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Diseño Estructural

De la chapa del liner de la contención

Design Report

Liner sheets of the cylindrical parts of the liner

0	22.03.2016	Hillebrand			23.03.2016	Hansen
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Indice / Content

1. Field of application

([D 01], Field of application)

This design report applies to the structural design of steel liner structures for the containment of CAREM 25 reactor building. Requirements on steel liner structures are defined, materials to be used and relevant loads to be applied for the design are stated. The safety and design concept for the containment liner are determined.

In CAREM project the containment liner is a metallic lining of the reinforced concrete containment vessel. That means the containment liner is backed by concrete, i.e. it does not act as pressure boundary. Steel liner structures covered by this specification comprise metallic liners backed by concrete including anchorage systems.

2. Codes, standards and guidelines

[C 01] US-ASME Boiler & Pressure Vessel Code, ASME BPVC III-2 – Rules for Construction of Nuclear Facility Components, Code for Concrete Containments, July 2013.

[C 02] ETC-C 2012: EPR Technical Code for Civil Works, afcen 2012.

[C 03] EN 1993-1-1 (Eurocode 3) – Design and construction for steel structures / Bemessung und Konstruktion von Stahlbauten - Part 1-1: General design rules and rules for buildings, December 2010.

[C 04] EN 1993-1-5 (Eurocode 3) – Design and construction for steel structures / Bemessung und Konstruktion von Stahlbauten - Part 1-5: Plated structural elements, December 2010.

[C 05] EN 1993-1-6 (Eurocode 3) – Design and construction for steel structures / Bemessung und Konstruktion von Stahlbauten - Part 1-6: Strength and stability of shell structures, December 2010.

[C 06] EN 1994-1-1 (Eurocode 4) – Design of composite steel and concrete structures / Bemessung und Konstruktion von Verbundtragwerken aus Stahl und Beton – Part 1-1: General rules and rules for buildings, December 2010

[C 07] E DIN 25459 - Sicherheitsbehälter aus Stahlbeton und Spannbeton für Kernkraftwerke, December 2014

[C 08] Nelson embedment properties of headed studs, Construction – Design Data, TRW Inc. 1977

[C 09] Nelson Test series: TU Kaiserslautern, Einschubversuche, Nelson Bolzen, B25 bis B35

[C 10] Nelson General Information for Stud Welding Studs

[C 11] EN 10028-1 – Flat products made of steels for pressure purposes
Part 1: General requirements (2009-07)
Part 3: Weldable fine grain steels, normalized (2009-09)

[C 12] EN 10029 – Hot-rolled steel plates 3 mm thick or above -
Tolerances on dimensions and shape

[C 13] ASTM A 20/A 20M – 07 – Standard Specification for General Requirements for Steel Plates for Pressure Vessels, 2008

[C 14] ASTM A 108 – 07 – Standard Specification for Steel Bar, Carbon and Alloy, Cold-Finished, 2009

3. Corresponding documents

[D 01] CAREM-90-0002-0: Design Specification, Design of steel liner structures.

[D 02] CAREM-90-0003-0: Load Specification for Steel Liner Structures.

[D 03] CAREM-90-0004-A: Erection Concept for the Containment Liner

[D 04] CAREM-90-0005-0: Requirements on the qualification of the Steel Liner Manufacturer.

[D 05] CAREM-10-0006-0: Design Report, Anchorage of the bottom liner

[D 06] CAREM-10-0007-A: Design Report, Liner sheets of the bottom liner (Level -12,10 m)

[D 07] CAREM-10-0008-A: Design Report, Liner sheets of the bottom liner and one cylindrical part of the liner (Bottom Level -10,10 m)

[D 08] CAREM-10-0011-A: Design Report, Piping penetrations of the containment liner

[D 09] EEIN-CAREM25C-4-r0 Rev 0: Structural analysis of containment of CAREM 25 reactor; 25 March 2013.

[D 10] TN-002, Technical Note / Project Note, Carem 25, Sum of concrete compressive strains to be applied as pre-strains on the steel liner structure of the containment, dated 31.03.2015

[D 11] TN-005, Technical Note / Project Note, Carem 25, Design of anchor plates as part of the liner, dated 27.05.2015

[D 12] Drawings:

1 EEPL-CAREM25C-341-r0_B

2 EEPL-CAREM25C-342-r0_B

3 EEPL-CAREM25C-343-r0_B

4 EEPL-CAREM25C-344-r0_B

4. Introduction

4.1 General

This report contains the Finite-Element-Model calculation of the cylindrical parts of the liner of the containment liner CAREM25. This detail of the liner structure includes the essential parts of the structural members of the liner structure [D 01], as the steel liner and the anchors of the anchor plates. The computation models include the liner sheets together with the required boundary conditions.
Analysing the liner for the static analysis it has to be considered that there is an interaction between the steel liner and the concrete structure, which is included through a contact-target relation.

The concrete strains (caused by normal or accidental situations or even by creeping and shrinking) have to be derived from a structural analysis of the concrete structure; in this case compressive strains are of interest.

The static analysis includes the verification of this local part of the containment under the terms which are mentioned in the associated chapter, as for example the specified geometry, loads, required verifications according to ASME, etc.

The finite-element-program utilized for the computation is: ANSYS Mechanical 16.1.

5. Static analysis: Cylindrical part of liner

5.1 Specification

5.1.1 General

This report contains the analysis of several FEM models which contain the segment of the interior cylinder, the segment of the exterior liner and the segment around the hatch at -10,10 m.
Parts of the models are the liner sheets with a thickness of 8 mm and 20 mm (cylindrical part),as well as the reinforcements around the liner penetrations and the hatch; the geometry of the single sheets can be taken from the relevant drawings [D 12].

In this report the steel liner is calculated relating to accidental load situations. For the containment steel liner the most unfavourable load case is loss of coolant accident (LOCA), wheras the steel liner adopts high temperatures while the backing concrete is still cold.

Listed below the following element types are utilized for the computation model:

Steel liner:	Shell elements
Anchors at anchor plates:	Link elements
Horizontal stiffness of anchors in concrete:	Multilinear spring elements
Contact:	Contact and target elements

The computation includes nonlinear material and nonlinear geometrical behaviour.

Numerical models 1a – 1g: Interior cylinder with radius 4200 mm

Numerical model 1h: Exterior cylinder with radius 9500 mm

Numerical model 1i: Exterior cylinder with radius 9500 mm at hatch -10,10 m

Cylindrical part of Liner, general (numerical models 1a – 1i)

The sheets of the cylindrical part are connected to the concrete via headed studs which have a distance of 150 mm in circumferential direction and 150 mm in vertical direction. The studs are directly welded to to steel liner. The analysis of the headed studs is part of this report.
The anchor plates of the cylindrical part are considered for the computation to get their displacement and forces, too. These anchors also are taken into account by each one link and spring element per anchor plate, which represent the total number of anchors for type A2 or B2 (= 9 anchors) or for type A1 (= 4 anchors). So the results indicate the displacements and forces for these types of plates.

In radial direction the studs are represented by one link element with a nonlinear stress-strain curve. This curve ensures that the bolts can keep the maximum tensile force. In circumferential and vertical direction, the studs are represented by spring elements with a multilinear load displacement curve. The curves are the results of tests with different studs in concrete.

Characterisation of examined pre-deformations

The following numerical models have been analysed, they differ in the type of pre-deformation:

1) Model No. 1a): Pre-deformation between 4 headed studs, area of 150*150 mm

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 150 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2).

2) Model No. 1b): Longitudinal pre-deformation between two columns of headed studs, width of 150 mm

One longitudinal buckle (pre-deformation) between two columns of headed studs; the dimension of the buckle is 2000 mm x 150 mm (distance between two columns), the height of the buckle is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2).

3) Model No. 1c): Pre-deformation between 4 headed studs, area of 150*150 mm, with failure of 1 stud

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 150 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2); additionally failure of 1 headed stud.

4) Model No. 1d): Vertical offset of 3mm between two columns of headed studs

Vertical offset of 3 mm in the middle of two columns of headed studs, the offset of 3 mm corresponds to class B (3 mm) [C 05], (8.4.3).

5) Model No. 1e): Sharp bend of 3 mm between two columns of headed studs

Sharp bend of 3 mm in the middle of two columns of headed studs, the offset of 3 mm corresponds to class B (3 mm), [C 05], (8.4.3).

6) Model No. 1f): Consideration of two different sheet thicknesses in one numerical model

One sheet has a thickness of 8,0 mm and an adjacent sheet has a thickness of 9,1 mm, these thicknesses correspond to the permissible variations in thickness for rectangular plates with a width of about 3300 mm [C 13], (Table A2.1). The pre-deformation is similar to numerical model 1b.

7) Model No. 1g): Consideration oft wo different yield strengths in one numerical model

One sheet has a yield strength of 1,0 fy and an adjacent sheet has an elevated yield strength of 1,3 fy; these different yield strengths consider the possible variations due to the rolling processes, etc. [C 07], (5.3.2); [C 01], (CC3810). The pre-deformation is similar to numerical model 1b.

8) Model No. 1h): <u>Exterior cylinder</u>, longitudinal pre-deformation between two columns of headed studs

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 2000 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2). This analysis contains the liner sheets of the exterior cylinder with a radius of 9500 mm.

9) Model No. 1i): <u>Exterior cylinder</u> at hatch

This numerical model has no pre-deformation; the discontinouity is the opening at the hatch.

5.1.2 Geometry and components of numerical models

Numerical models No. 1a – 1g)

The geometry of models 1a – 1g is represented in the following (The lines indicated in the following picture are auxiliary lines for the buildup of the computational model).

