TABLE OF CONTENT

1. GENERAL/MEASUREMENTS

1.1 STRUCTURAL TYPE

This report describes the design of Power Station spiral case and its interaction with concrete and rock.

The structure is exposed to the loads mentioned bellow.

- Dead load (concrete structure / spiral case)
- Water load (runaway pressure)
- Headcover / pressure force
- Stator / upper brackets / bearing.
- Turbine / generator / bearing.

1.2 PRODUCTION SCHEME

The production scheme assumes that the structure is cast-in situ.

1.3 CONCRETE MODELL

If concrete is to modelled in the design of the spiral case then the effect of concrete cracking is to be considered in areas where tensional forces arise.

Concrete properties of concrete C30/37 :

$f_{cck} = 27MPa$: compressive strength
$f_{ctk} = 1.9MPa$: tensional strength
$E_{ck} = 33GPa$: E-modulus

$\phi(t_1 = 0) = 0$: creep value at time of casting
$\phi(t_2 = 100\,years) = 2.0$: creep value at end of technical use 100 years

Remark A study should be made at t_1 and t_2 which cover the technical life span of structure.

Material stiffness in uncracked reinforced concrete :

If tensional stress in concrete $\sigma_{ct} < f_{ctk}$

$$E_{rc.uncracked} = \frac{0.8E_{ck}}{1+\phi}$$

Material stiffness in cracked reinforced concrete :

If tensional stress in concrete $\sigma_{ct} \geq f_{ctk}$

$$E_{rc.cracked} = \frac{0.4E_{ck}}{1+\phi}$$

Material stiffness in cracked concrete without reinforcement :

If tensional stress in concrete $\sigma_{ct} \geq f_{ctk}$ then no additional stress can be transferred to concrete.

$$E_{cc.cracked} = 0GPa$$

Material stiffness in uncracked concrete without reinforcement :

If tensional stress in concrete $\sigma_{ct} < f_{ctk}$ then the concrete is considered uncracked.

$$E_{cc.uncracked} = \frac{E_{ck}}{1+\phi}$$

1.4 PERMISSIBLE SHEAR FORCE

If concrete is to modelled in the design of the spiral case a highest permissible shear force at the surface between concrete and spiral is to considered as seen below.

Permissible shear force :

q_w	: normal force acting in the radial direction
$f_{cck} = 27MPa$	: compressive strength
$f_f = (0.3 \cdot q_w; 0.4 \cdot f_{cck})^{\min}$	: permissible shear resistance
f_s	: shear stress

Remark

Friction between concrete and steel is assumed to be 100 % in the analysis. If shear stress between concrete and steel is greater than permissible shear resistance the connection is released at this point.

$f_s < f_f$	$\Rightarrow$	No release
$f_s \geq f_f$	$\Rightarrow$	Release

In the performed analysis the shear resistance is assumed greater than shear stress. In chapter D this will be verified.

1.5 INITIAL GAP BETWEEN STEEL AND CONCRETE

When casting concrete around a steel spiral a small gap will arise due to the heat generated during casting and the following cooling.

The gap varies around the circumference of the spiral casing but a formula for determining the average value use when designing the spiral casing is seen below.

r	: Radius of spiral casing
$\Delta = r \cdot 2.5 \cdot 10^{-4}$	: Width of initial gap before applying pressure

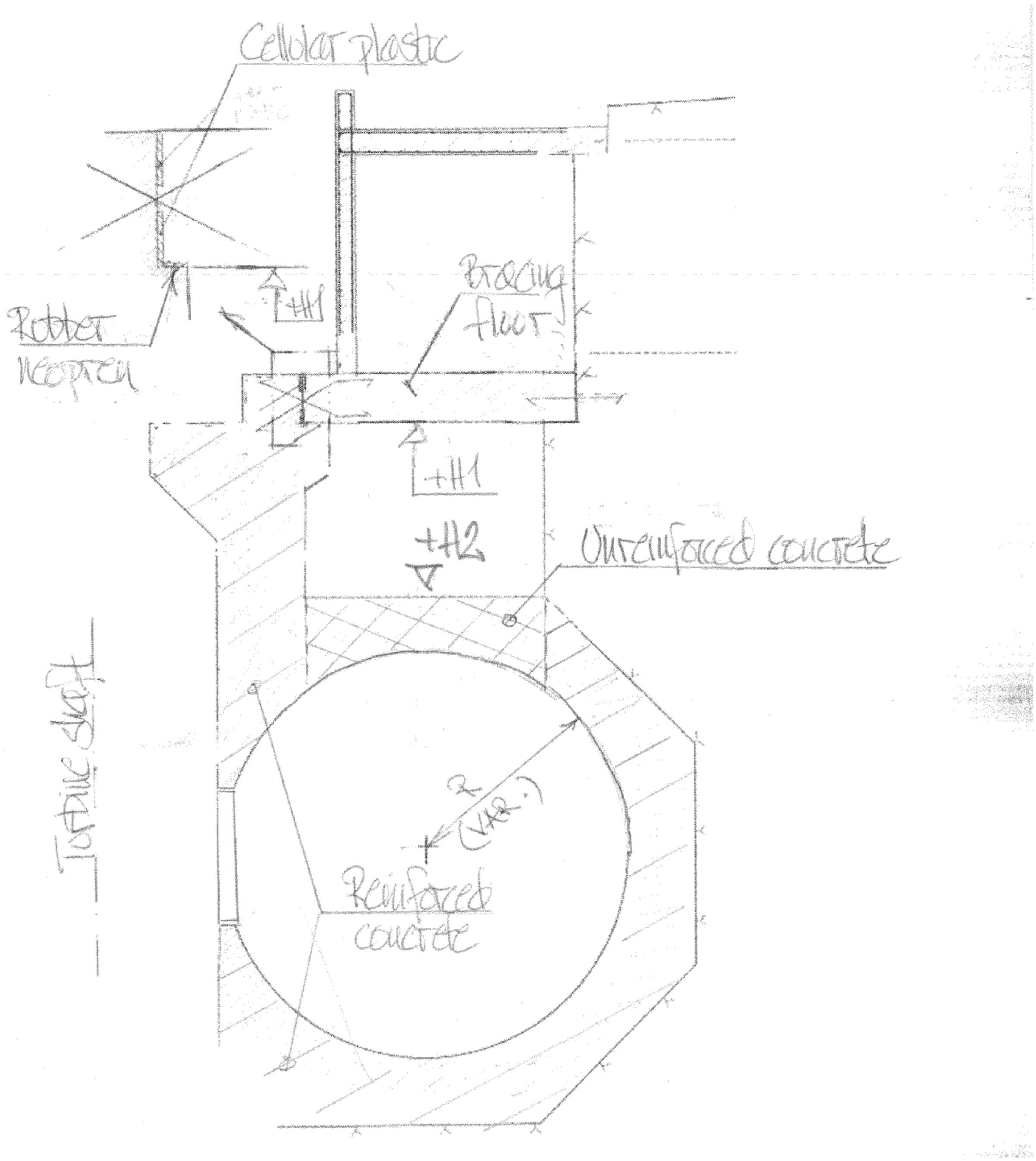
Before any contact forces are established between spiral casing and concrete the spiral case must first expand the distance of the gap, Δ.

Remark At Power Station the spiral casing is assumed not to be grouted.

1.6 TECHNICAL SPECIFICATION AND BUILDNING CODE

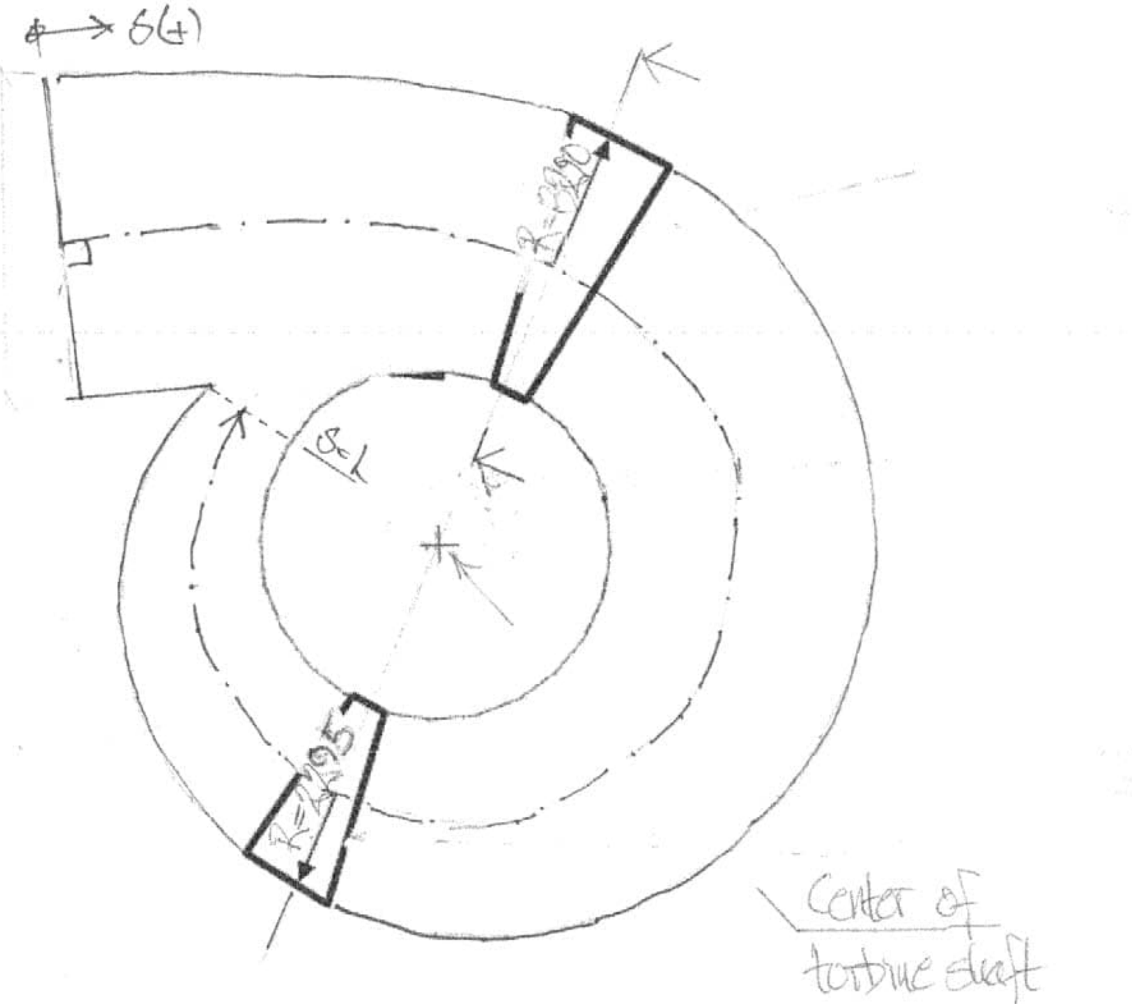
- Boverkets handbok om stålkonstruktioner, BSK 07.
- Boverkets handbok om betongkonstruktioner, BBK 04.

