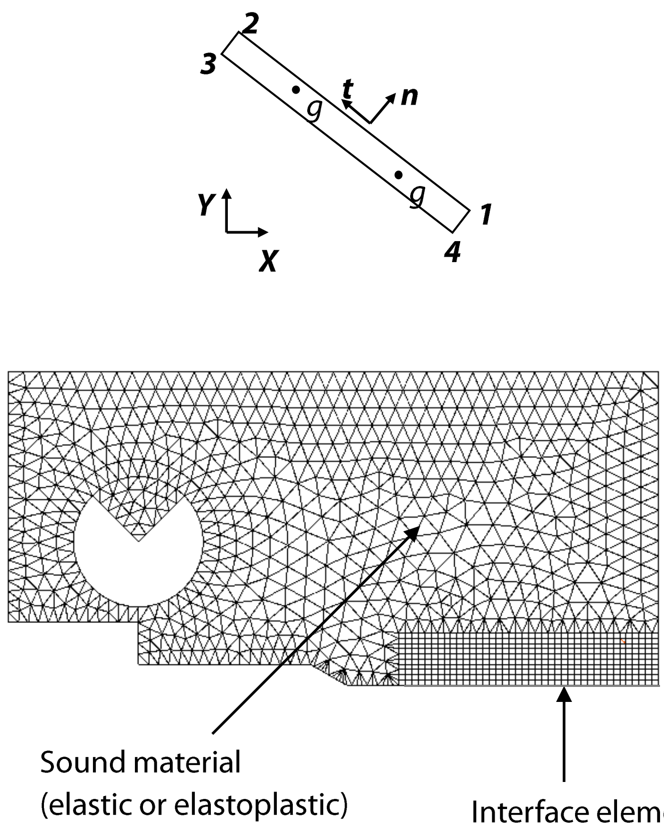


Surface energy density vs. jump displacement

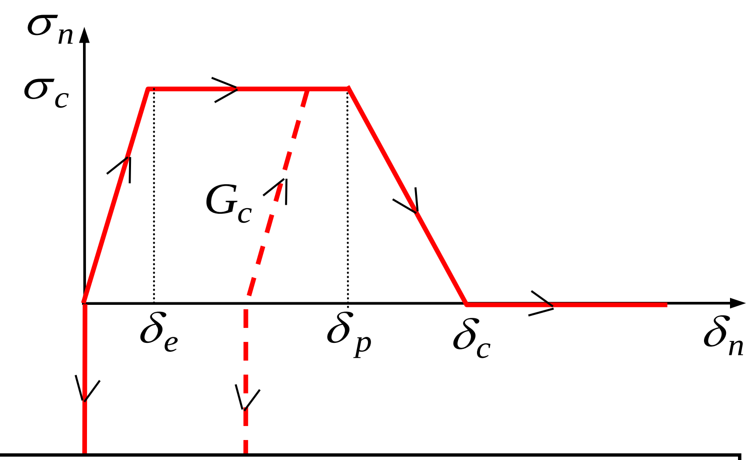
Liner tearing constitutive model

Known as "CZM", Cohesive zone model

Interface elements introduced along the « supposed » crack path



The cohesive law for ductile fracture



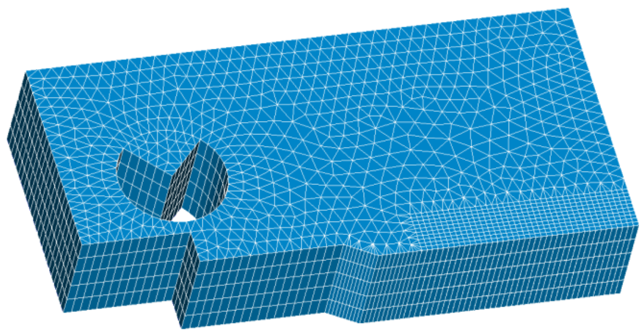
$$\sigma_n(\delta_n) = \sigma_c \begin{cases} \dfrac{\delta_n}{\delta_e} & \text{if} \quad \delta_n \le \delta_e \\ 1 & \text{if} \quad \delta_e < \delta_n < \delta_p \\ \dfrac{\delta_c - \delta_n}{\delta_c - \delta_p} & \text{if} \quad \delta_p \le \delta_n < \delta_c \\ 0 & \text{if} \quad \delta_n \ge \delta_c \end{cases}$$