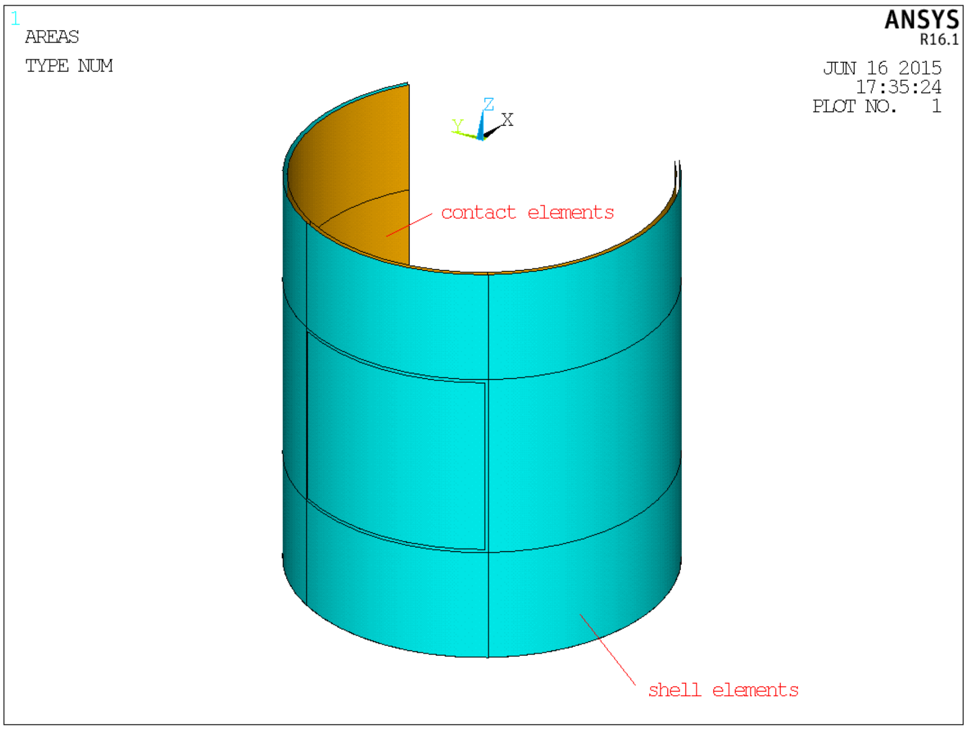


Fig. 5-1: Structure of numerical models 1a – 1g (1)

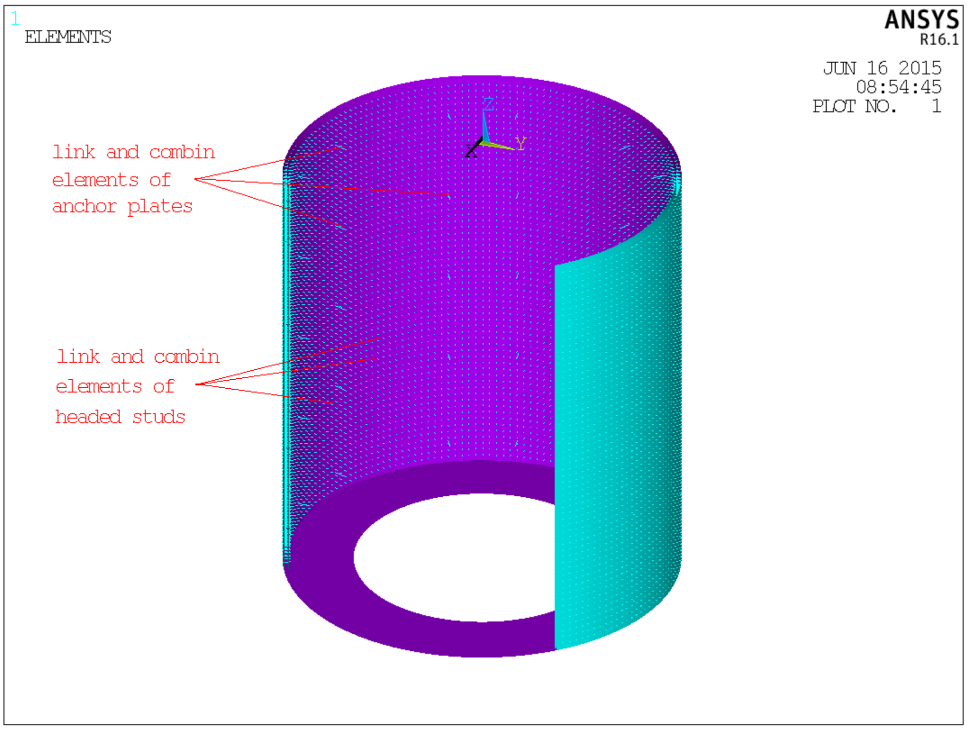


Fig. 5-2: Structure of numerical models 1a – 1g (2)

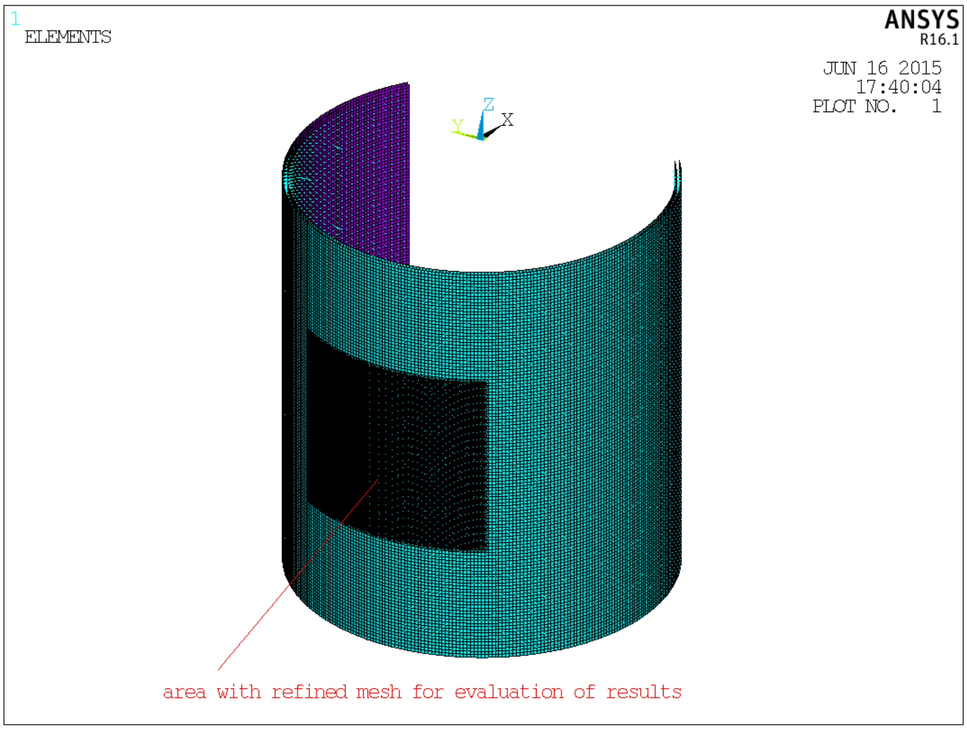


Fig. 5-3: Element mesh of numerical models 1a – 1g

The cylindrical part of the liner has a radius of 4200 mm. Due to the fact that all essential parts of this kind of segment are the same (liner, headed studs, anchor plates), the results of the analysis indicated in this report can be applied for the similar cylindrical parts of this containment liner with a radius of 4200 mm.

Numerical model No. 1h)

The geometry of model 1h is represented in the following (The lines indicated in the following picture are auxiliary lines for the buildup of the computational model).

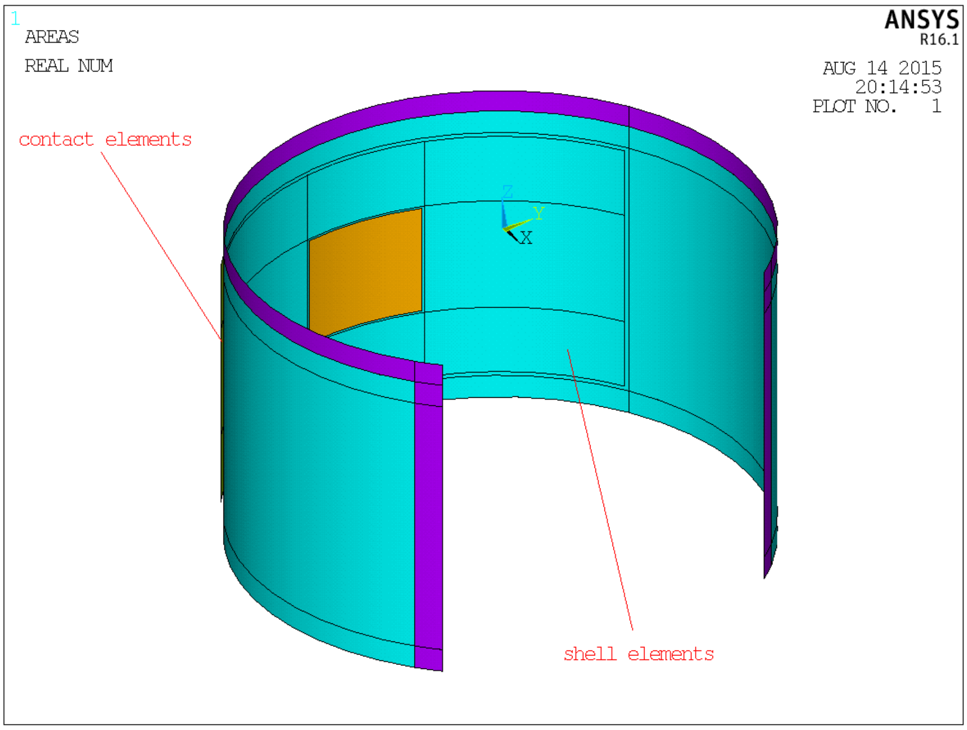


Fig. 5-4: Structure of numerical model 1h (1)