1.7 MEASUREMENTS



Cross section

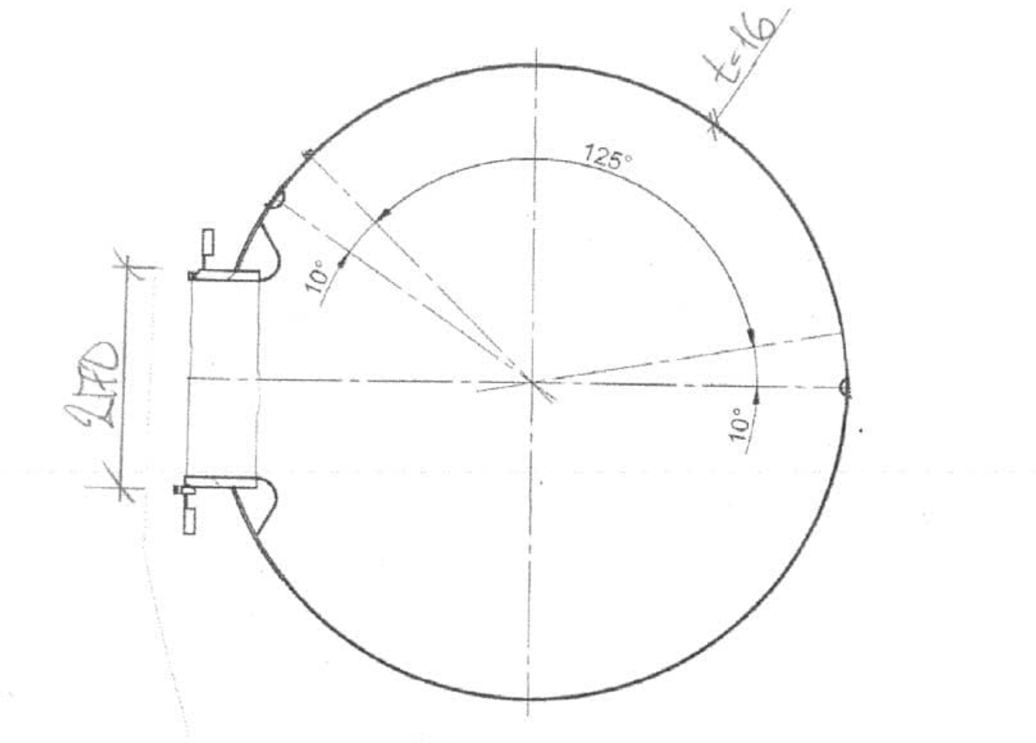
Overview



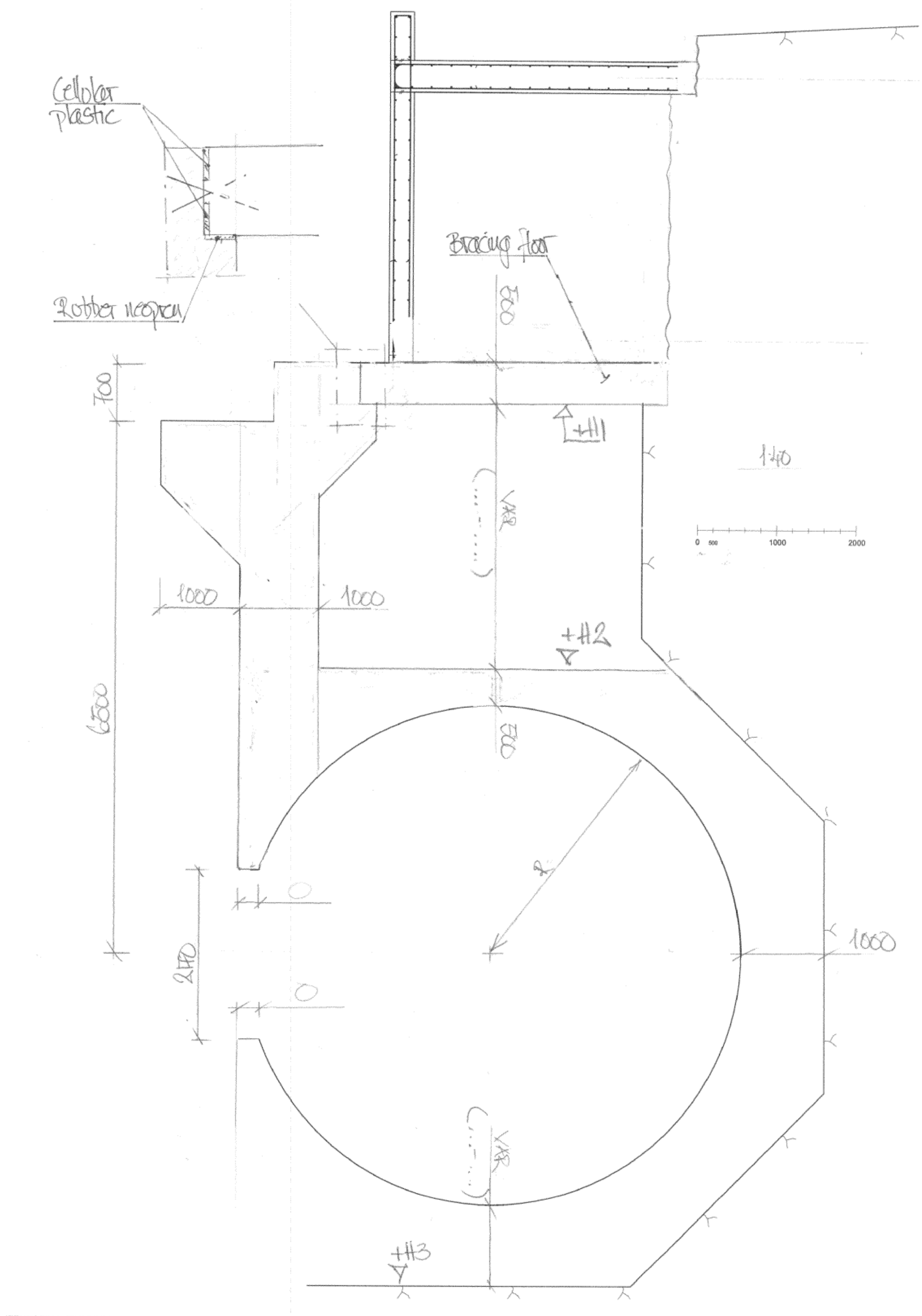
s	R(s)
0	….
…	…
…	…
…	…
L	…
m	m

<u>Plain view spiral</u>

Principle



Cross section spiral

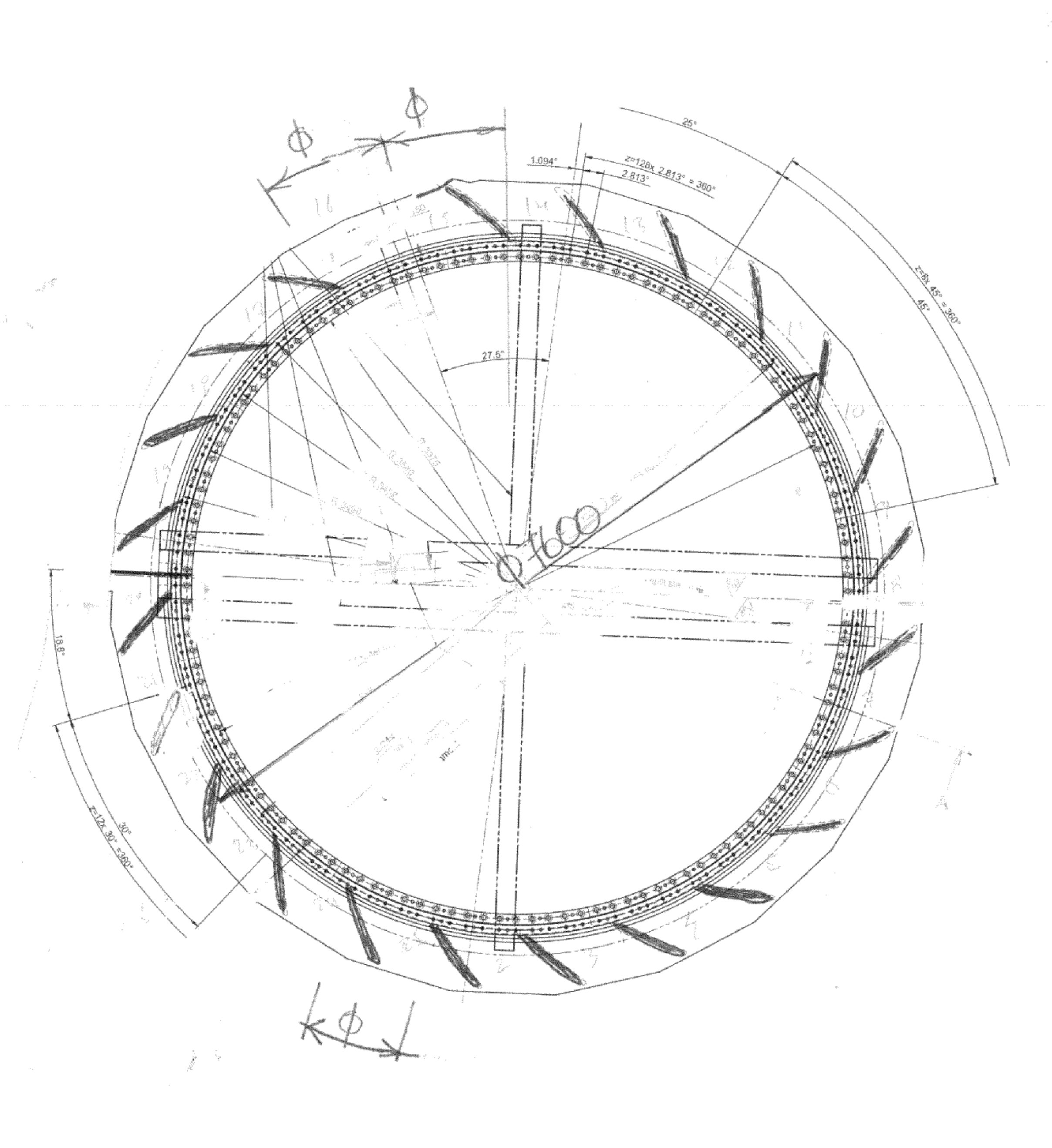


Cellular plastic
Rubber neopren
Bracing floor
800
700
+H1
1:40
0
1000
2000
1000
1000
+H2
6500
R
2400
0
0
1000
+H3

s	+H1	+H2	+H3
0	….	….	….
…	…	…	…
…	…	…	…
…	…	…	…
L	…	…	…
m	m	m	m

Cross section

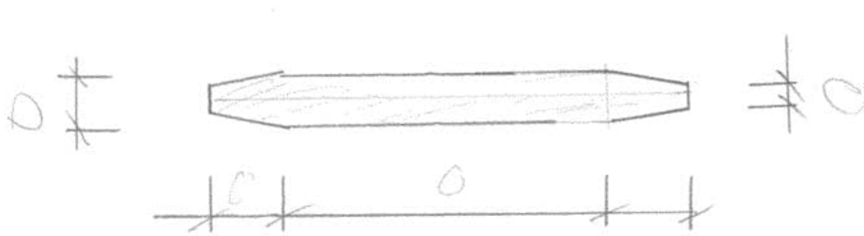
Definition of concrete



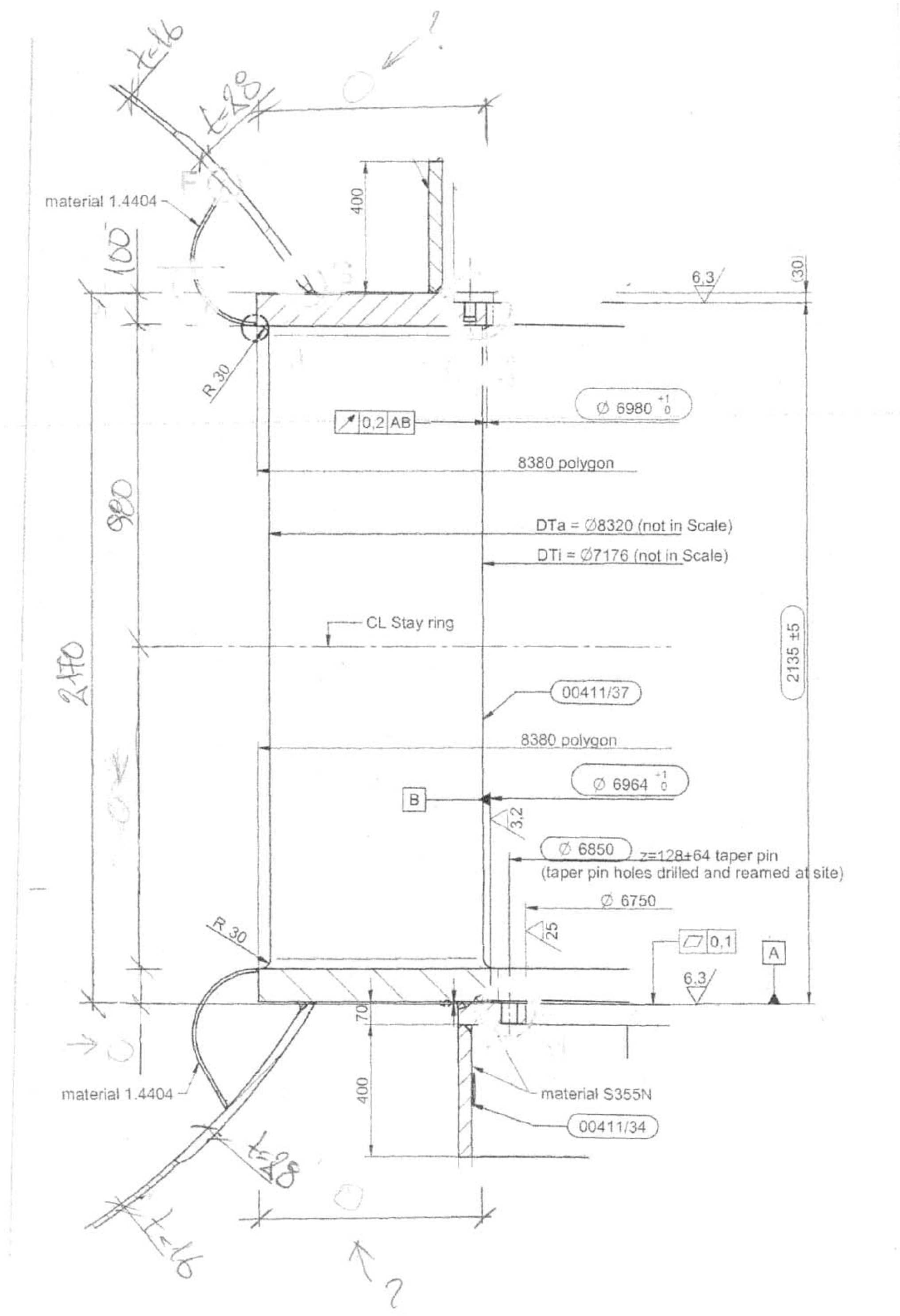
$$25\phi = 360° \quad \Rightarrow \qquad \phi = 14.4°$$

<u>Plan view</u>

Strut column



Cross section strut column



<u>View strut column</u>

All are assumed identical

2. STATICAL SYSTEM

2.1 GENERAL

The structure considered is the spiral case and the surrounding concrete/rock.