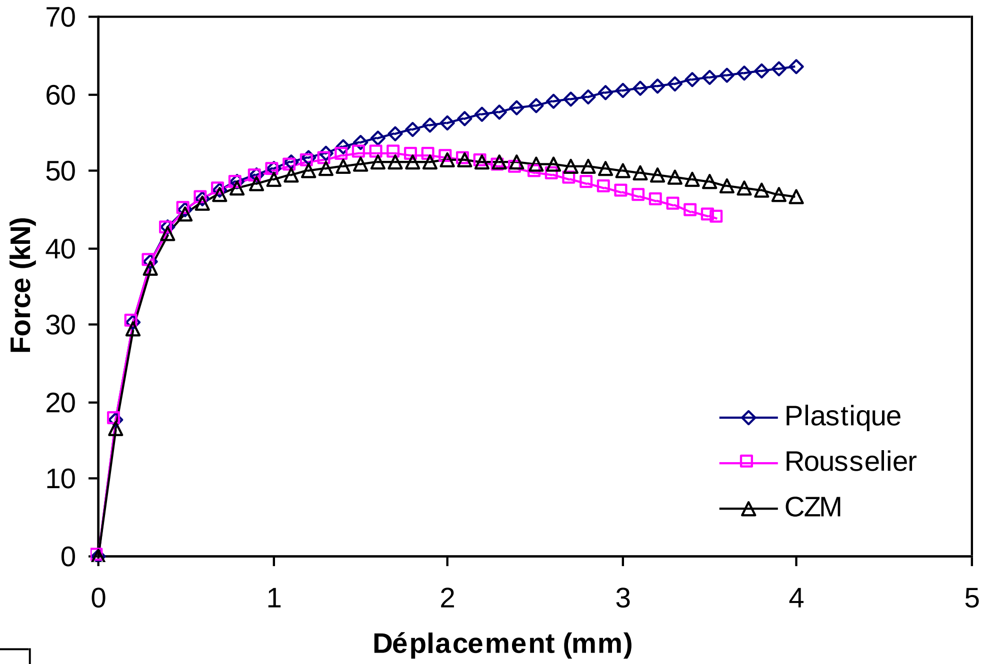
$$\delta_c = 2G_c/\sigma_c + \delta_e - \delta_p \qquad \delta_e \le \delta_p < \delta_c$$