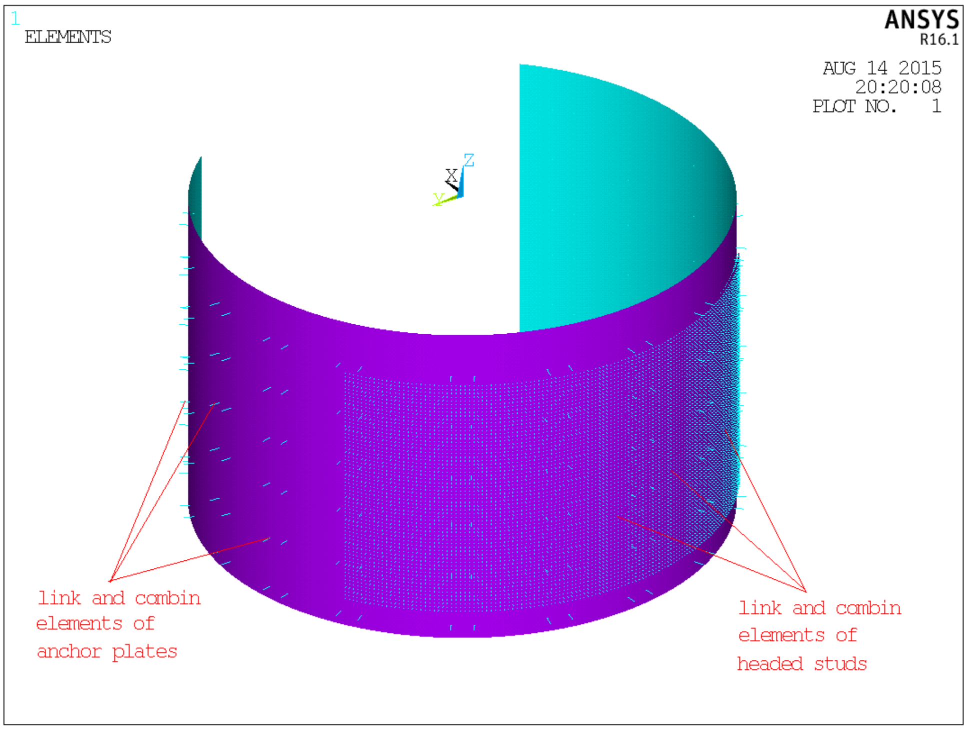


Fig. 5-5: Structure of numerical model 1h (2)

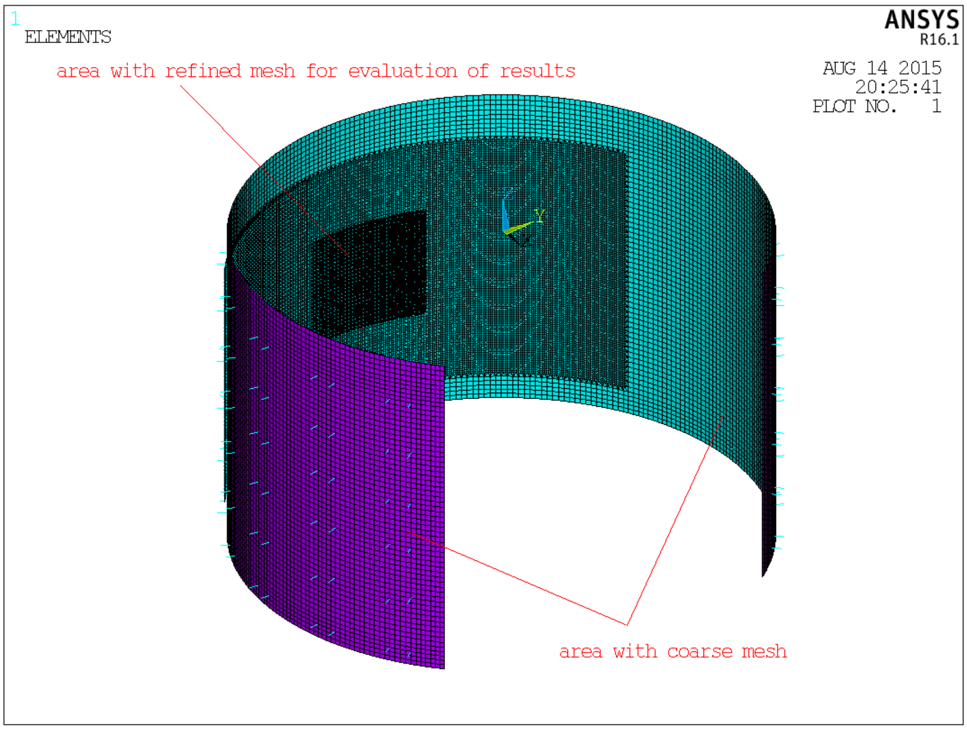


Fig. 5-6: Element mesh of numerical model 1h

The cylindrical part of the liner has a radius of 9500 mm. Due to the fact that all essential parts of this kind of segment are the same (liner, headed studs, anchor plates), the results of the analysis indicated in this report can be applied for the similar cylindrical parts of this containment liner with a radius of 9500 mm.

Numerical model No. 1i)

The geometry of model 1i is represented in the following (The lines indicated in the following picture are auxiliary lines for the buildup of the computational model).

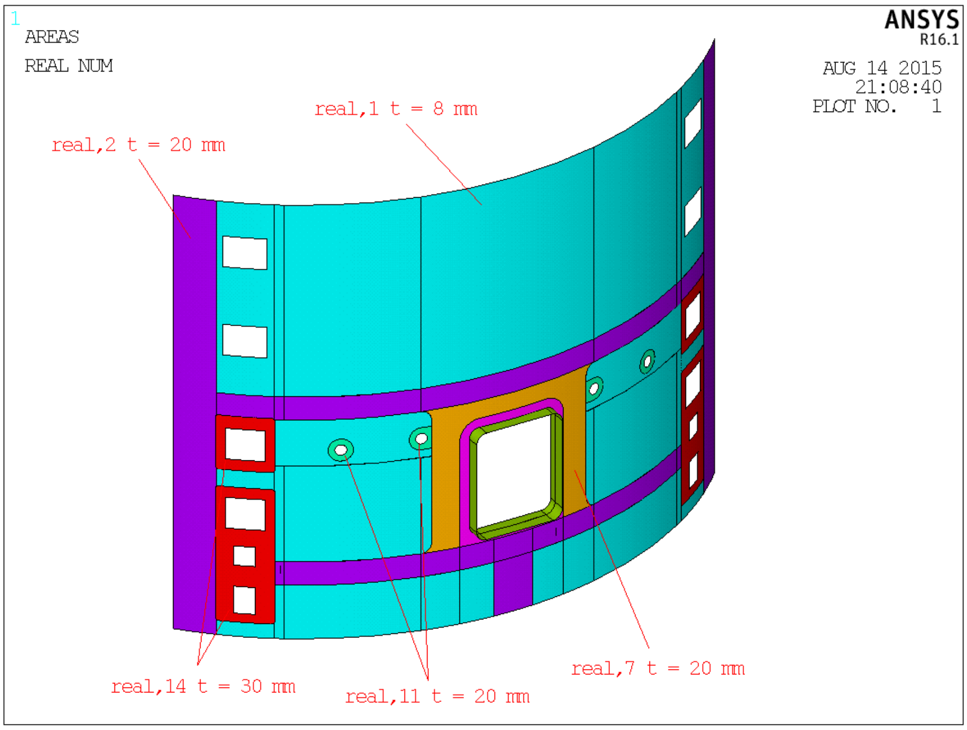


Fig. 5-7: Structure of numerical model 1i (1)

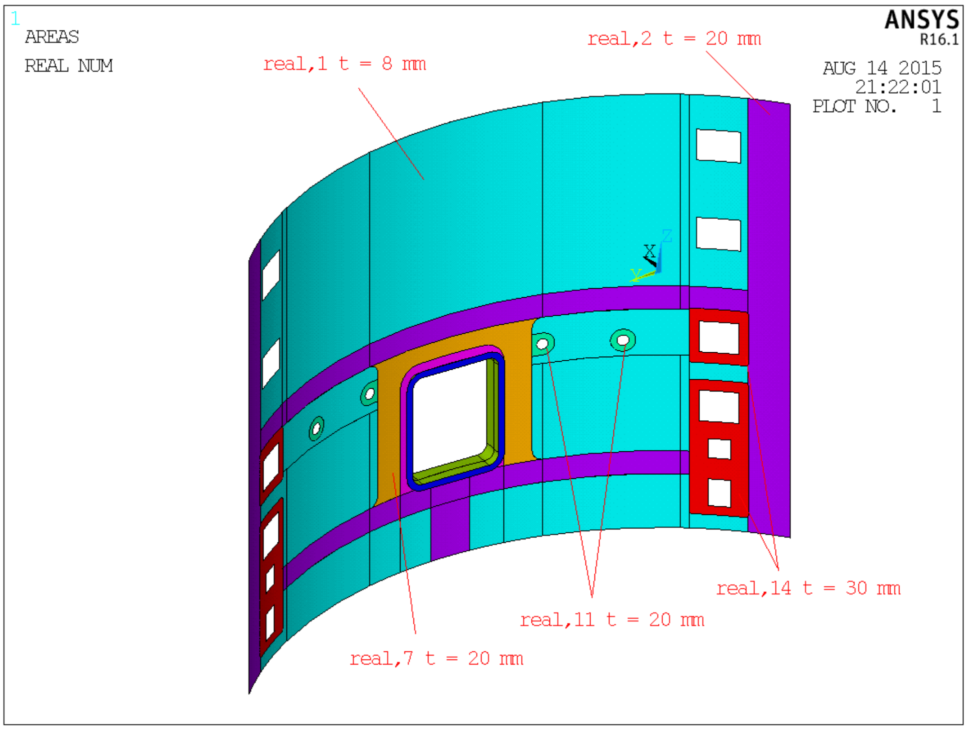


Fig. 5-8: Structure of numerical model 1i (2)