The concrete is modelled as a 2D plain stress continuum while the spiral shell is modelled as a 2D thick beam. The strut column is also modelled as a 2D thick beam. The rock is considered by applying fixed loading conditions.

To avoid horizontal movement at level of stator a horizontal support is introduced. This support corresponds to a slab at level of support.

The analysis is performed using a width of 1 m strip. Cross sectional properties for the column is determined using an equivalent thickness. This stiffness depends on the angular rotation of column and the distance between them.

Since the columns flanges are considered rigid a fictive E-modulus is used corresponding to $1000 \cdot E_s$

The structure is nonlinear both with regard to material and geometrically. In order to avoid using a nonlinear analysis the structure is modelled using as a “segmental construction”. To stages are considered as seen below. In the two stages the total water pressure termed q_w is divided into two parts as seen below.

$q_w = q_{w1} + q_{w2}$

- Stage 1 : During this stage only the water pressure needed to move close the gap between concrete and spiral is considered. The required pressure is termed Δq_{w1}. The concrete is during this stage considered infinitely weak to resist movement.

- Stage 2 : During this stage the remaining water pressure is considered (Δq_{w2}),   loads from cover head (p_D), loads from stator (p_E) and loads from the turbine (p_F) is considered.
  During this stage of the analysis areas with in the concrete the principal stress cause tension are removed from the structural model.

The analysis is performed as a linear elastic analysis even though the material properties of concrete is nonlinear. In order to handle this through with an elastic analysis three iterations of the structure is performed in other to determine the material properties during normal operations.

After each analysis assumed material properties are compared to the condition for cracking which is weather or not maximum principle stress is greater than permissible tensional stress as seen below.

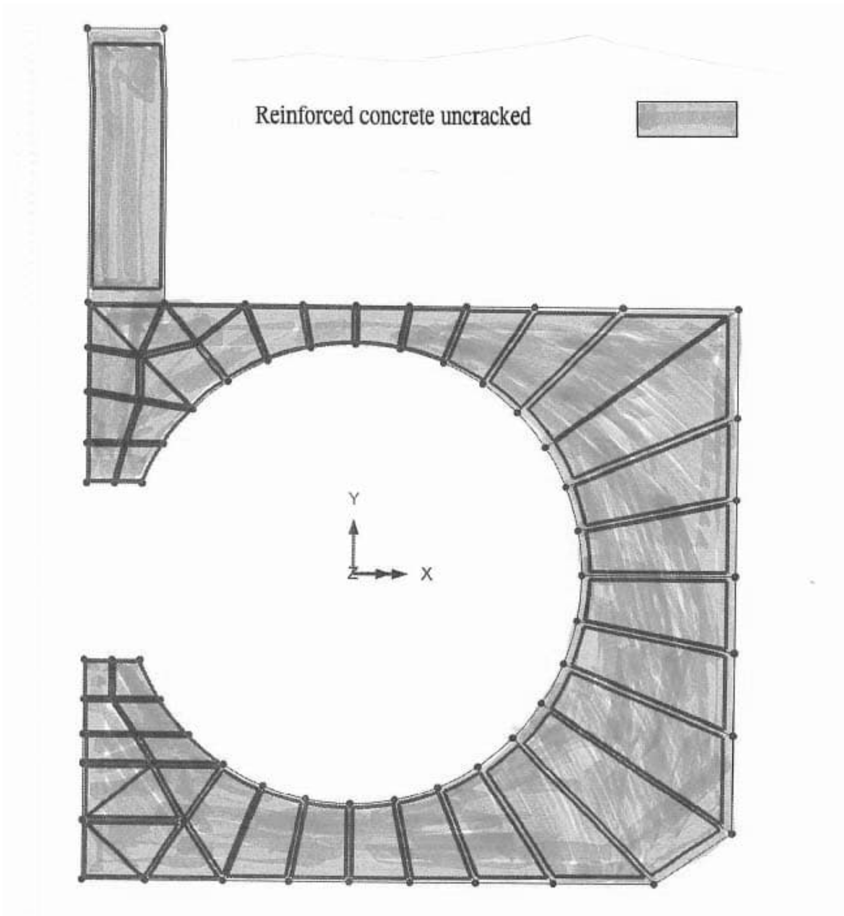
$\sigma_{max} > f_{ct} = 1900$ kPa $\Rightarrow$ Cracked concrete

$\sigma_{max} \leq f_{ct} = 1900$ kPa $\Rightarrow$ Uncracked conrete

Analysis I :

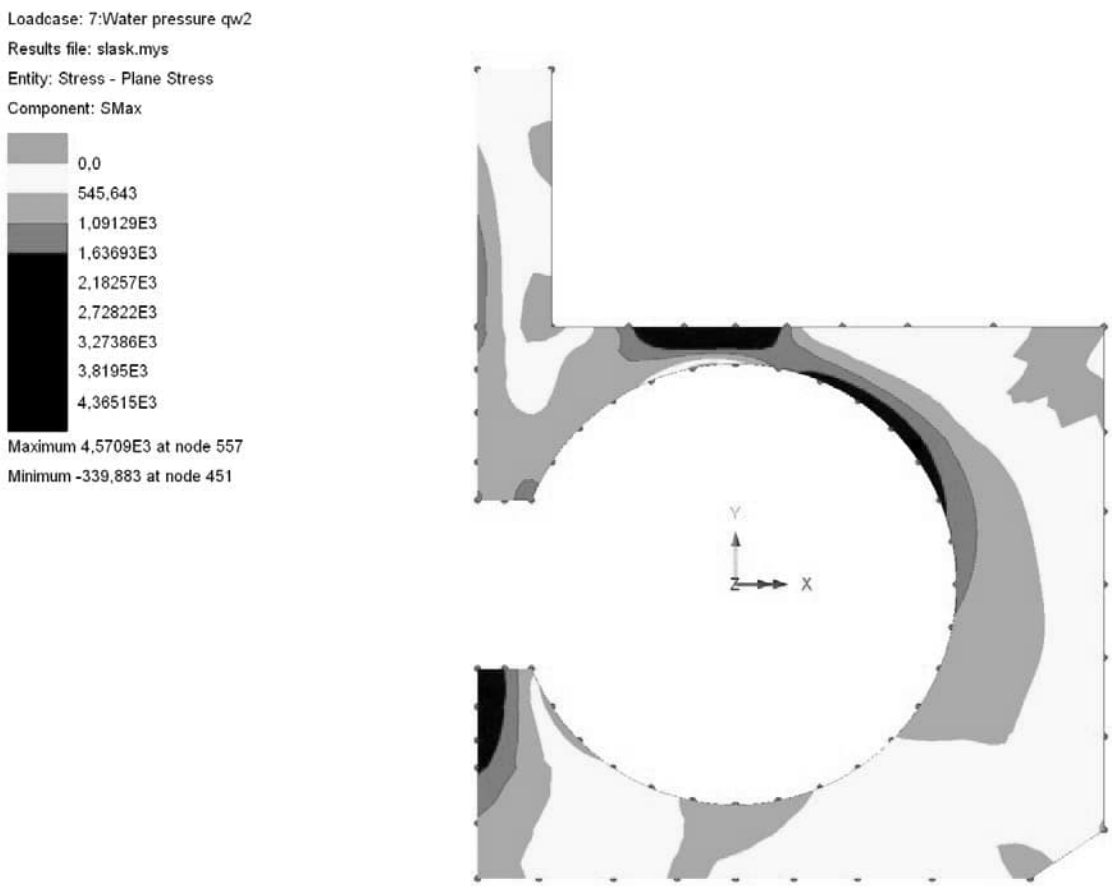
In this analysis the entire structure is considered uncracked as seen below.

Material :



Contour plot of Smax :

The maximum principal tension stress is retrieved as seen below.

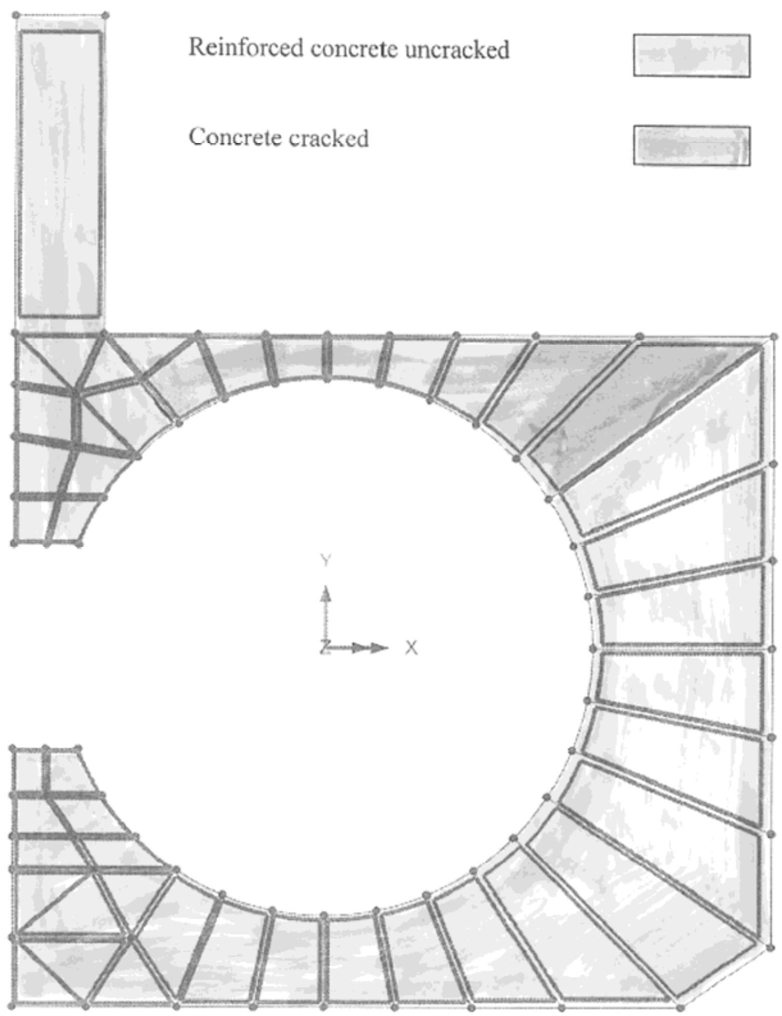


Remark In areas that are marked "black" the maximum principle stress $\sigma_{max} > f_{ct}$ = 1900 kPa.

Analysis II :

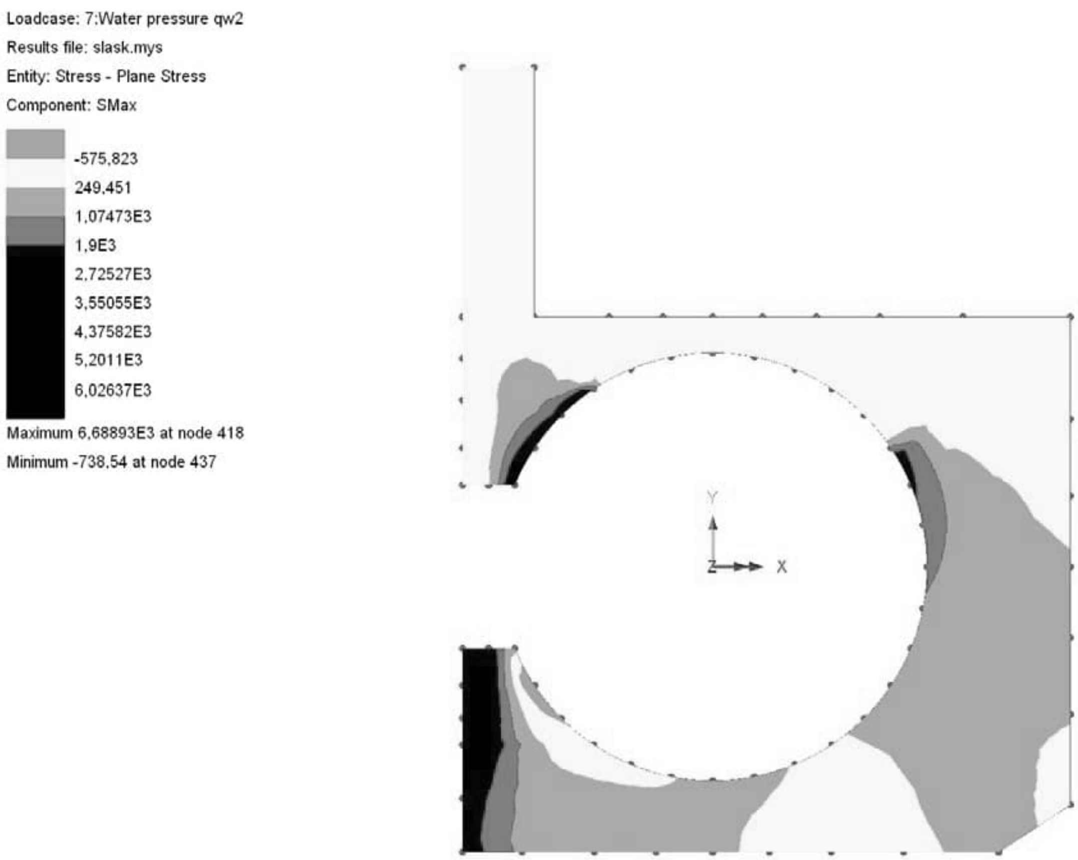
Due to the fact that several areas are cracked according to assumptions found in analysis I material properties are adjusted as seen below.