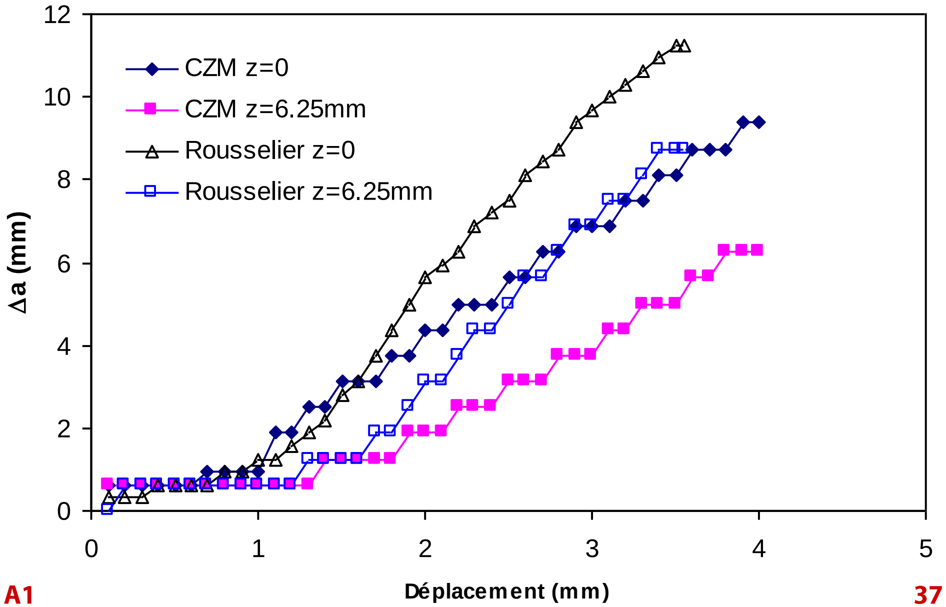
Liner tearing constitutive model

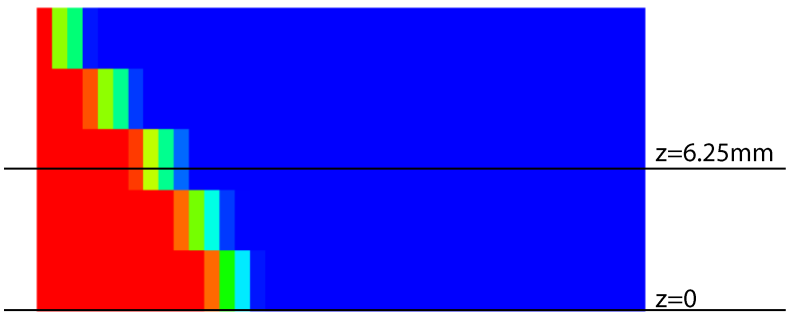
Known as "CZM", Cohesive zone model

Test case









Meshing: steel reinforcement

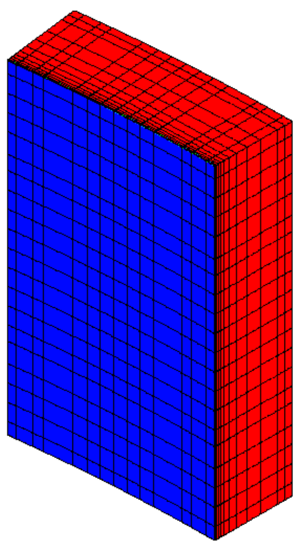
Grid elements

Shell element with uniaxial behaviour

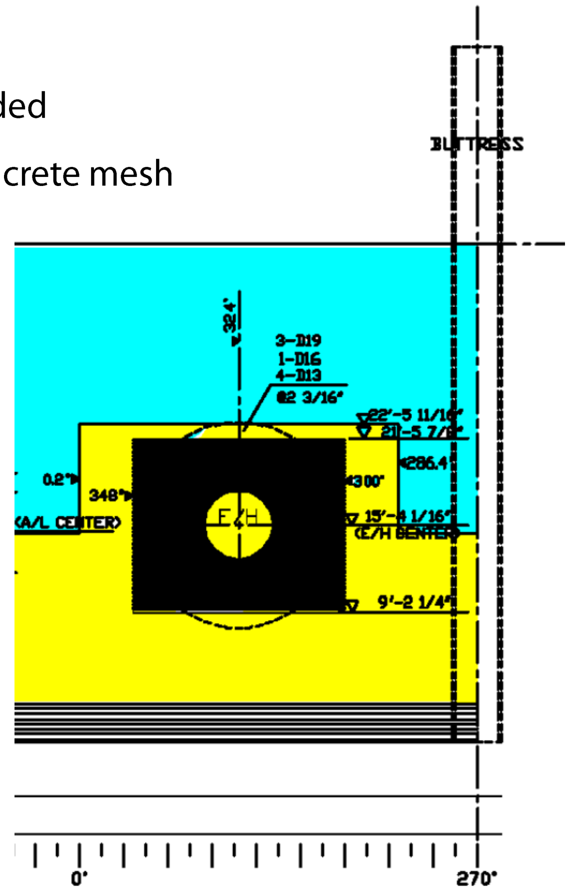
Linear

Rebar / concrete interface: perfectly bonded

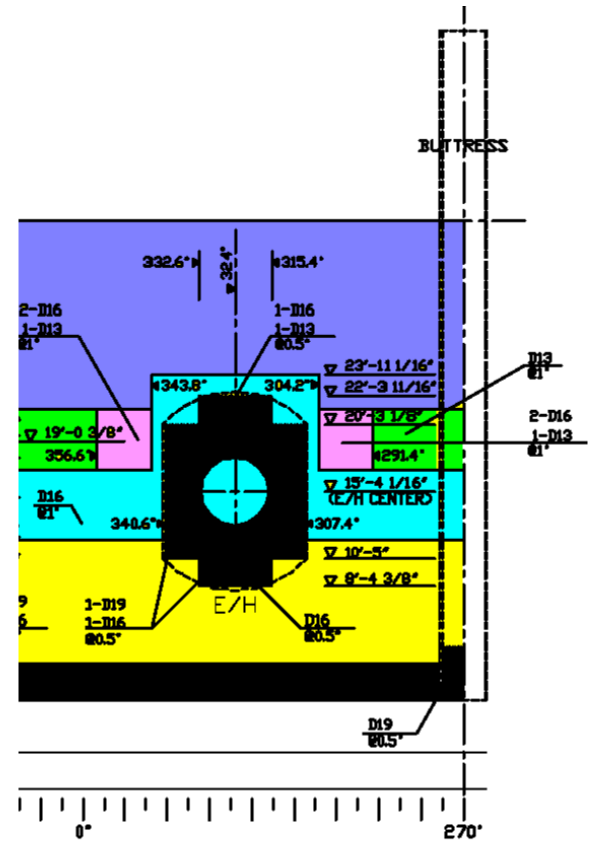
Placed on inner and outer surfaces of concrete mesh