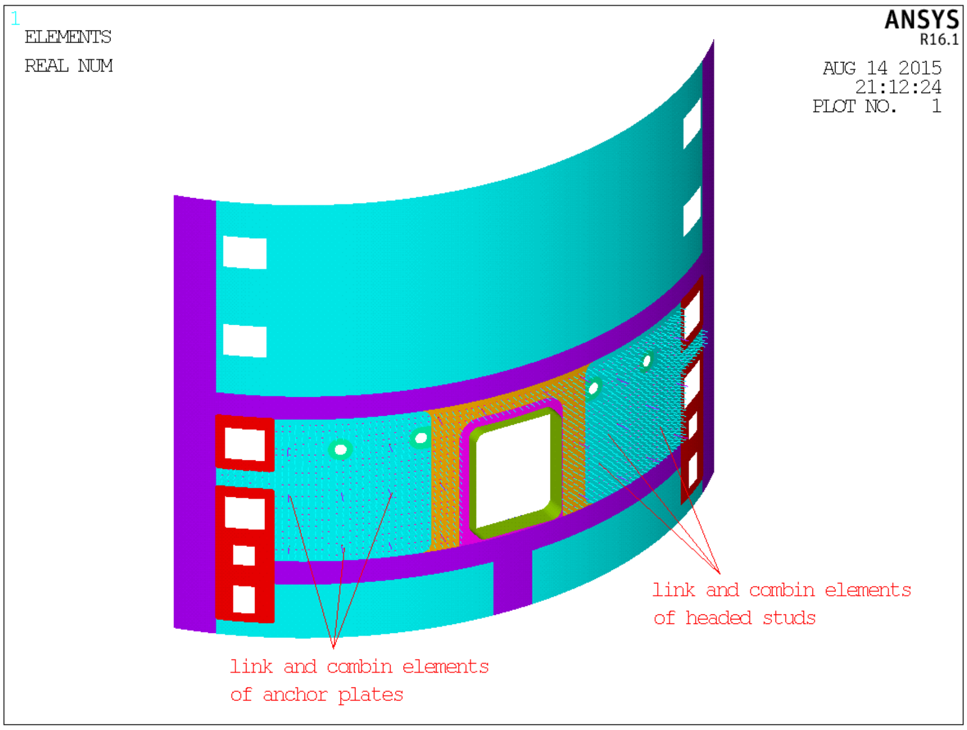


Fig. 5-9: Structure of numerical model 1i (3)

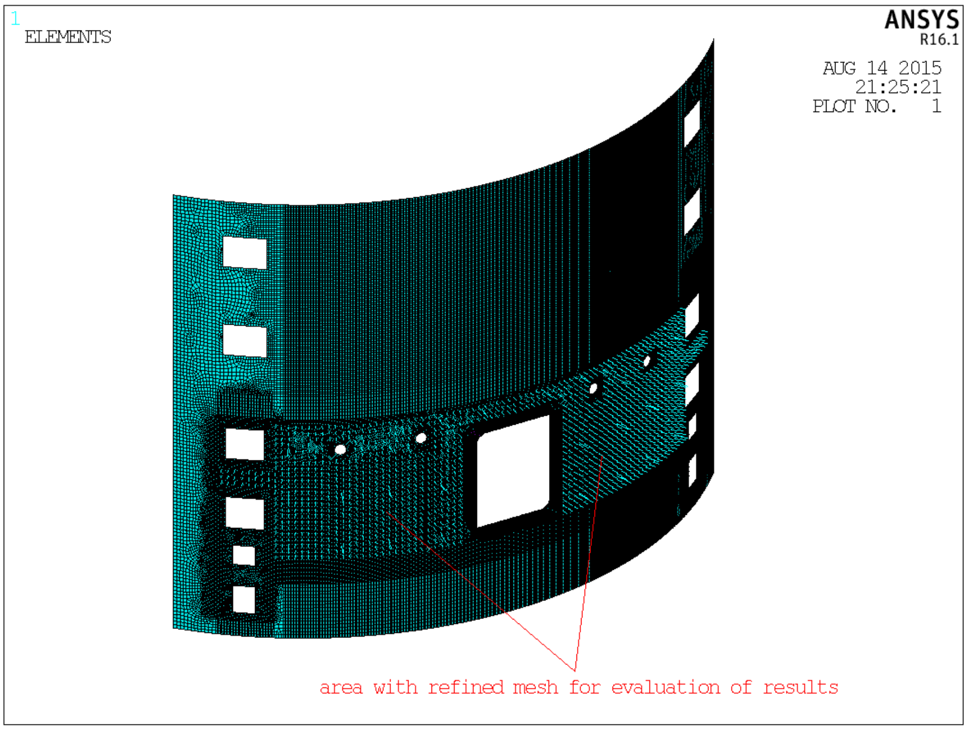


Fig. 5-10: Element mesh of numerical model 1i

The cylindrical part of the liner has a radius of 9500 mm at a hatch. Due to the fact that all essential parts of this kind of segment are the same (liner, headed studs, anchor plates), the results of the analysis indicated in this report can be applied for similar cylindrical parts of this containment liner with a radius of 9500 mm at a hatch.

5.1.3 Material properties

Numerical models No. 1a – 1i

The material for the liner sheets is Carbon steel SA-516 grade 60 with yield strength of 220 MPa (N/mm^2).
To consider an above-standard stability of the materials, the yield strength of the material is increased by a factor of 1,3.

Minimal tensile strength at ambient temperature:	R_m^{min} = 415 MPa (N/mm^2)
Minimal yield strength at ambient temperature:	R_{eH}^{min} = 220 MPa (N/mm^2)
Minimal yield strength at elevated temperature (T=150°C) (1,0 * f_y):	$R_{p0.2}^{min}$ = 195 MPa (N/mm^2)
Maximal yield strength at elevated temperature (T=150°C) (1,3 * f_y):	1.3 $R_{p0.2}^{max}$ = 253,5 MPa (N/mm^2)

Reduction of area shall be minimal 45%
Elongation at fracture shall be minimal ε_u = 22% in 5 x diameter

The following picture indicates the multilinear stress-strain curve of the liner sheets utilized for LOCA (T = 150°C):

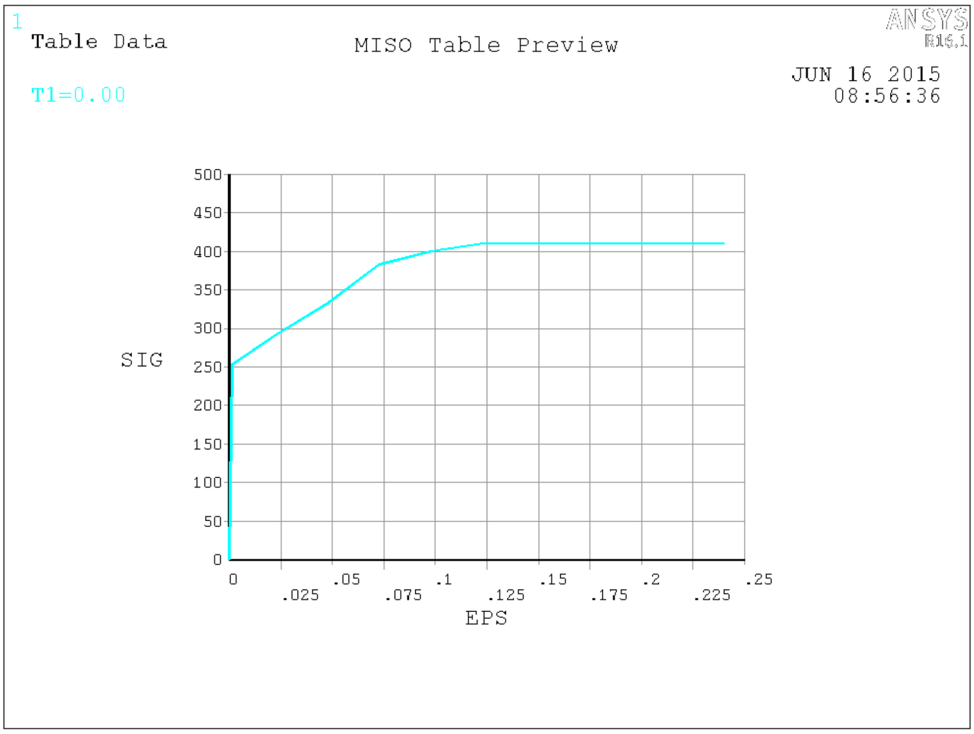


Fig. 5-11: Multilinear material stress-strain curve for LOCA (T = 150°C)

- Liner design allowables for **global analysis** of the shell structure:

Strains associated with construction-related liner deformations may be excluded when calculating liner strains for the service and factored load combinations.

The stress and strain allowables according to ASME [C 01] (CC3720) are:

Category	**Membrane**	**Combined Membrane and Bending**
Construction	$R_d = 0.67\ f_{yk}$ [stress]	$R_d = 0.67\ f_{yk}$ [stress]
Normal	$R_d = 0.002$ [strain]	$R_d = 0.004$ [strain]
Abnormal	$R_{d,c} = 0.005$ [strain] $R_{d,t} = 0.003$ [strain]	$R_{d,c} = 0.014$ [strain] $R_{d,t} = 0.010$ [strain]
The types of strains limited by this table are strains induced by other than construction related liner deformations.		