Material :



Contour plot of Smax :

The maximum principal tension stress is retrieved as seen below.

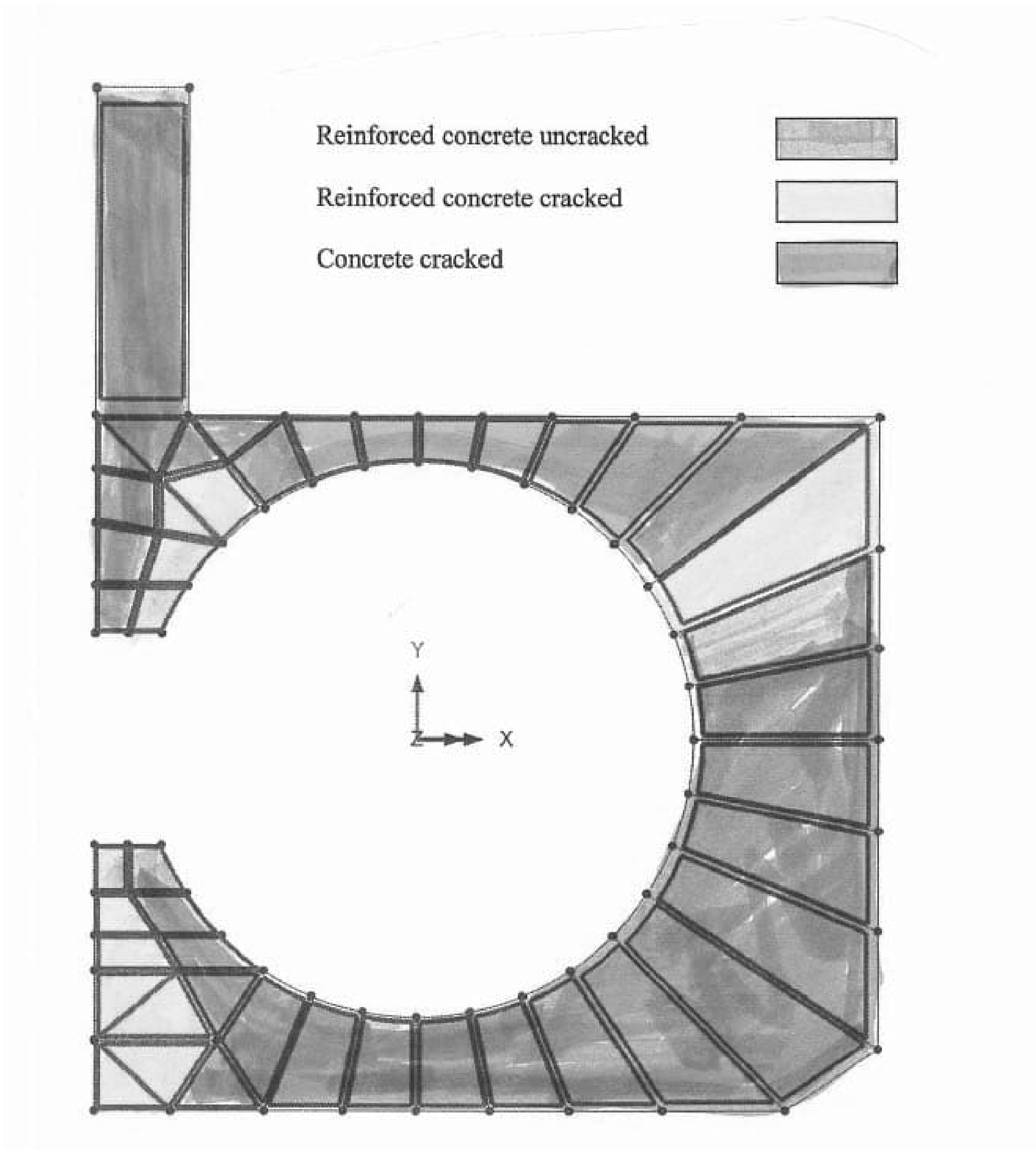


Remark In areas that are marked “black” the maximum principle stress $\sigma_{max} > f_{ct}$ = 1900 kPa.

Analysis III :

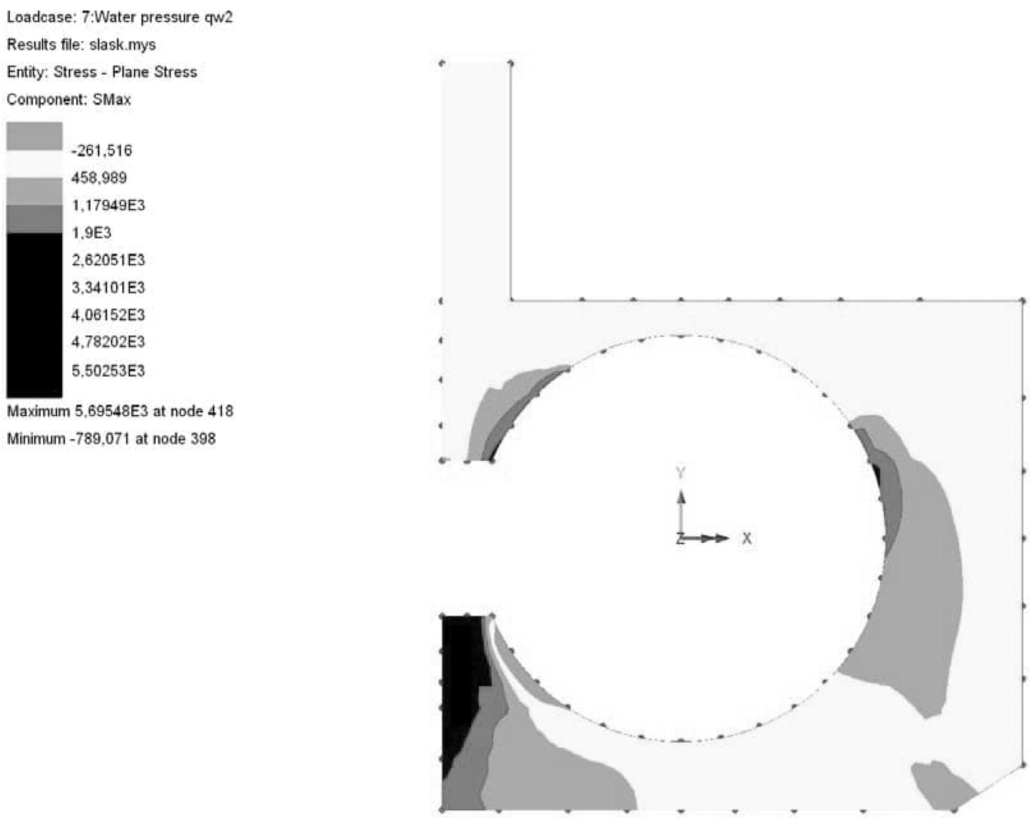
Due to the fact that several areas are cracked according to assumptions found in analysis II material properties are adjusted once again as seen below.

Material :



Contour plot of Smax :

The maximum principal tension stress is retrieved as seen below.



Remark In areas that are marked “black” the maximum principle stress $\sigma_{max} > f_{ct}$ = 1900 kPa. These area correspond well to assumed material properties. No further iteration is conducted.

2.2 STATICAL MODELL

2.2.1 Geometry

In order to describe the structures geometry first *POINTS* have to be defined. From these *LINES* and *SURFACES* are generated.

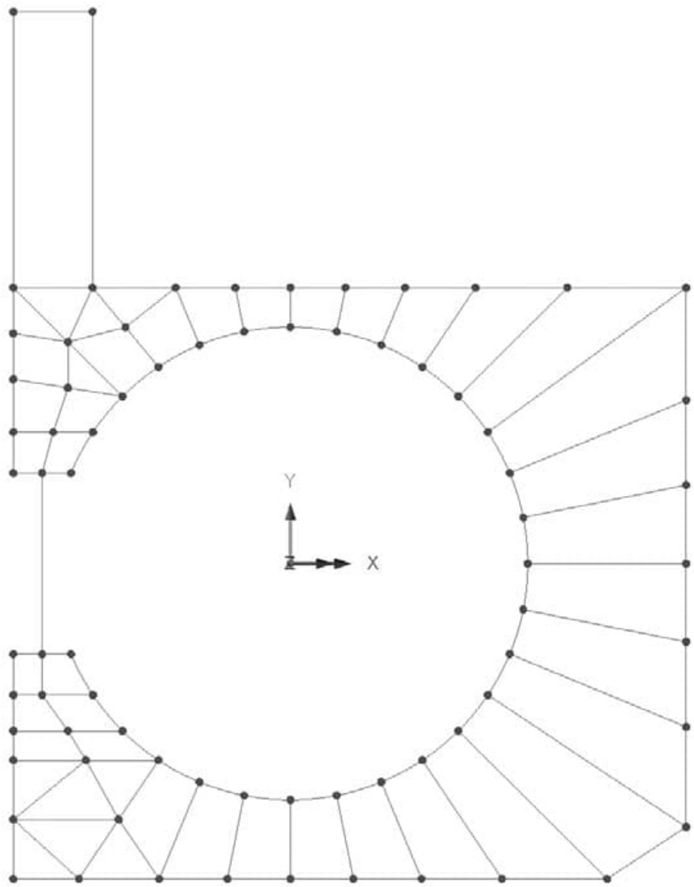
Shell elements are applied to *SURFACES*.

Beam elements are applied to *LINES*.

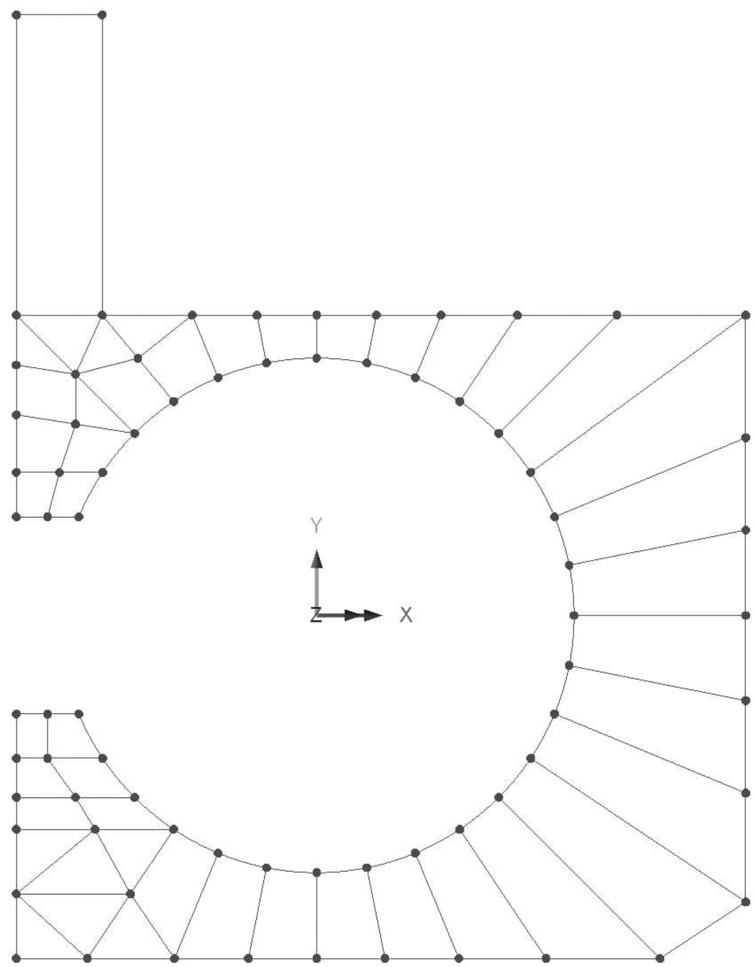
All coordinates defining *POINTS* are presented in appendix 1.

All *LINES* used to define *SURFACES* are presented in appendix 1.