Rebars ratios and localisations (from PCCV-QCON-12 and PCCV-QCON-16)

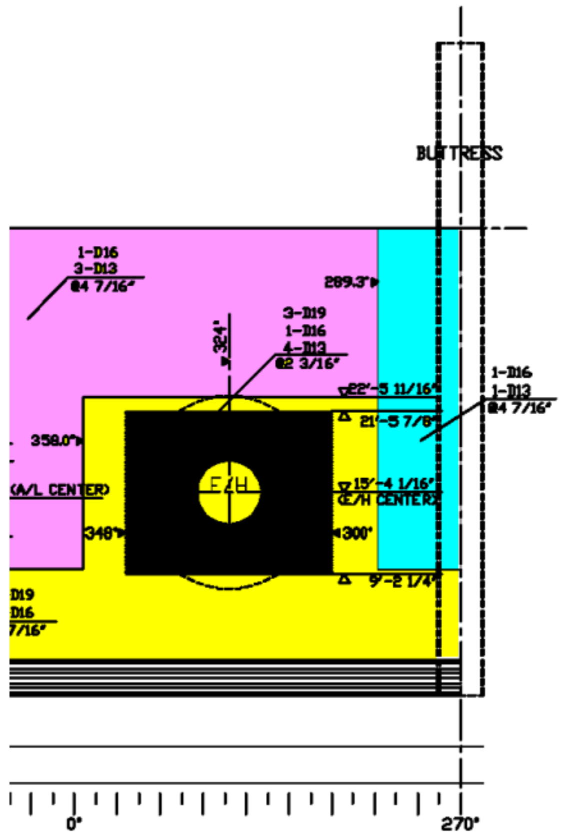


Inner hoop rebars

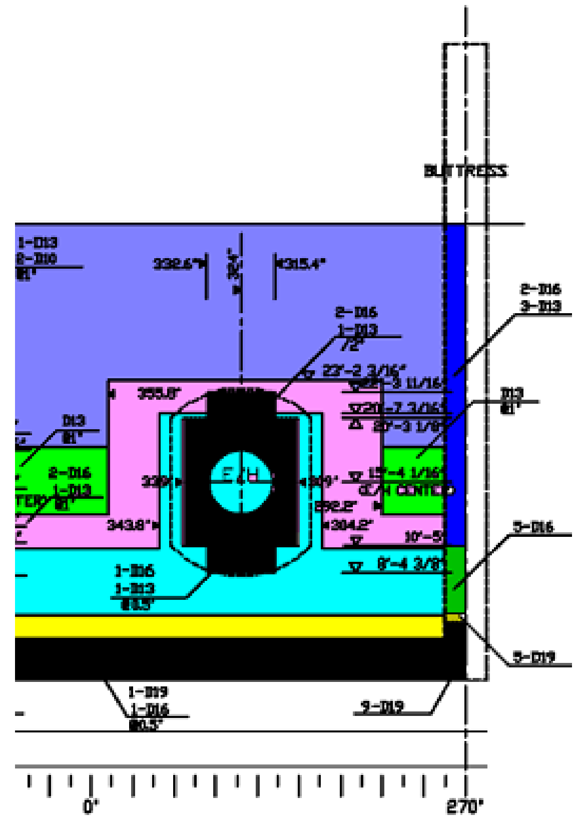


Inner vertical rebars

Meshing: steel reinforcement



Outer hoop rebars



Outer vertical rebars

Rebars ratios and localisations (from PCCV-QCON-12 and PCCV-QCON-16)