The given strain allowables are applicable only for undisturbed steel liner areas. In zones with discontinouities, e.g. at interferences or openings these strains will arise so that the use of a local liner model together with higher allowable strains is necessary. These strains are presented in the following.
In general the maximal allowable value for the principal strains (1st, 2nd, 3rd principal strain) is normally limited to 5%, which is much higher than the values in the following table.

- Liner design allowables for **local analysis** of the shell structure according to [D 01] are:

Category	**Membrane**		**Combined Membrane and Bending**	
	Tabular value	**$\varepsilon_v \le \varepsilon_u$ / Tabular value**	**Tabular value**	**$\varepsilon_v \le \varepsilon_u$ / Tabular value**
A1	40	0.0055	20	0.0110
A2	24	0.0092	12	0.0183
A3	12	0.0183	6	0.0367

The strains in the table mentioned above are applicable for the zones of the steel liner which imply local discontinouities as liner corners, connections to penetration liners or openings or similar. The calculation and evaluation of these discontinouities requires the use of detailed finite element models. The size of these detailed models is chosen in the way that one complete individual component is included (e.g., one part of the cylindrical shell) with the appropriate boundary conditions.
As indicated above the detailed model acts as a composite structure which considers the interaction between liner and concrete quite realistic. So the unfavourable effects of the structure are taken into account.
With the numerical calculation the local stability of the steel liner (e.g. buckling) and the resistance of the headed studs have to be verified. The stability of the steel liner with regard to liner integrity can be analysed by means of representative local models which contain different geometrical imperfections due to liner manufacturing.
The shape and size of these imperfections can mainly be found in adequate codes and standards [C 02], [C 05] and they have to be applied to the single local models to get the maximum strains and deformations of the liner. Also the forces and deformations of the headed studs have to be determined by means of this calculation.

In detail the following structural verifications have to be performed:
- Computation of local peak strain values of the steel liner at most critical locations (bottom of buckle at connection to headed studs and top of buckle at midspan of predeformed area between headed studs).
- Analysis of the connecting devices (headed studs) with regard to the axial and shear forces
- Analysis of the deformations of the connecting devices (headed studs)

Liner Anchors

Nelson headed studs with a diameter of ½″ (13 mm) for the cylindrical part will be used as connecting devices for the parts of the steel liner. These studs have a nonlinear load-displacement curve which can be taken from the results of a test series of Nelson studs [C 09].

Type: Nelson headed studs type B (Mild steel shear and concrete anchors)

Ultimate tensile strength (at ambient temperature): R_m = 450 MPa
Yield 0.2% offset (at ambient temperature): $R_{p0.2}$ = 350 MPa
For ductile behaviour: $\delta_{uk} \leq 6$ mm [C 06] (6.6.1.1)

Reduction of area shall be minimal 50%
Elongation at fracture shall be minimal 20% in 5 x diameter

Liner anchor allowables:

Category	**Force allowables** for mechanical loads, lesser of:	**Displacement allowables** for displacement limited loads
Construction	$R_d = 0.67\ F_y$ $R_d = 0.33\ F_u$	$R_d = 0.25\delta_u \leq 1{,}5$ mm
Normal	$R_d = 0.67\ F_y$ $R_d = 0.33\ F_u$	$R_d = 0.25\delta_u \leq 1{,}5$ mm
Abnormal	$R_d = 0.90\ F_y$ $R_d = 0.50\ F_u$	$R_d = 0.50\delta_u \leq 3$ mm

According to ASME [C 01] (CC3730) the liner shall be anchored to the concrete so that the liner strains do not exceed the above given design allowables for global analysis of the shell structure. The anchor size and spacing shall be chosen so that the response of the liner is predicatable for the loads and load combinations mentioned in this report. The anchorage system shall be designed so that it can accommodate the design in-plane (shear) loads or deformations exerted by the liner and loads applied normal to the liner surface.
The allowable force and displacement capacity of the headed studs is given in the table above. The load combination indicated in the load chapter is applicable to the liner anchors, except that load factors for all load cases are taken equal to 1.0. **Mechanical loads** are those that are not self-limiting or self-relieving with load application. **Displacement limited loads** are those resulting from constraint or adjacent material and are self-limiting or self-relieving.

According to ASME [C 01] (CC3810) the anchor design and analysis shall consider the effects of the following:

- The unbalanced loads resulting from the variation of liner curvature. Some areas of the liner may have inward curvature between the anchors, whereas other areas will have outward curvature. The variation will result in shear load and displacement at the anchor.
- Yield strength higher than the minimum specified due to the rolling processes and biaxial loading. Adequate consideration of yield strength in excess of the minimums may be provided amongst others.
- Weld offset (not applicable in this case), structural discontinuities or concrete voids behind the liner.

5.2 Liner imperfections

5.2.1 General

<u>Numerical model No. 1a</u>

Pre-deformation between 4 headed studs, area of 150*150 mm:

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 150 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2).

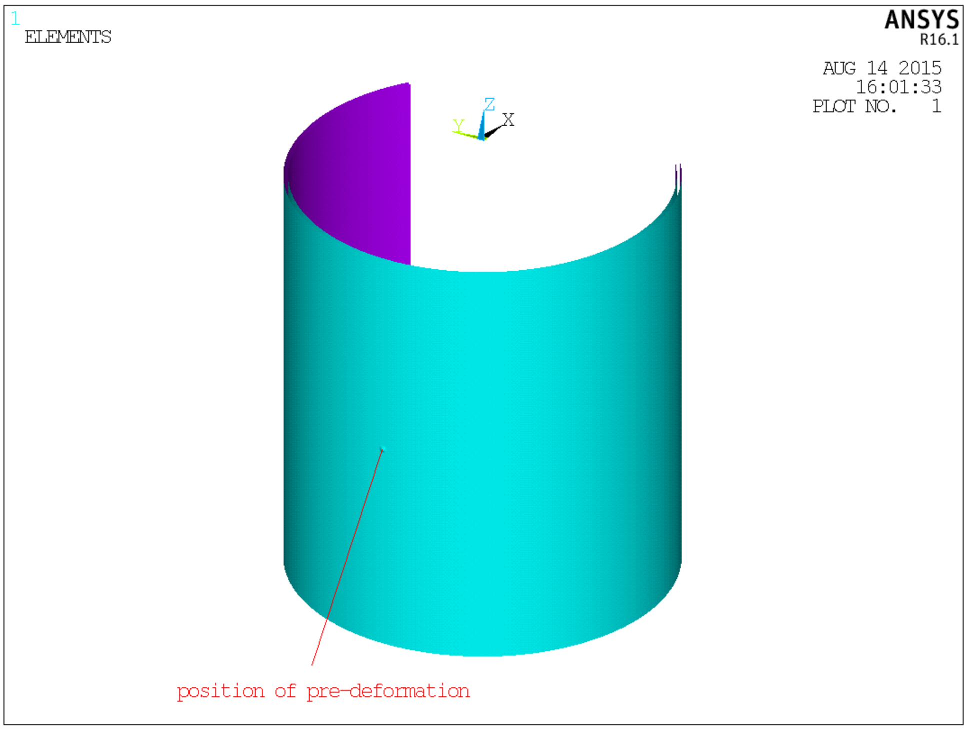


Fig. 5-12: Position of pre-deformation, numerical model 1a

Numerical model No. 1b

Longitudinal pre-deformation between two columns of headed studs, width of 150 mm:

One longitudinal buckle (pre-deformation) between two columns of headed studs; the dimension of the buckle is 2000 mm x 150 mm (distance between two columns), the height of the buckle is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2).

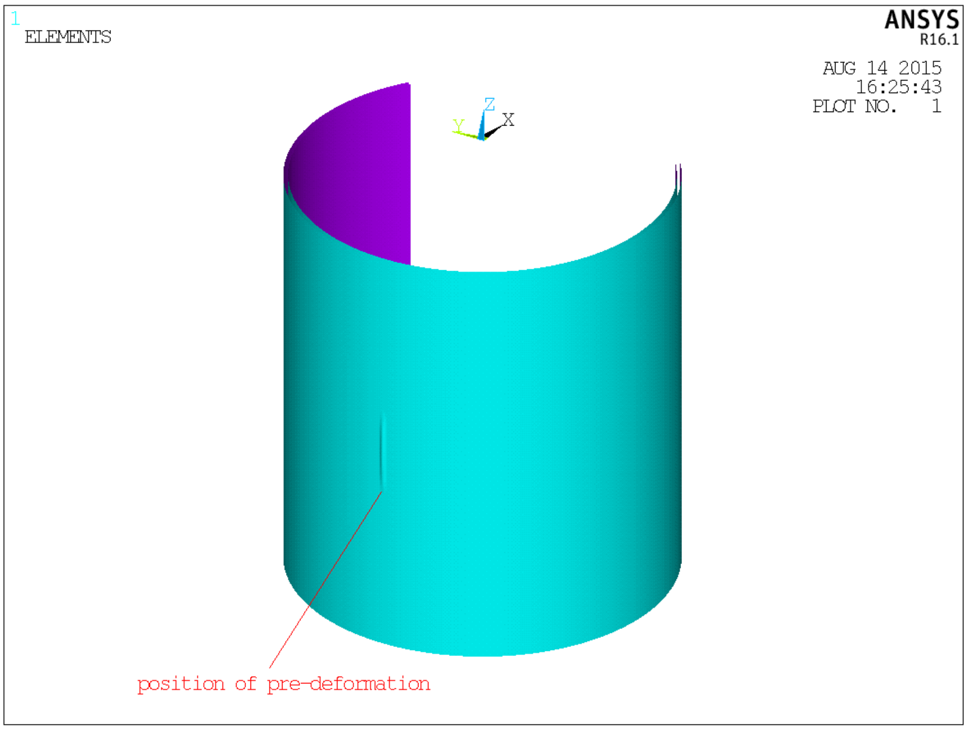


Fig. 5-13: Position of pre-deformation, numerical model 1b

Numerical model No. 1c

Pre-deformation between 4 headed studs, area of 150*150 mm, with failure of 1 headed stud:

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 150 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2); additionally failure of 1 headed stud.