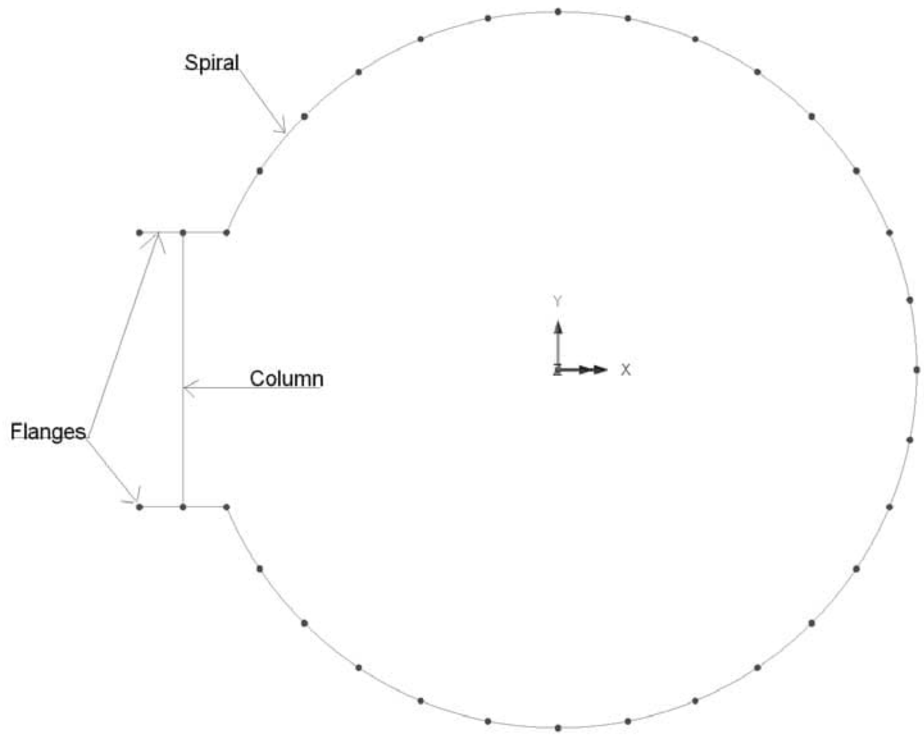
Overview :



View - Concrete :

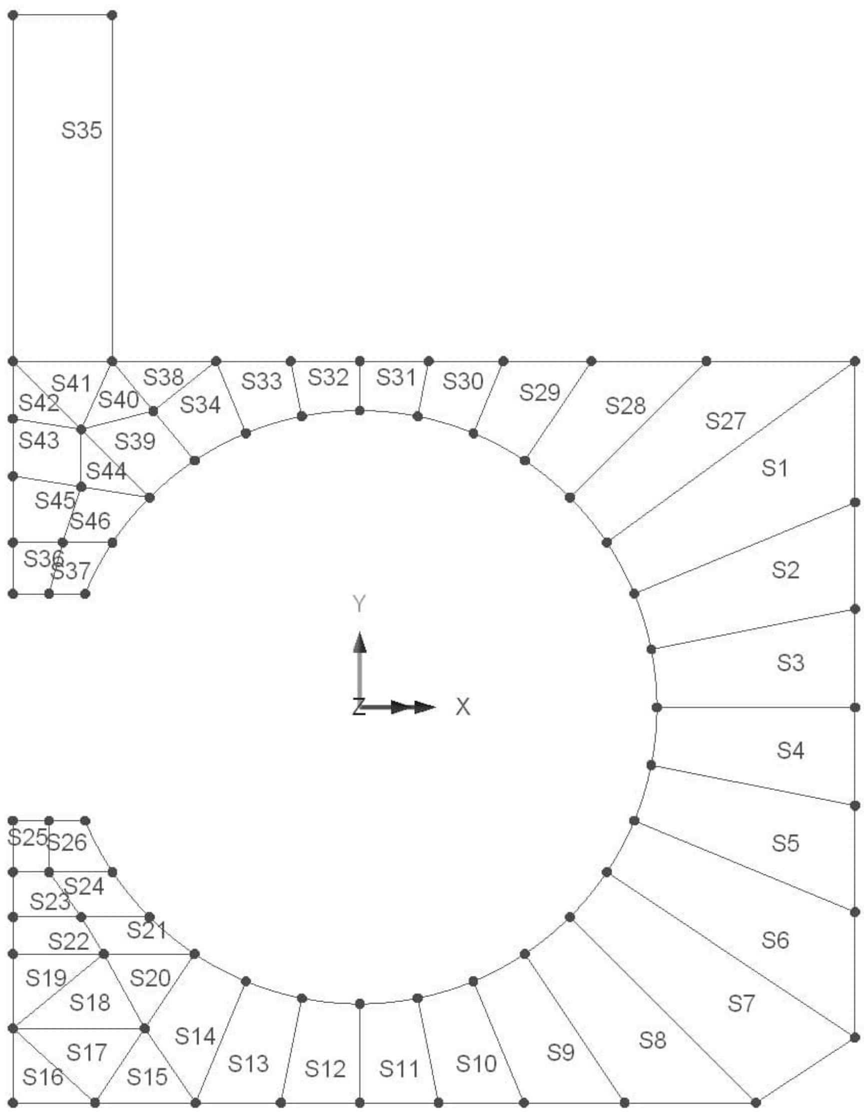


View - Column / Flange / Spiral :



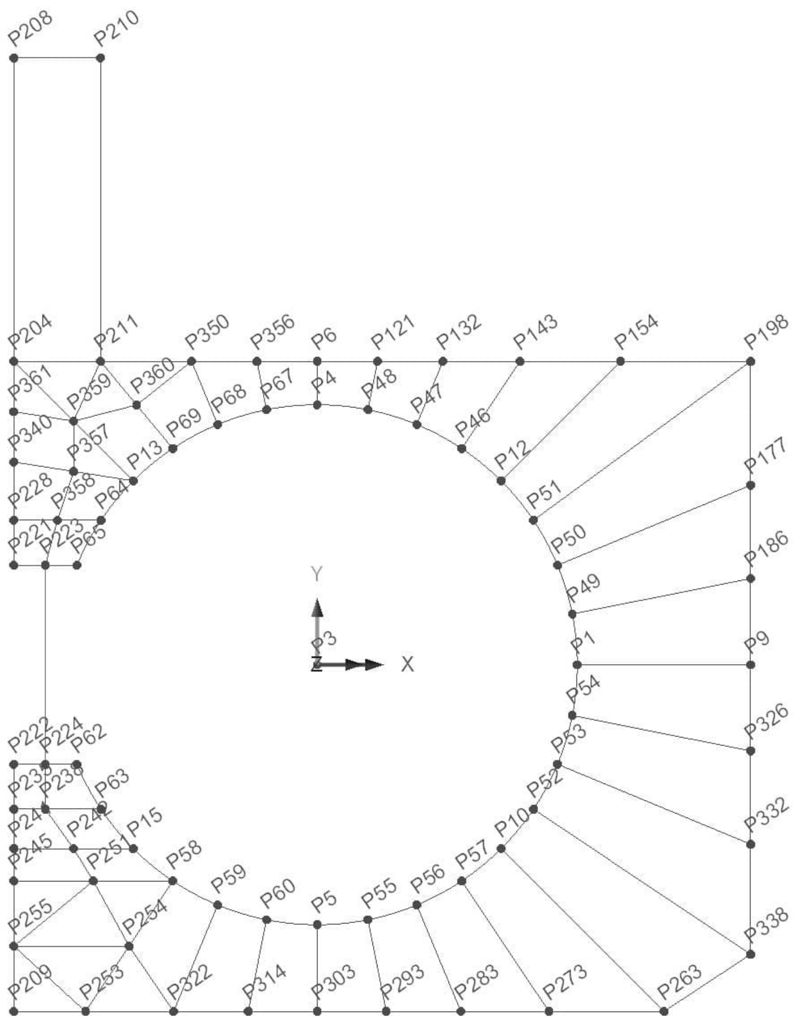
2.2.1.1 Geometry : SURFACES

Concrete structure :



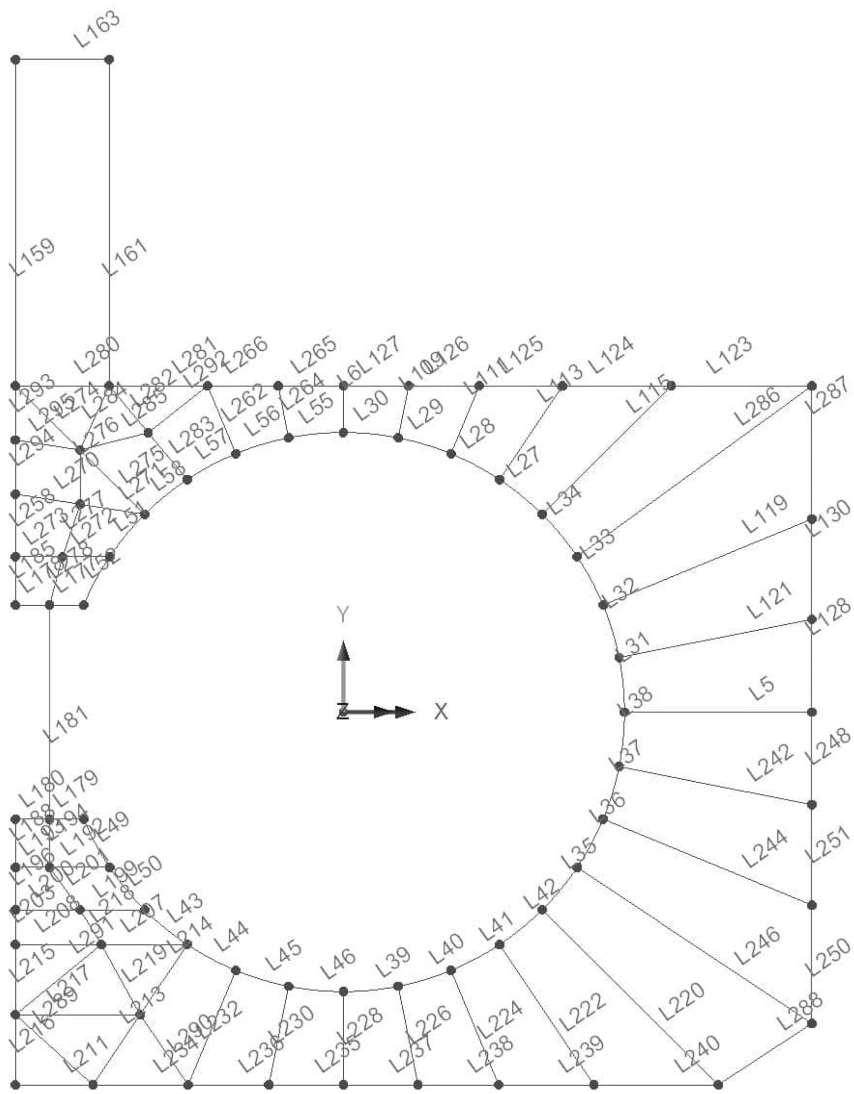
2.2.1.2 Geometry : POINTS

Structure :



2.2.1.3 Geometry : LINES

Structure :



2.2.2 MESH

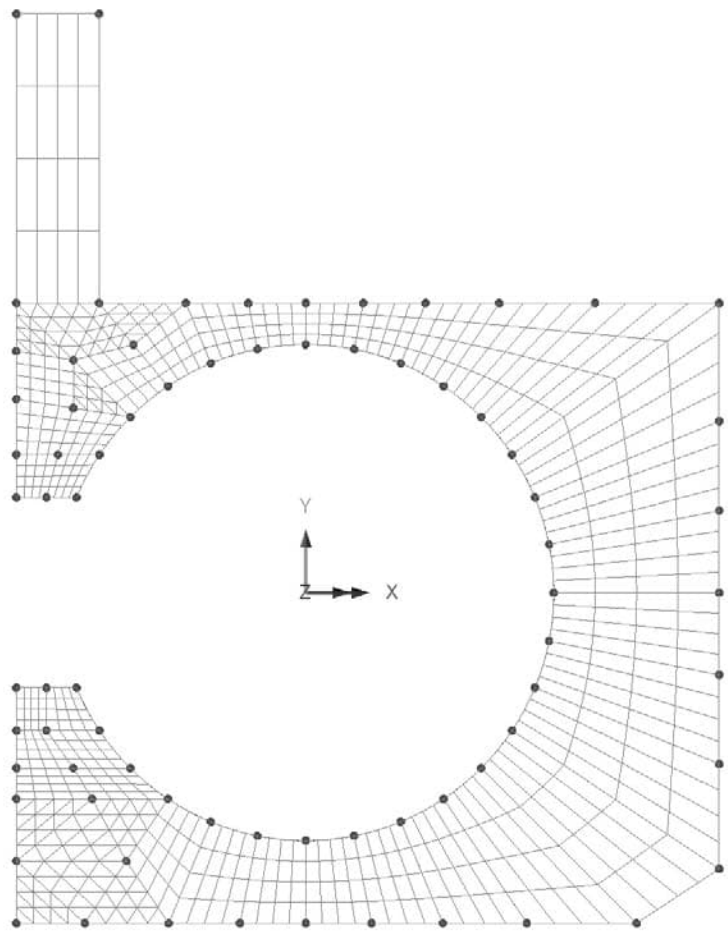
The proviously defined *SURFACES* are given attributes for generation of *MESH*.

During the generation of *MESH* the underlying *ELEMENTS* and *NODES* are created. They are found in appendix 1.