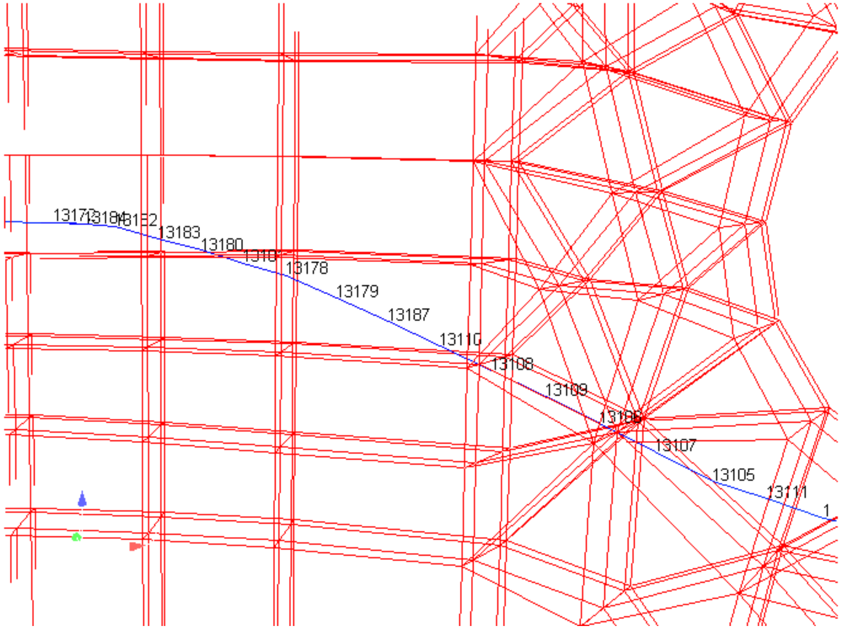
Meshing: tendons

Truss elements

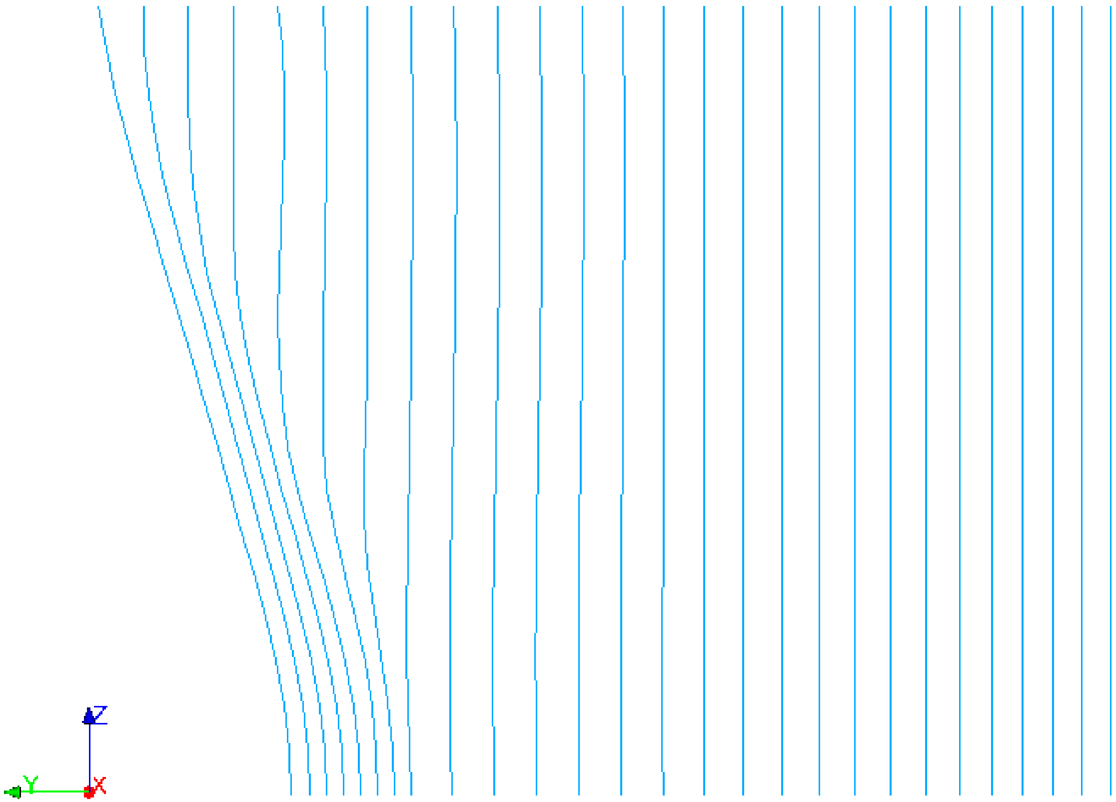
Tendon / concrete interface:

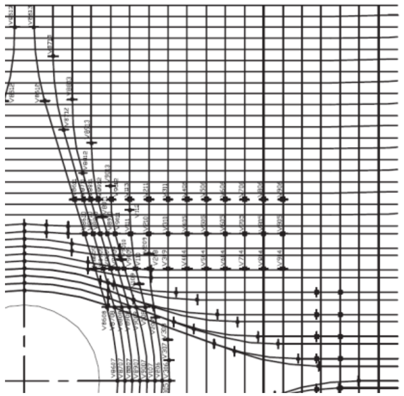
- perfectly bonded in vertical and radial directions

- friction elements between tendon / concrete elements



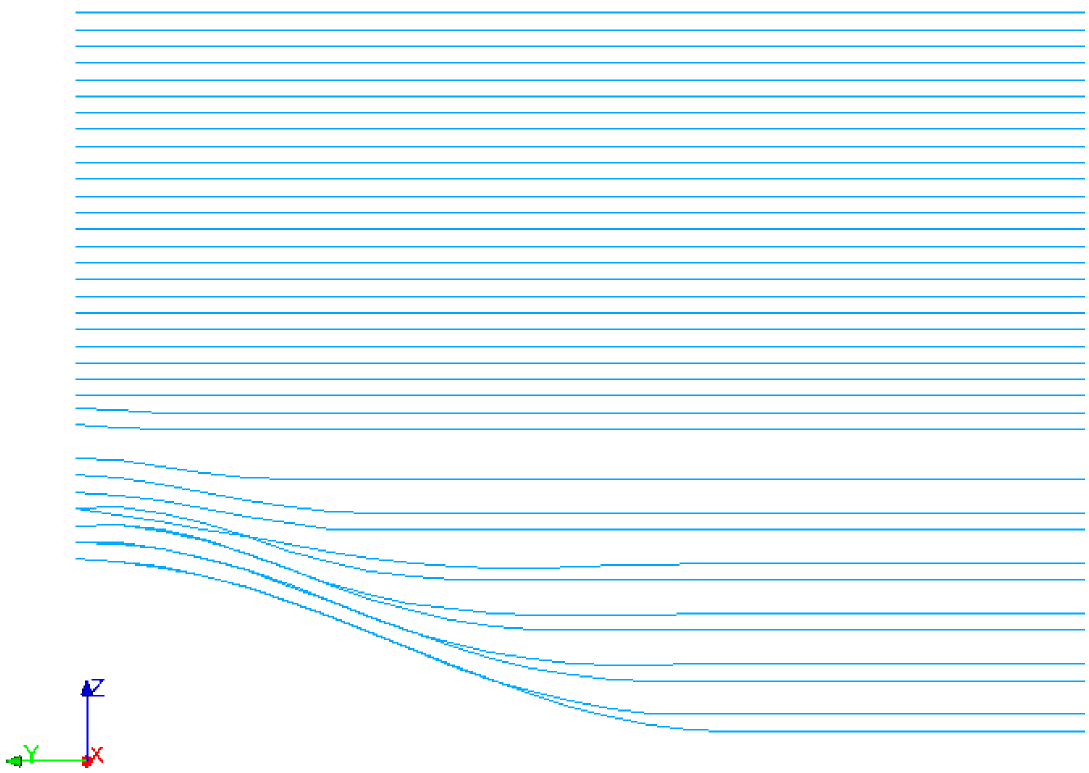
Meshing: tendons

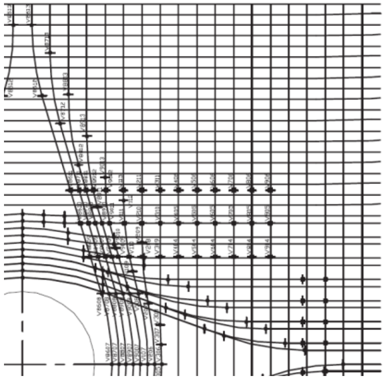




Actual vertical tendons position and inflections (from PCCV-QCON-07 and PCCV-QCON-08)