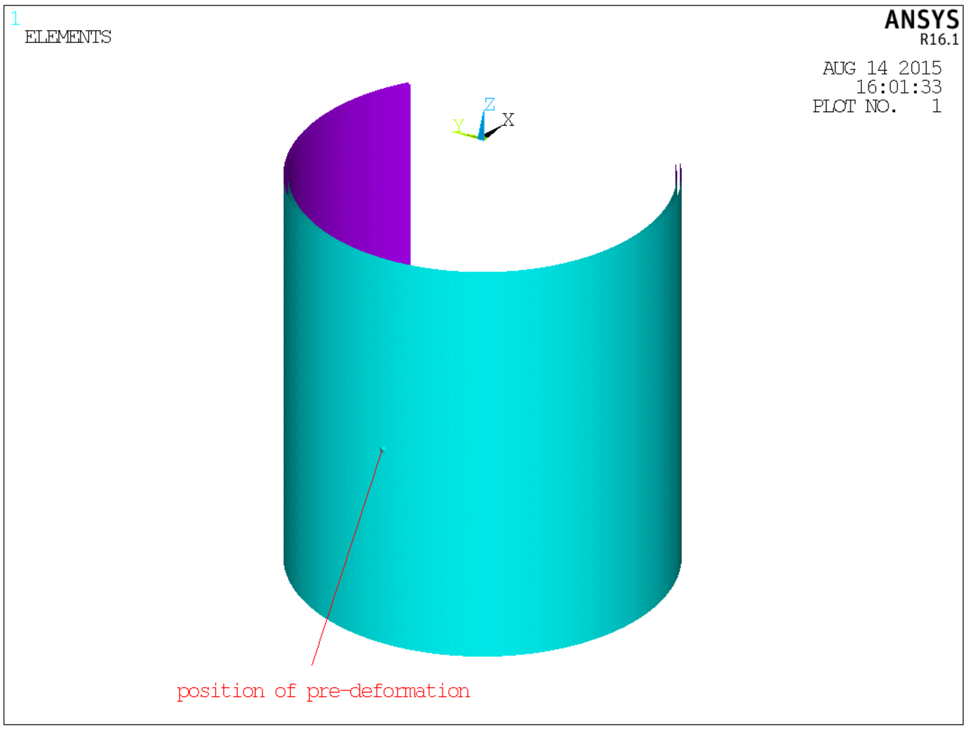


Fig. 5-14: Position of pre-deformation, numerical model 1c

Numerical model No. 1d

Vertical offset of 3mm between two columns of headed studs:

Vertical offset of 3 mm in the middle of two columns of headed studs, the offset of 3 mm corresponds to class B (3 mm) [C 05], (8.4.3).

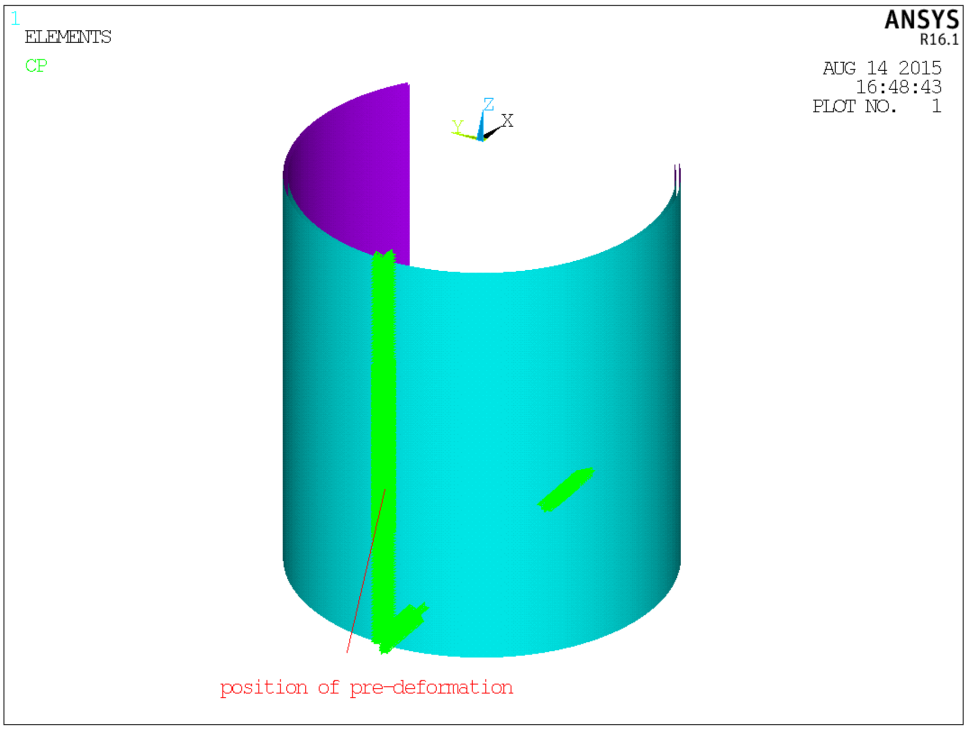


Fig. 5-15: Position of pre-deformation, numerical model 1d

Numerical model No. 1e

Sharp bend of 3 mm between two columns of headed studs:

Sharp bend of 3 mm in the middle of two columns of headed studs, the offset of 3 mm corresponds to class B (3 mm), [C 05], (8.4.3).

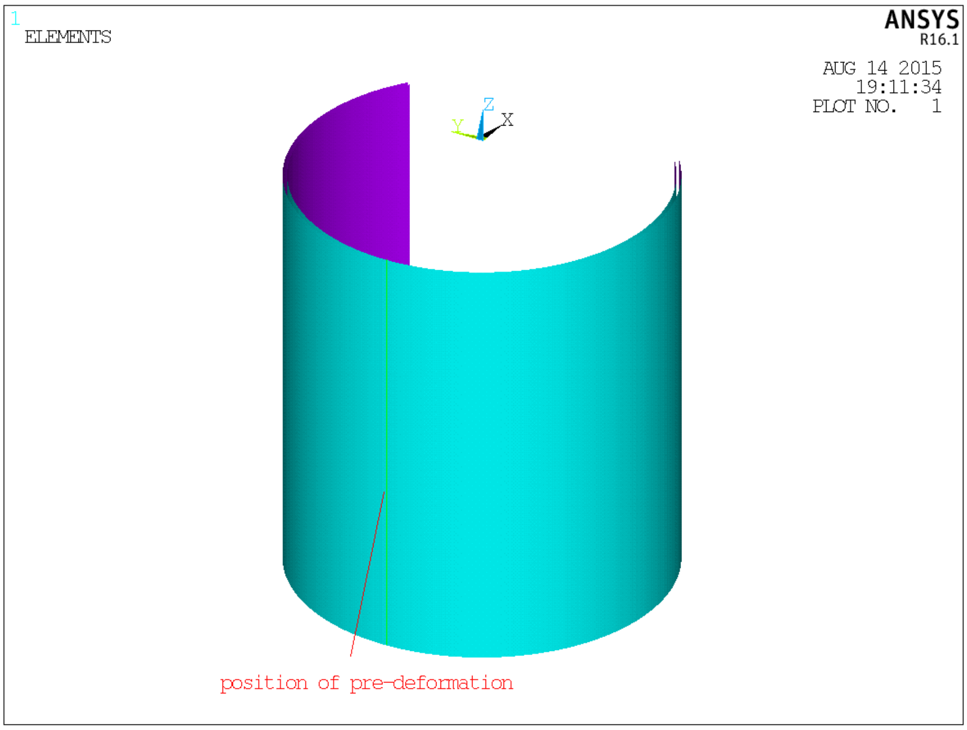


Fig. 5-16: Position of pre-deformation, numerical model 1e

Numerical model No. 1f

Consideration of two different sheet thicknesses in one numerical model:

One sheet has a thickness of 8,0 mm and an adjacent sheet has a thickness of 9,1 mm, these thicknesses correspond to the permissible variations in thickness for rectangular plates with a width of about 3300 mm [C 13], (Table A2.1).