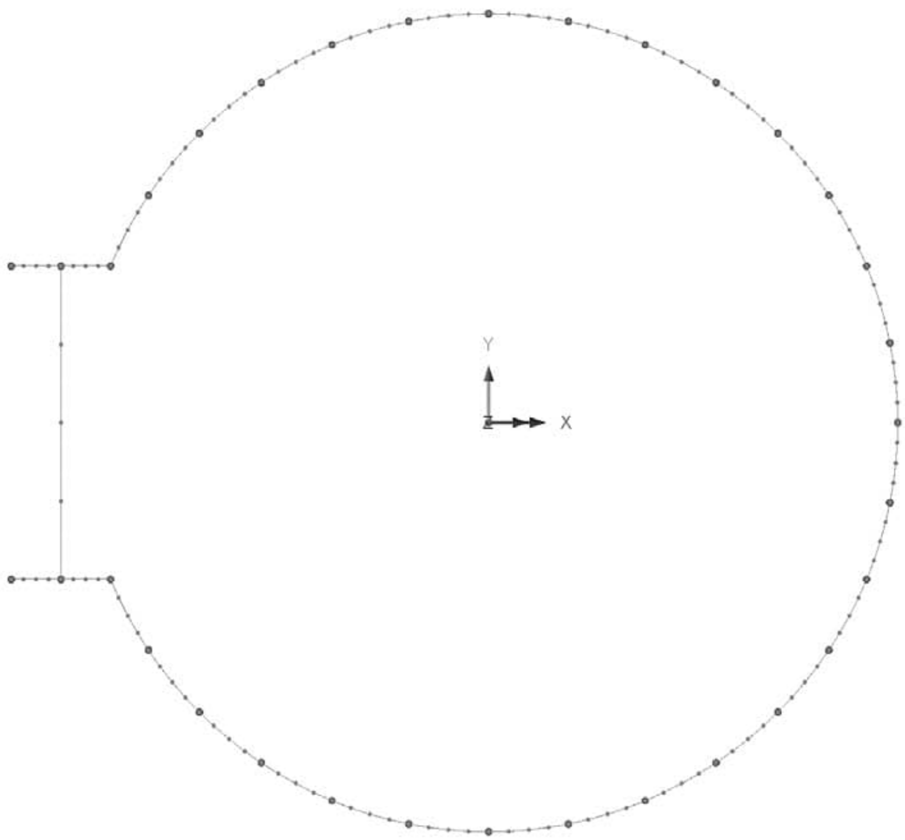
The concrete structure is modeled using 2D continuum element of type “plain stress” elements. The elements are either triangular (TPM3) or quadrilateral (QPM4M). The use of plain stress element assumes that there is no out of plane stresses.

The steel structure is modeled as 2D beam elements of type “thick beams” (BEAMS).

Concrete structure (TPM3 / QPM4M).:



Steel structure (BEAM) :

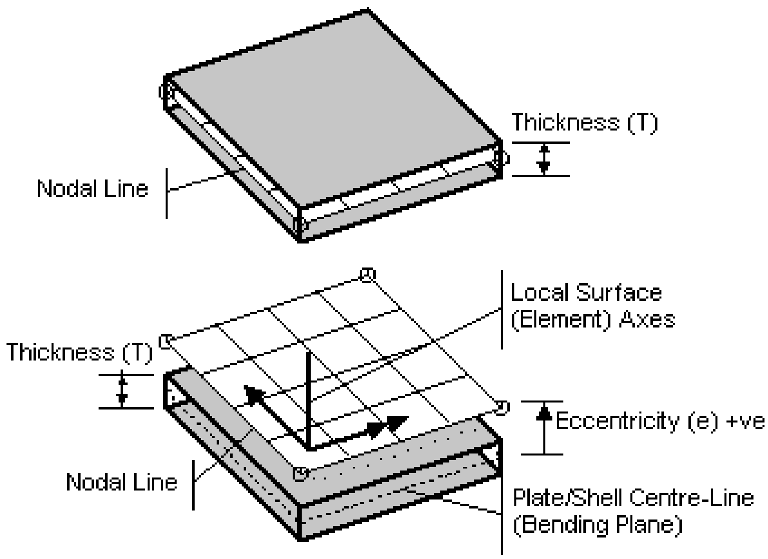


2.3 CROSSECTION PROPORTIES

The concrete structure is modeled using 2D continuum element of type “plain stress” elements.

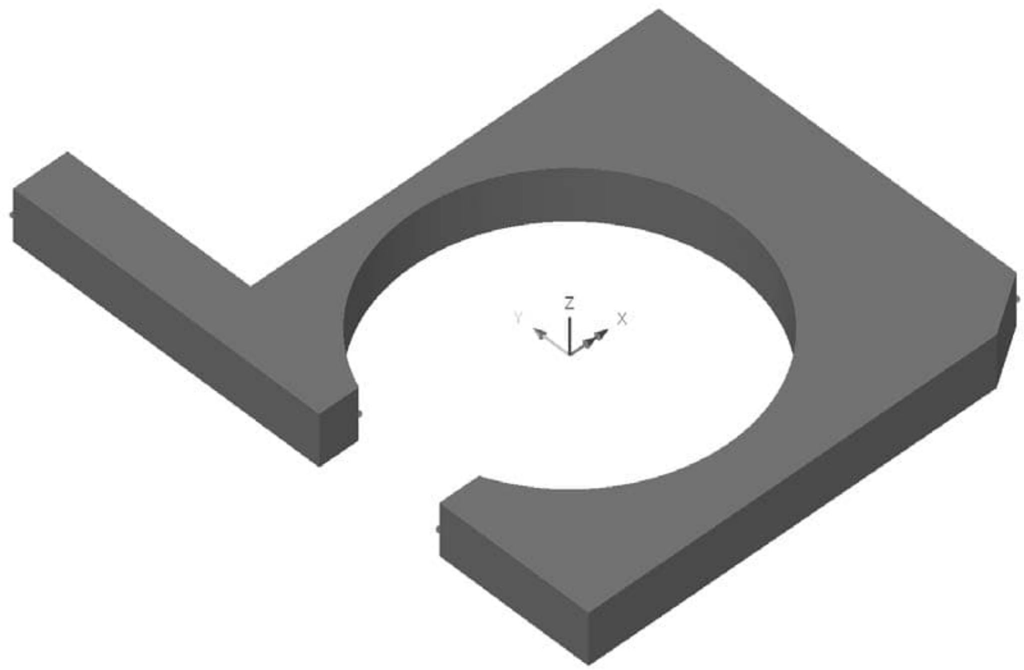
The steel structure is modeled as 2D beam elements of type “thick beams”.

2.3.1 2D continuum elements (TPM3 / QPM4M)

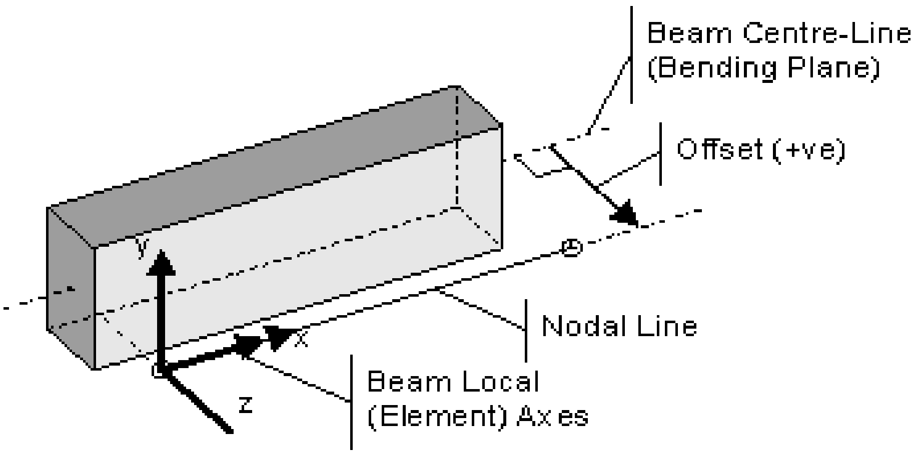


Geometry	t	e_z	Remark
t = 1.0 m	1.00	0	Concrete
-	m	m	-

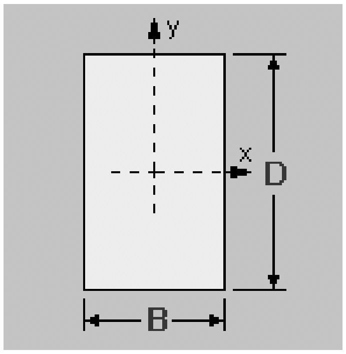
View – Geometry t = 1.0 m :



2.3.2 2D beam elements (BEAM)

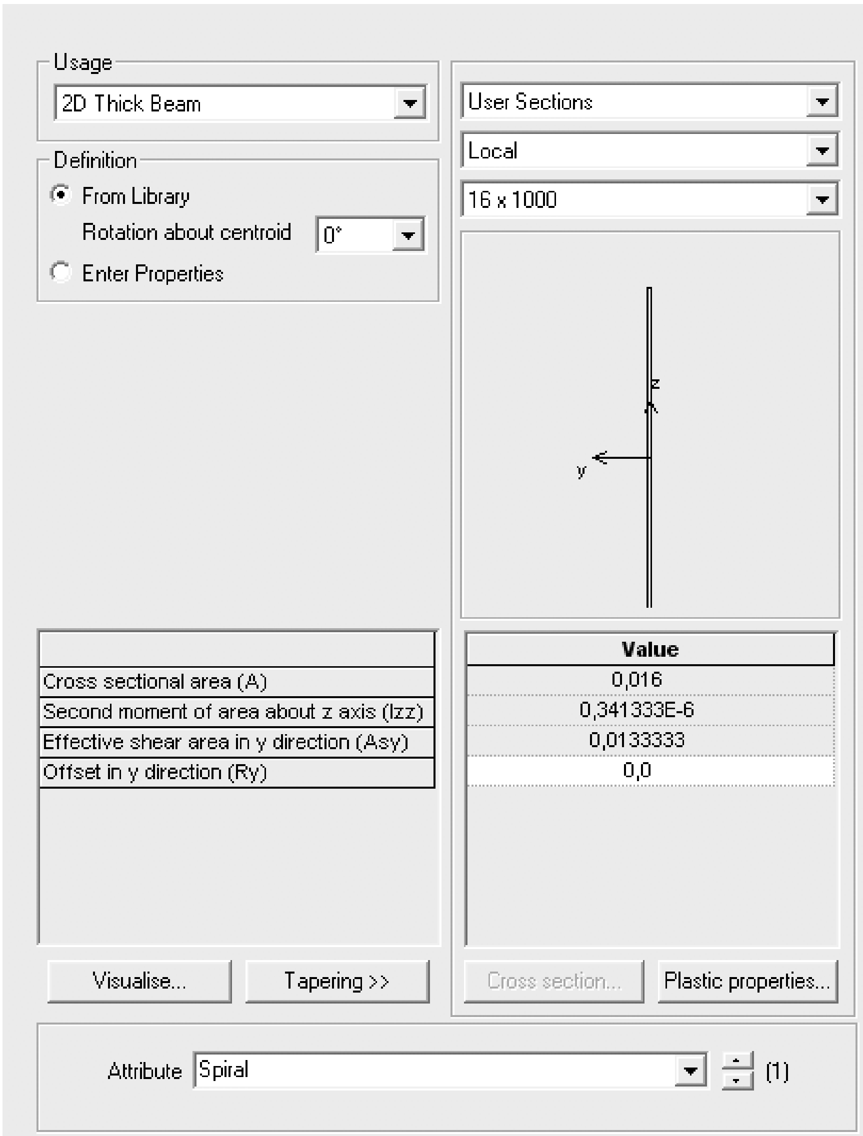


The various cross sections properties are determined using a *Section Property Calculator* within program. All cross sections are considered rectangular and are defined using B x D defined as seen below.