Meshing: tendons





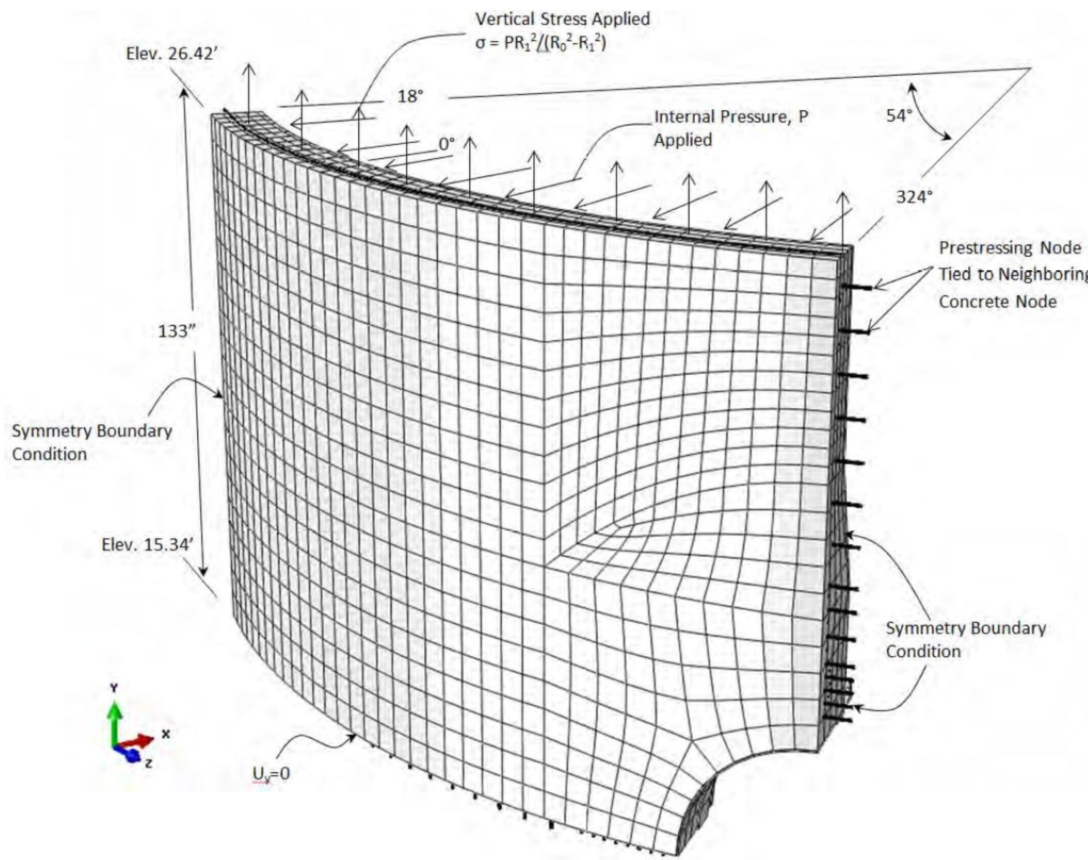
Actual horizontal tendons position and inflections (from PCCV-QCON-07 and PCCV-QCON-08)

Boundary conditions

Lateral surface: rotation constrained to zero

Bottom surface: no vertical displacement

Top surface: vertical stress applied (same as model 1)



Preliminary analyses

Numerical and implementation of CZM elements checks (recently implemented in Code_Aster)

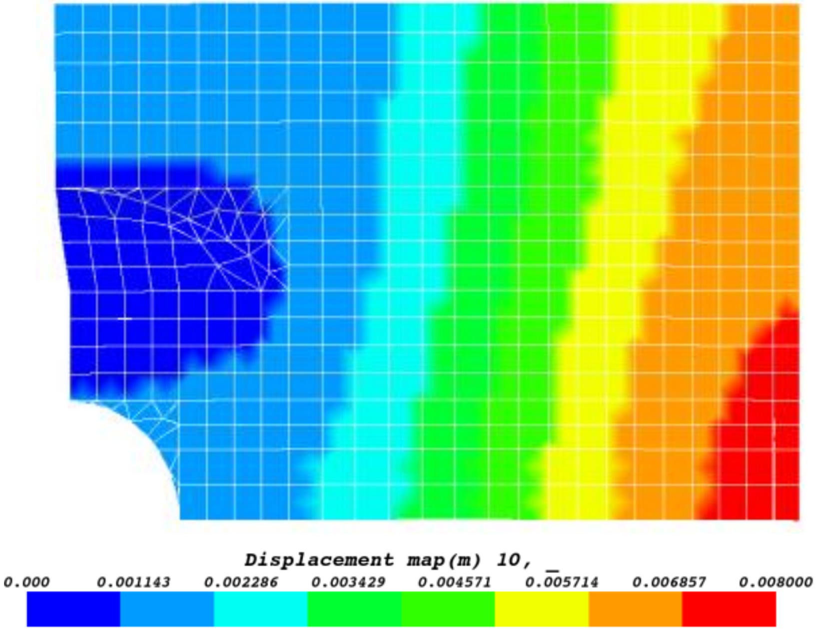
Test analysis 1:

- Concrete remains elastic for tests
- Only one vertical seal
- Prestressing= initial tension set to mean value of tendons A and B close to the E/H
- Increase of internal pressure from 0 up to 3xPd in 30 uniform load steps

<u>Test 1: displacement map of liner at 3xPd (elastic concrete)</u>

Maximum radial displacement of 7.5mm (half of nonlinear forecasts)

Embossment stiffer than current zone



Preliminary analyses

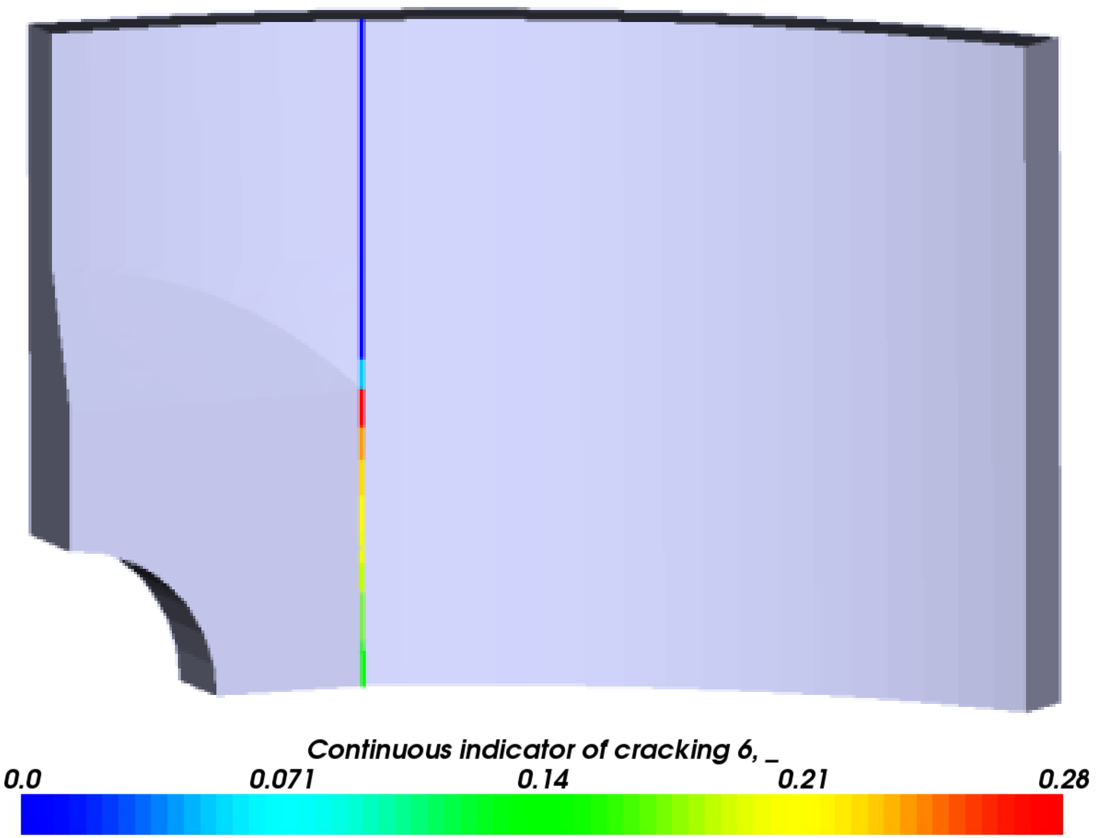
Test 1: liner tearing within seals (fracture indicator)

Initiation of crack at geometrical and stiffness discontinuity (stress concentration)

Relatively stable calculation

Mesh to refined

Addition numerical implementations needed allowing to simultaneously use both CZM and nonlinear concrete constitutive models



0= sound element

0.5= damaged

1= fractured