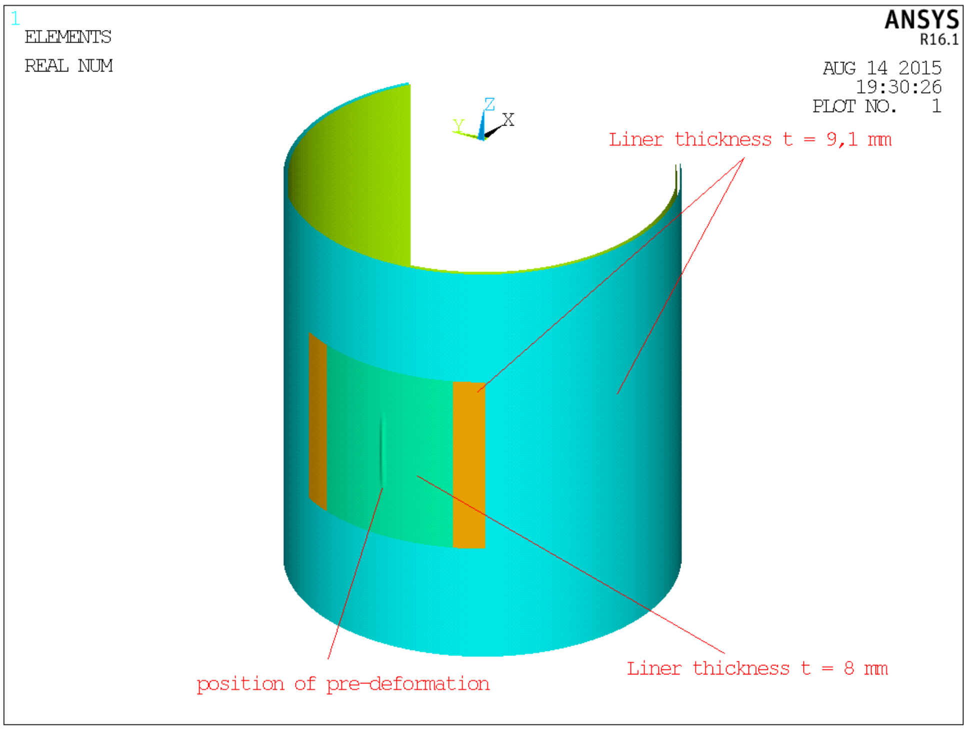


Fig. 5-17: Position of pre-deformation, numerical model 1f

Numerical model No. 1g

Consideration oft wo different yield strengths in one numerical model

One sheet has a yield strength of 1,0 fy and an adjacent sheet has an elevated yield strength of 1,3 fy; these different yield strengths consider the possible variations due to the rolling processes, etc. [C 07], (5.3.2); [C 01], (CC3810).

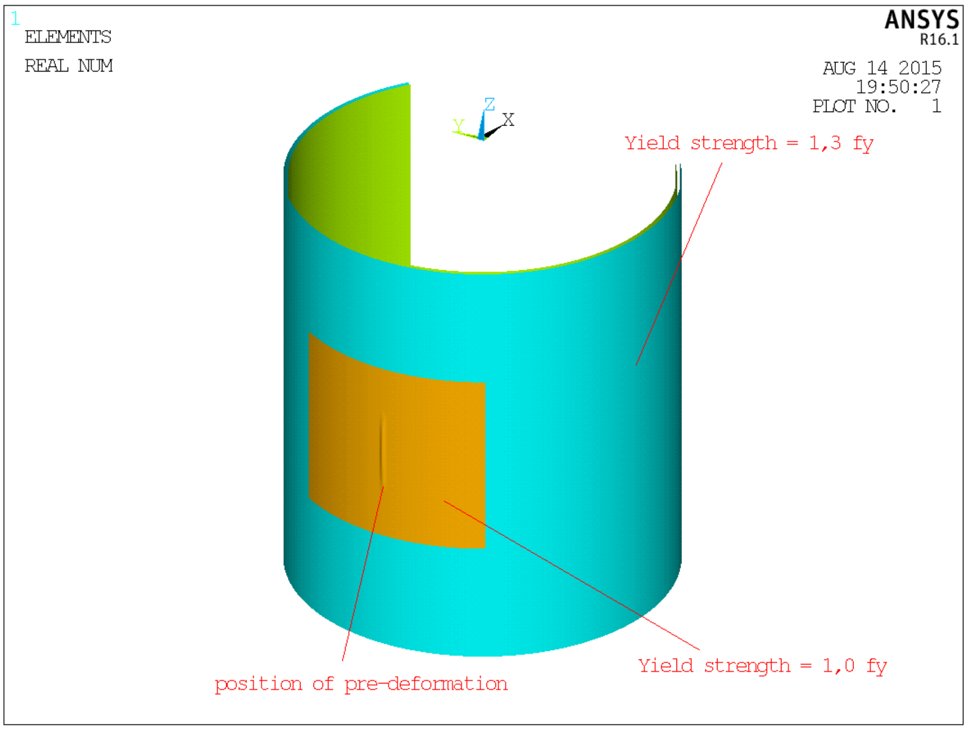


Fig. 5-18: Position of pre-deformation, numerical model 1g

Numerical model No. 1h

Exterior cylinder, longitudinal pre-deformation between two columns of headed studs

One single buckle (pre-deformation) in the middle of the cylindrical liner sheet; the dimension of the buckle is 2000 mm x 150 mm (area between headed studs), the height is 2,4 mm, class B: 2.4 / 150 = 0,016 [C 05], (8.7.2). This analysis contains the liner sheets of the exterior cylinder with a radius of 9500 mm.

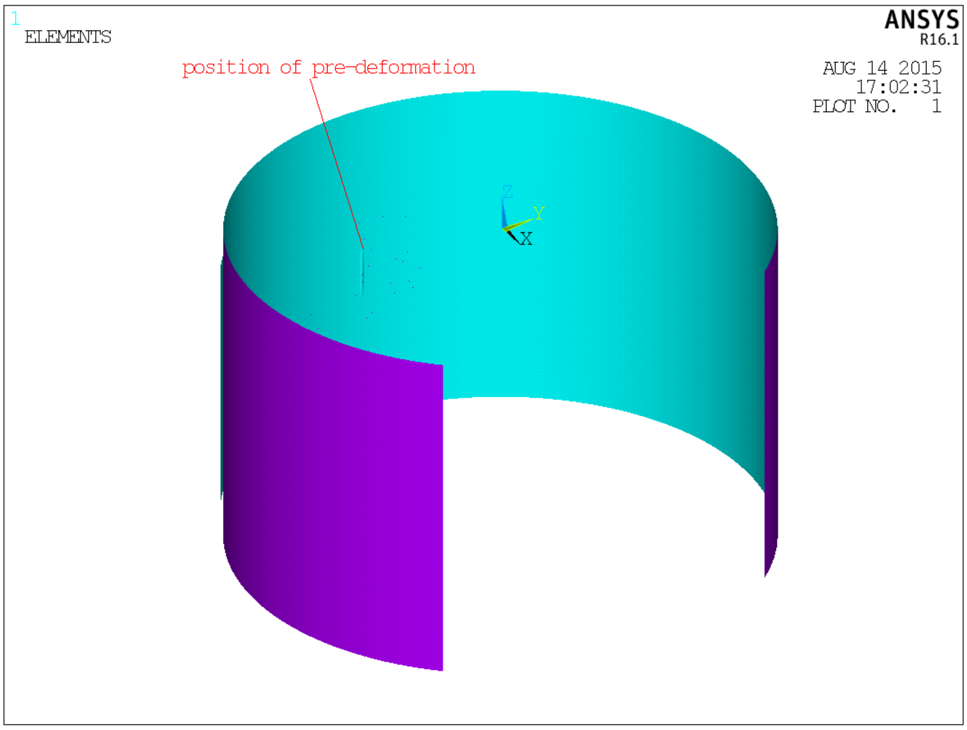


Fig. 5-19: Position of pre-deformation, numerical model 1h

5.3 Loads

5.3.1 General

([C 01], CC3130):

The following load condition is considered for the design of this liner structure:

LOCA: The “abnormal or extremely rare”- condition

For these different plant conditions, the following actions will be differentiated:

Permanent actions G_k
Variable actions Q_k
Accidental actions A_k

Service load category

Service loads are any loads encountered during the normal operation of a nuclear power plant.

Factored load category

Factored loads include loads encountered infrequently, such as severe environmental, extreme environmental and abnormal loads.

Serviceability

Serviceability defines behaviour for service or factored load conditions that are not defined by strength or stress limitations.

([C 01], CC3136):

Primary force

Primary force is a local, internal force (N/m) or moment (N-m/m) which is required to equilibrate applied loads.

Secondary force

Secondary force is a local, internal force (N/m) or moment (N-M/m) that is not required for equilibrating the applied loads. Thus, a secondary force may be either:

(a) a local, internal force or moment that results from applied loads, but is not required to equilibrate such loads, or

(b) a local, internal force or moment that results from nonload, volume change effects, such as shrinkage strain and thermal strain.

5.3.2 Permanent actions G_k

For the computation of the cylindrical liner models no self-weight of the structure is considered.

5.3.3 Varable actions Q_k

i) Assumptions for LOCA:

For this calculation the specified temperature difference is classified as an accidental or abnormal load.

Temperature load: T_{LOCA} = 152 – 25 = 127 K
Safety factor: γ = 1.0

5.3.4 Load combinations

The load combinations and load factors for the containment design can be found in table CC-3230-1 of ASME code [C 01]. For the calculation of the steel liner according to chapter CC-3720, these combinations can be used and all load factors are taken equal to 1.0.

In detail: LC for LOCA: T_{LOCA}

Due to the fact that the computation is nonlinear, the loads have to be combined in one single loadcase.

5.3.5 Initial strain

Based on the connection between liner and concrete structure by the use of anchors there is an interaction among these two structural members.
So if calculating the liner the concrete strains on the surface faced to the liner sheets have to be included.
This strain is applied on the FE-model of the steel liner via a supplementary temperature.

The initial strain of the cylindrical part of the liner is composed of three different parts, as described in [D 10].

- Concrete strains due to shrinkage: ε_{cs} = 0,40 ‰
- Concrete strains due to creeping: ε_{cc} = 0,35 ‰
- Concrete strains during operational or accidental situations: $\varepsilon_{c,LOCA}$ = 0.23 ‰

<u>Numerical models No. 1a – 1i</u>

i) Assumptions for LOCA:

The total concrete compressive strain ε_c which is taken as the initial steel liner strain ε_s for the containment cylindrical liner calculation for LOCA can be summed up as follows:

$$\varepsilon_s = \Sigma\, \varepsilon_c = \varepsilon_{cs} + \varepsilon_{cc} + \varepsilon_{c,LOCA} = -0{,}40\ ‰ - 0{,}35\ ‰ - 0{,}23\ ‰ = -0.98\ ‰ = -1{,}0\ ‰$$

This strain has to be converted into an equivalent temperature of 83,0 K, which then is added to the temperature load from LOCA.