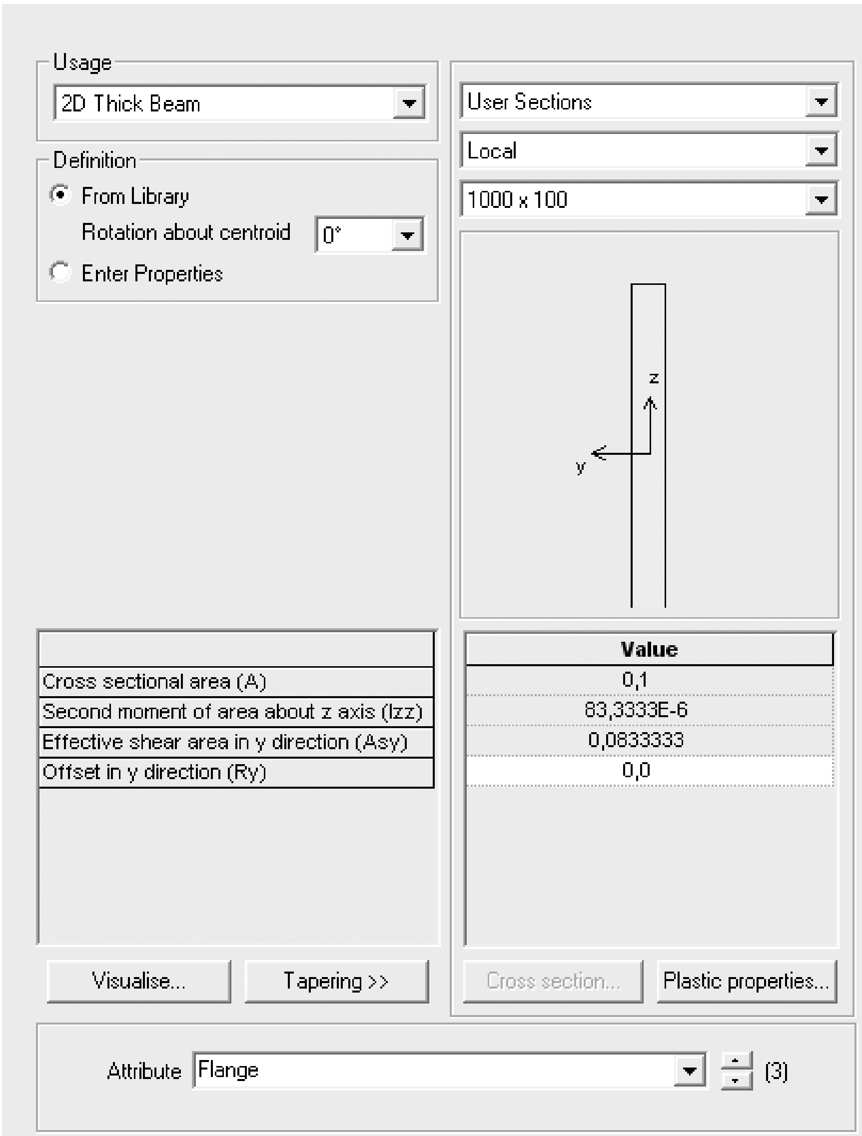
Cross section	B	D
Spiral	1000	16
Flange	1000	100
Column	50	500
-	mm	mm

2.3.2.1 Spiral



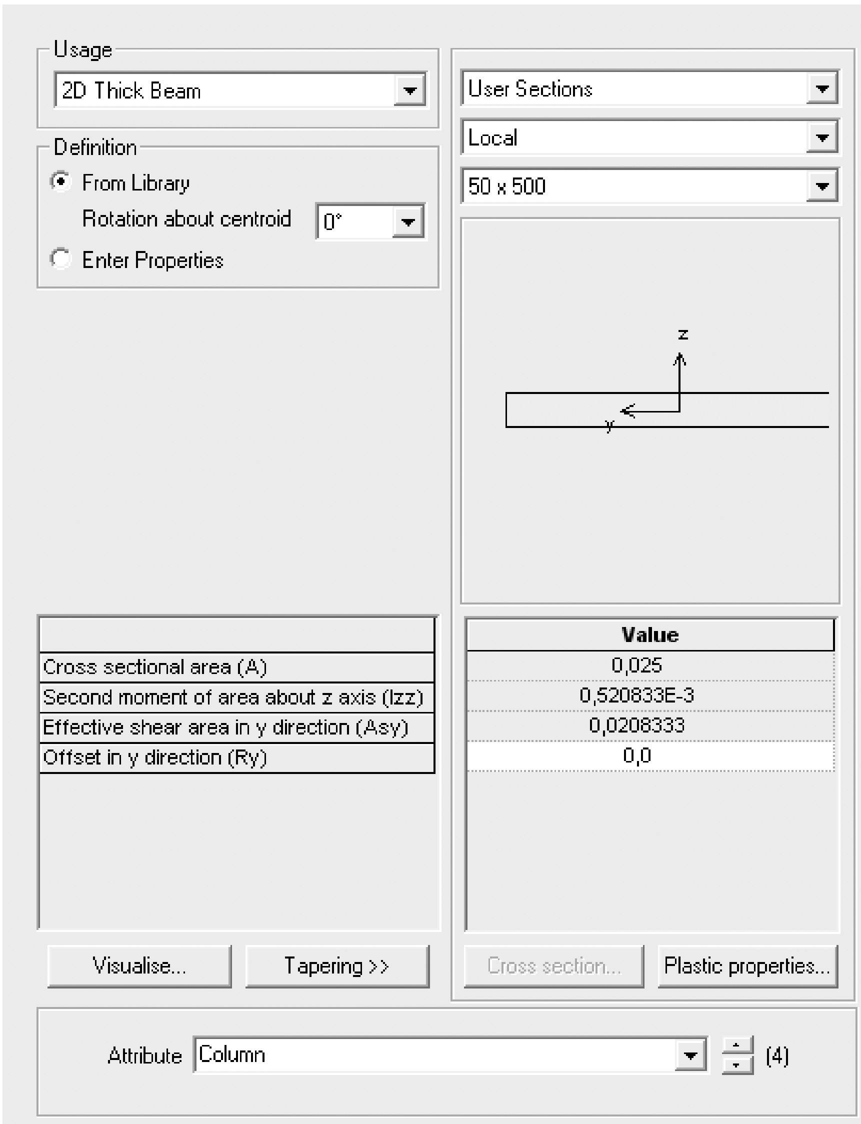
Usage
2D Thick Beam
Definition
From Library
Rotation about centroid
0°
Enter Properties
User Sections
Local
16 x 1000
z
y
Value
Cross sectional area (A)
0,016
Second moment of area about z axis (Izz)
0,341333E-6
Effective shear area in y direction (Asy)
0,0133333
Offset in y direction (Ry)
0,0
Visualise...
Tapering >>
Cross section...
Plastic properties...
Attribute
Spiral
(1)

2.3.2.2 Flange



Usage
2D Thick Beam
Definition
From Library
Rotation about centroid
0°
Enter Properties
User Sections
Local
1000 x 100
z
y
Value
Cross sectional area (A)
0,1
Second moment of area about z axis (Izz)
83,3333E-6
Effective shear area in y direction (Asy)
0,0833333
Offset in y direction (Ry)
0,0
Visualise...
Tapering >>
Cross section...
Plastic properties...
Attribute
Flange
(3)

2.3.2.3 Column


Usage
2D Thick Beam
Definition
From Library
Rotation about centroid
0°
Enter Properties
User Sections
Local
50 x 500
z
y
Value
Cross sectional area (A)
0,025
Second moment of area about z axis (Izz)
0,520833E-3
Effective shear area in y direction (Asy)
0,0208333
Offset in y direction (Ry)
0,0
Visualise...
Tapering >>
Cross section...
Plastic properties...
Attribute
Column
(4)

2.4 MATERIAL

The structure is studied for two stages termed “Stage 1” and “Stage 2” in order to handle the gap between steel and concrete.

Material properties during – ”Stage 1” :

In this analysis 3 material properties are used as seen below.

Material	Subgroup	Structures	Remark
Steel	Elastic	Spiral and column	“Steel elastic”
Steel	Rigid	Flange	“Steel rigid”
Concrete	Cracked	-	“Concrete cracked”

Material properties during – ”Stage 2” :

In this analysis 6 material properties are used as seen below.

Steel

Material #	Subgroup	Structures	Remark
2	Elastic	Spiral and column	“Steel elastic”
4	Rigid	Flange	“Steel rigid”

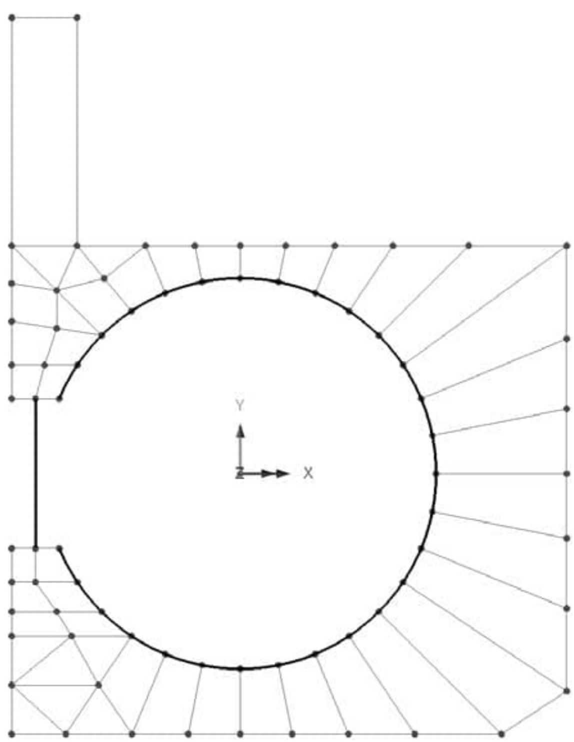
Concrete

Material #	Reinforcement	Cracked	Remark
1	Yes	No	“Reinforced concrete uncracked”
5	Yes	Yes	“Reinforced concrete cracked”
6	No	No	“Concrete uncracked”
7	No	Yes	“Concrete cracked”

2.4.1 Steel : elastic

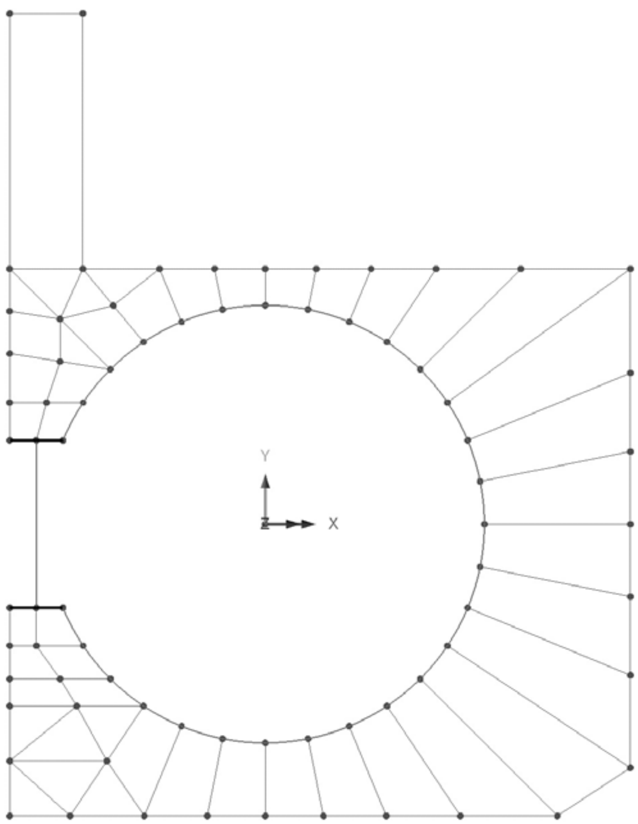
$$G_s = \frac{E_s}{2(1+\nu)} \rightarrow \nu = \frac{E_s}{2G_s} - 1 = \frac{210GPa}{2 \cdot 81GPa} - 1 = 0.3$$

Properties	Value
E_S	$210 \cdot 10^6$ kPa
ν	0.3
ρ_s	7700 kg/m^3



2.4.2 Steel : rigid

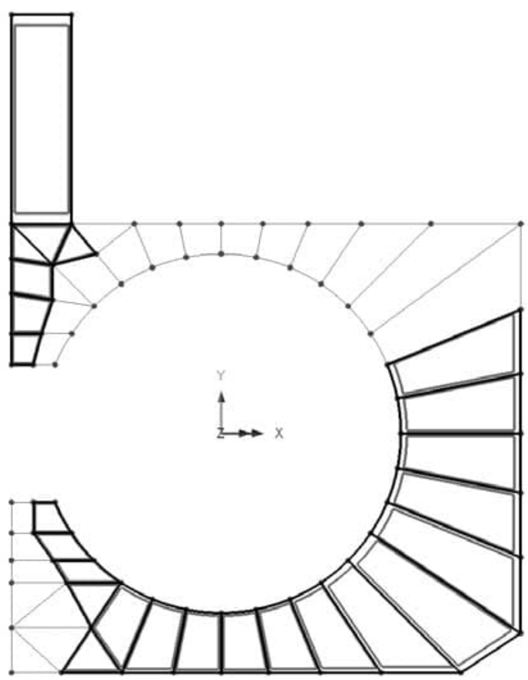
Properties	Value
$1000 \cdot E_S$	$210 \cdot 10^9$ kPa
ν	0.3
ρ_s	7700 kg/m^3



2.4.3 Reinforced concrete uncracked

$$E_{rc,uncracked} = \frac{0.8E_c}{1+\phi} = \frac{0.8 \cdot 33GPa}{1+2.0} = 8.8GPa$$

Properties	Value
$E_{rc,uncracked}$	$8.8 \cdot 10^6$ kPa
ν	0.2
ρ_c	2400 kg/m^3



Remark Due to bending the concrete is considered cracked. Creep value at time t_2 is assumed critical.

2.4.4 Reinforced concrete cracked

$$E_{rc,cracked} = \frac{0.4E_c}{1+\phi} = \frac{0.4 \cdot 33GPa}{1+2.0} = 4.4GPa$$

Properties	Value
$E_{rc,cracked}$	$4.4 \cdot 10^6$ kPa
ν	0.2
ρ_c	2400 kg/m^3

Remark Not used.

2.4.5 Concrete : uncracked

$$E_{cc,uncracked} = \frac{E_c}{1+\phi} = \frac{33GPa}{1+2.0} = 11GPa$$

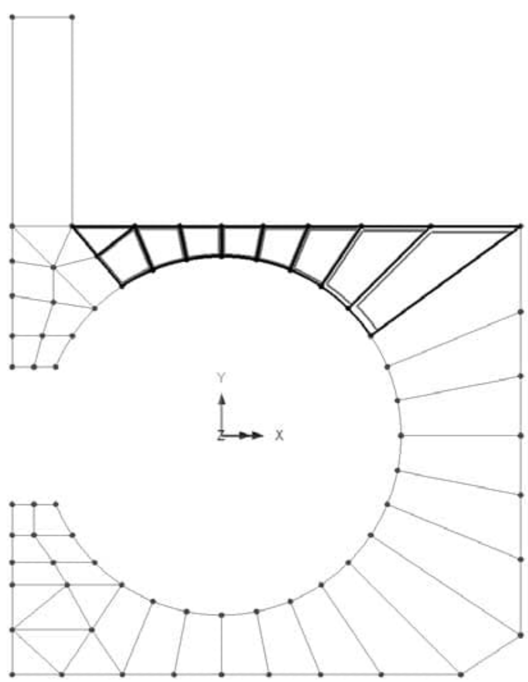
Properties	Value
$E_{cc,uncracked}$	$11 \cdot 10^6$ kPa
ν	0.2
ρ_c	2400 kg/m^3

Remark Not used.

2.4.5 Concrete : cracked

$E_{cc,cracked} = 0GPa$ but since area in the structural model $E_c / 1000$ is applied.

Properties	Value
$E_c / 10^3$	$33{\cdot}10^3$ kPa
ν	0.2
ρ_c	2400 kg/m^3

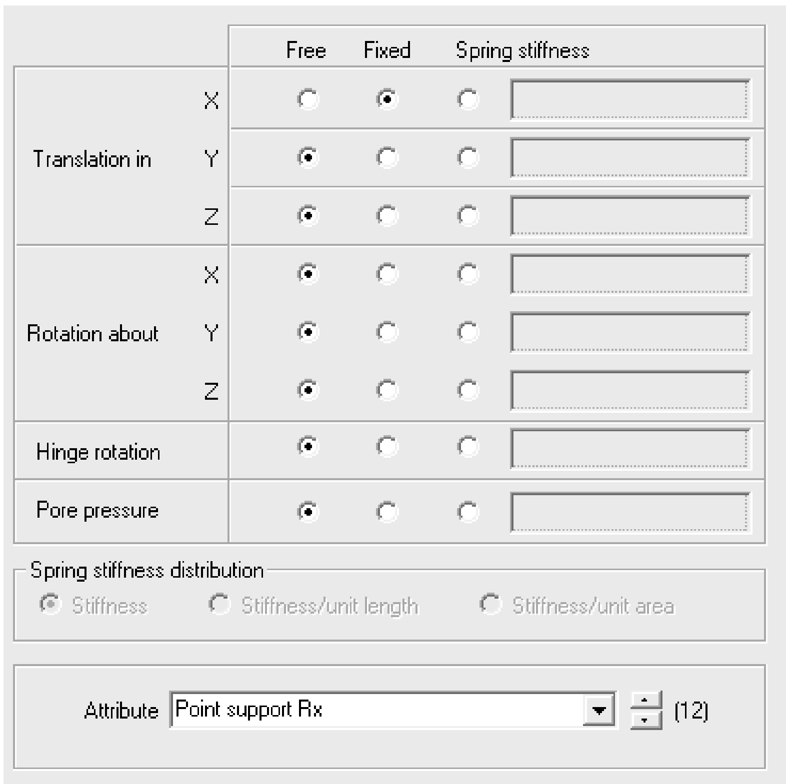


Remark The material properties are applied to concrete without reinforcement in areas where tensional stress acts

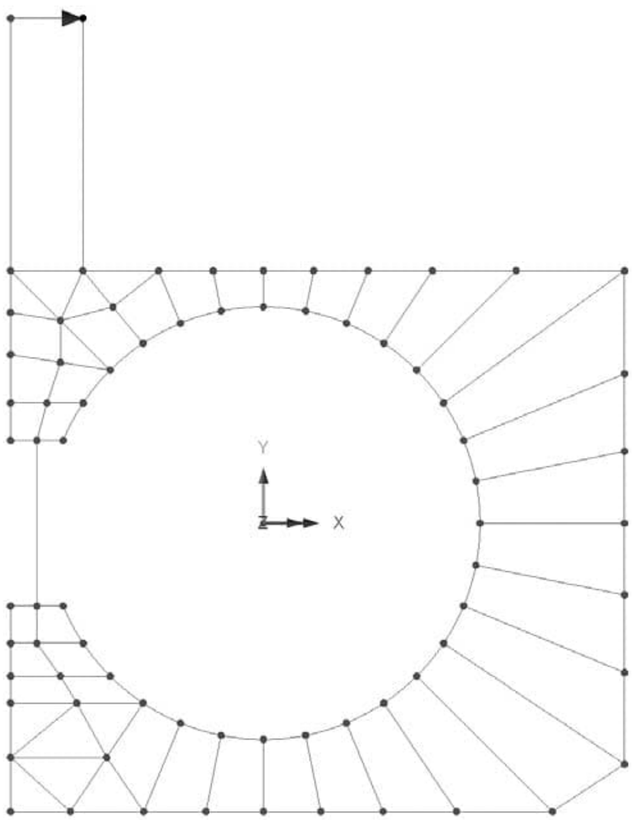
2.5 BOUNDARY CONDITIONS

The structure is modeled with 3 different boundry conditions as seen below.

2.5.1 Boundary condition : Point support RX

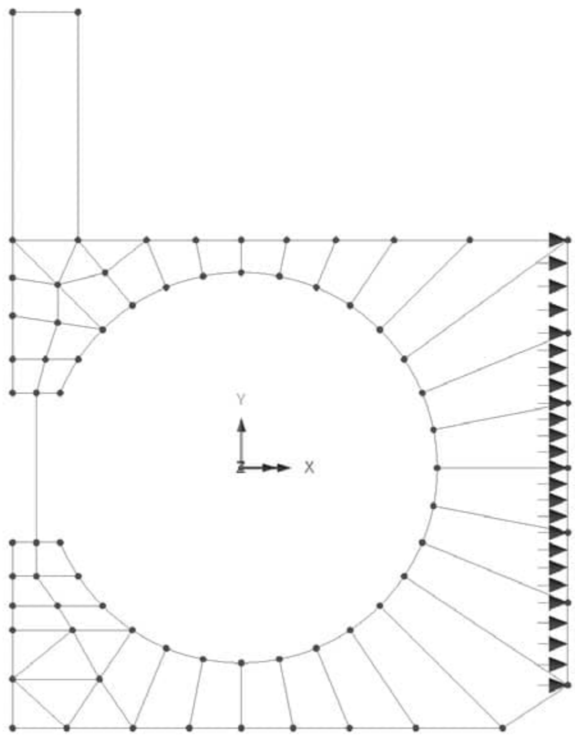


View – "Point support : RX"

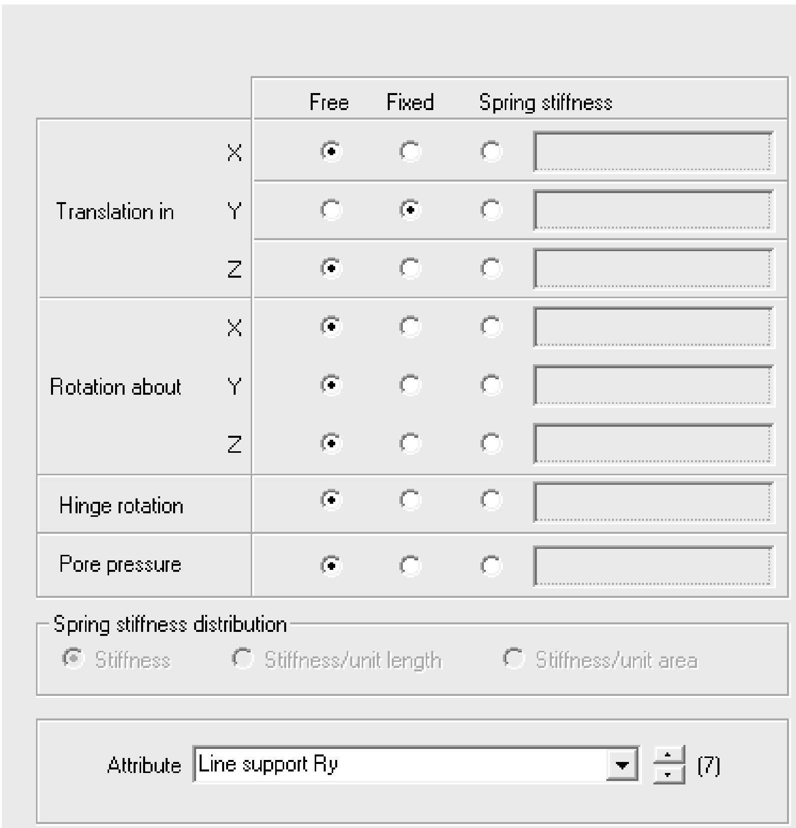


2.5.2 Boundary condition : Line support RX

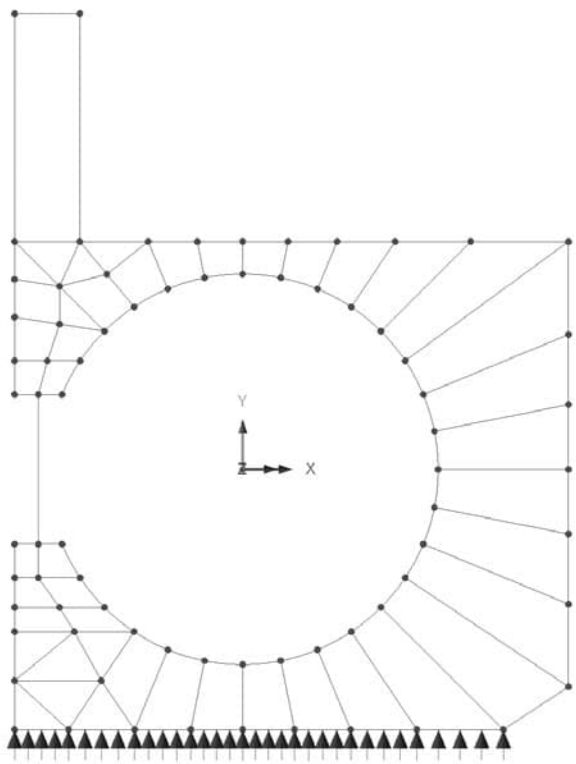
View – "Line support : RX"



2.5.3 Boundary condition : Line support RY



View – "Line support : RY"



3. LOADS

3.1 DEAD WEIGHT

3.1.1 Reinforced concrete

$\gamma_c = 24 \ \frac{kN}{m^3}$

Loadcase : Concrete

Structural loading : Body force

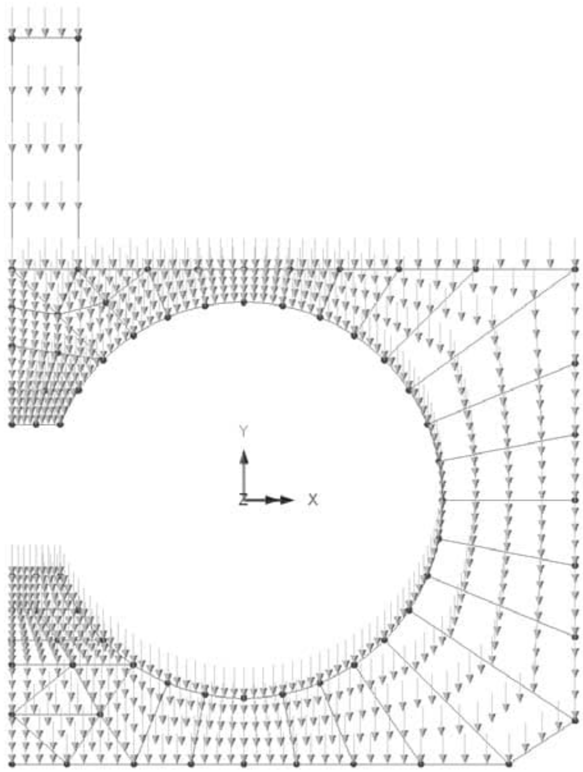
Acceleration in y direction (a_y) : -10 $\frac{m}{s^2}$

Component	Value
Linear acceleration in X	0,0
Linear acceleration in Y	-10,0
Linear acceleration in Z	0,0
Angular velocity about X axis	0,0
Angular velocity about Y axis	0,0
Angular velocity about Z axis	0,0
Angular acceleration about X axis	0,0
Angular acceleration about Y axis	0,0
Angular acceleration about Z axis	0,0

Attribute Concrete (4)

-

Remark This loading condition is termed "Stage 2" corresponding to resistance from concrete and rock.



2D continuum elements : $q = a_y \cdot t \cdot \rho_c$

<u>Remark</u> Load intensity is found by applying density and geometric properties to all SURFACES.

3.1.2 Steel structure

$\gamma_s = 77\ \frac{kN}{m^3}$

Loadcase : Steel

Structural loading : Body force

Acceleration in y direction (a_y) : -10 $\frac{m}{s^2}$

Component	Value
Linear acceleration in X	0,0
Linear acceleration in Y	-10,0
Linear acceleration in Z	0,0
Angular velocity about X axis	0,0
Angular velocity about Y axis	0,0
Angular velocity about Z axis	0,0
Angular acceleration about X axis	0,0
Angular acceleration about Y axis	0,0
Angular acceleration about Z axis	0,0

Attribute Steel (5)

Remark This loading condition is termed "Stage 2" corresponding to resistance from concrete and rock.