5.3.6 Boundary comditions

Numerical models No. 1a – 1g

The support conditions indicated below have been utilized for the analysed numeric model of the cylindrical part of the liner. The link and spring elements of the anchor plates and the headed studs are supported in x-, y- and z-direction; they are not part of the following picture.

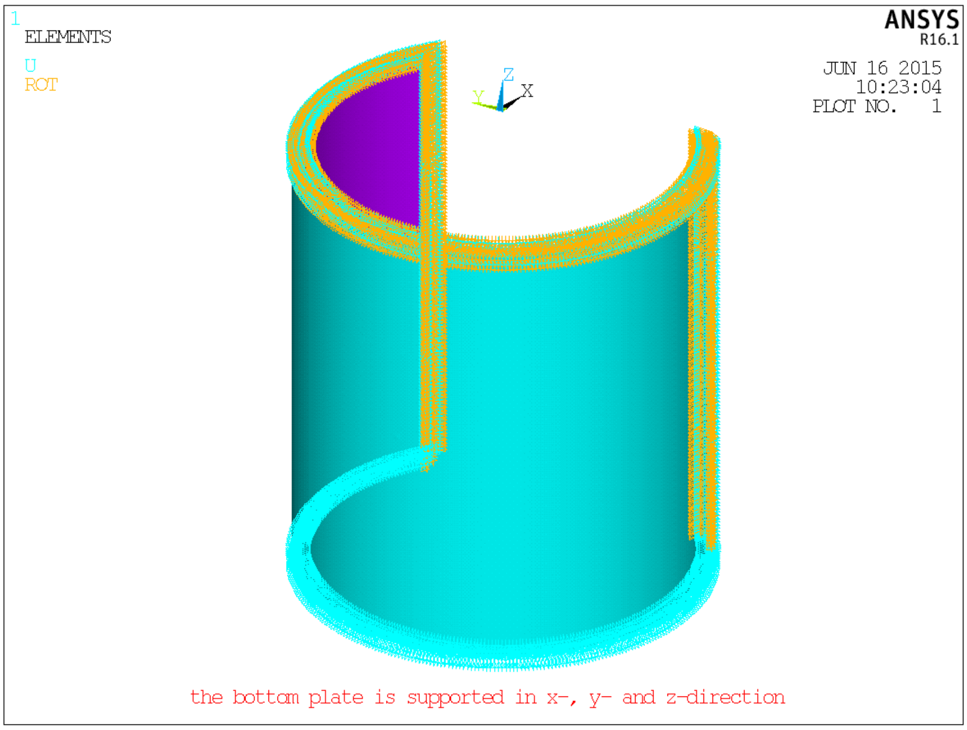


Fig. 5-20: Boundary conditions of numerical models No. 1a – 1g

Numerical model No. 1h)

The support conditions indicated below have been utilized for the analysed numeric model of the cylindrical part of the liner. The link and spring elements of the anchor plates and the headed studs are supported in x-, y- and z-direction; they are not part of the following picture.

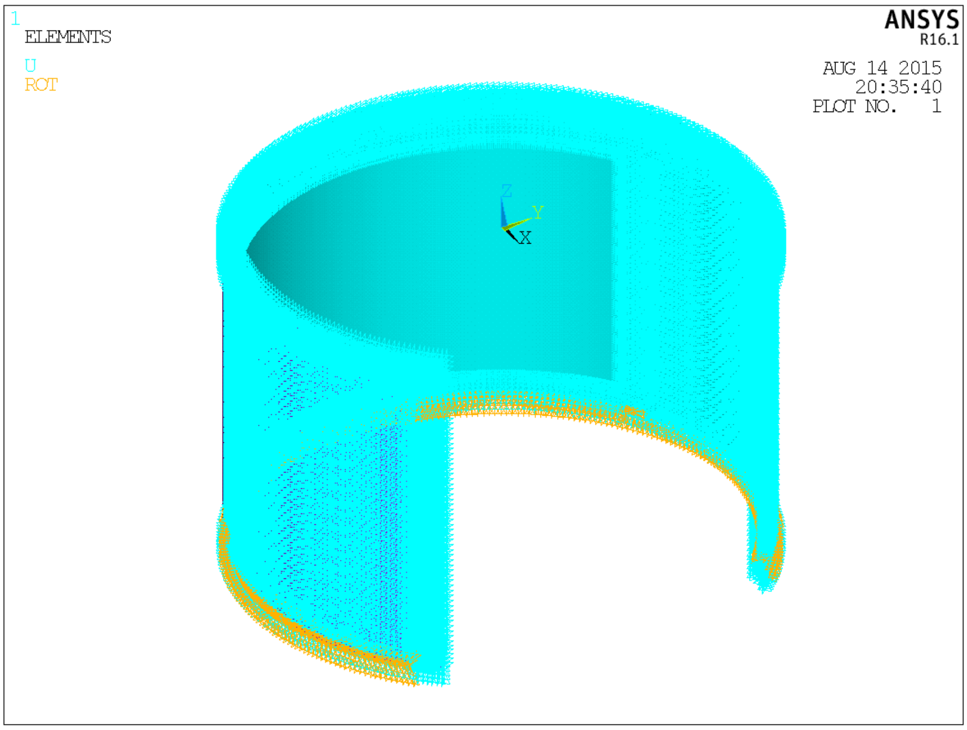


Fig. 5-21: Boundary conditions of numerical models No. 1h

6. Summary of results

6.1 Displacements and forces at anchor plates and headed studs

6.1.1 General

Cylindrical parts of Liner

The following pages contain the must unfavourable displacements and forces of all anchor plates combined in one table, separated for the models 1a – 1h.
For the dimensioning of the anchor plates, these most disadvantageous values have to be taken into account. The complete results of the analysises can be found in Appendix A.

For LOCA the **displacement limited loads** have to be considered and therefore only the displacements are given in tabular form.

All following results (as well as in Appendix A) are given in a **global cylindrical coordinate system** with the x-axis in radial direction, the y-axis in tangential direction and the z-axis in vertical direction. The origin of the coordinate system is in the center of the whole containment liner structure.

Note: The coordinate system of the headed studs / anchor plates of the cylindrical part is as follows: headed studs in longitudinal direction = x-direction).

In principle the displacements and forces indicated in the subsequent tables **can occur on every anchor plate** (node number), not only on the indicated anchor plates (node numbers) – depending on the pre-deformation.

The results are given for the following numerical models:

Numerical models 1a – 1g: Interior cylinder with radius 4200 mm

Numerical model 1h: Exterior cylinder with radius 9500 mm

Numerical model 1i: Exterior cylinder with radius 9500 mm at hatch -10,10 m:
By looking at the results of computational model 1i, it has to be considered that some of the reinforcing elements of the hatch (e.g. the steel case of the penetration) are not part of the numerical model and so the results are unfavourable.

6.1.2 Node numbers of anchor plates

<u>Cylindrical part of Liner, interior cylinder</u>

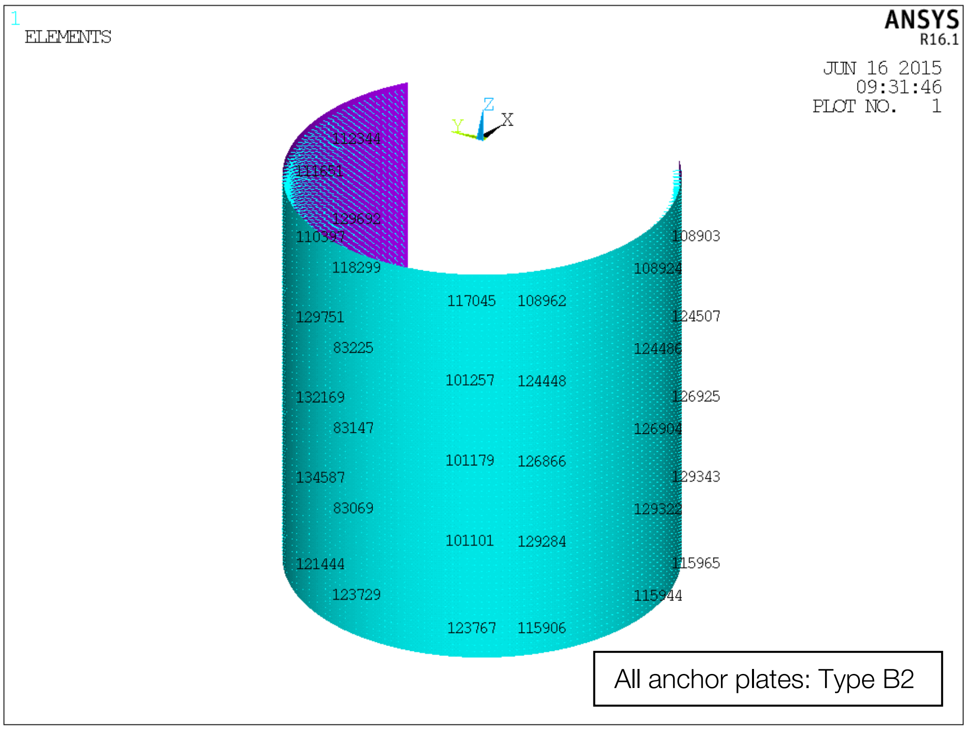


Fig. 6-1: Node numbering of anchor plates, Numerical model No. 1a (1) (examplary)

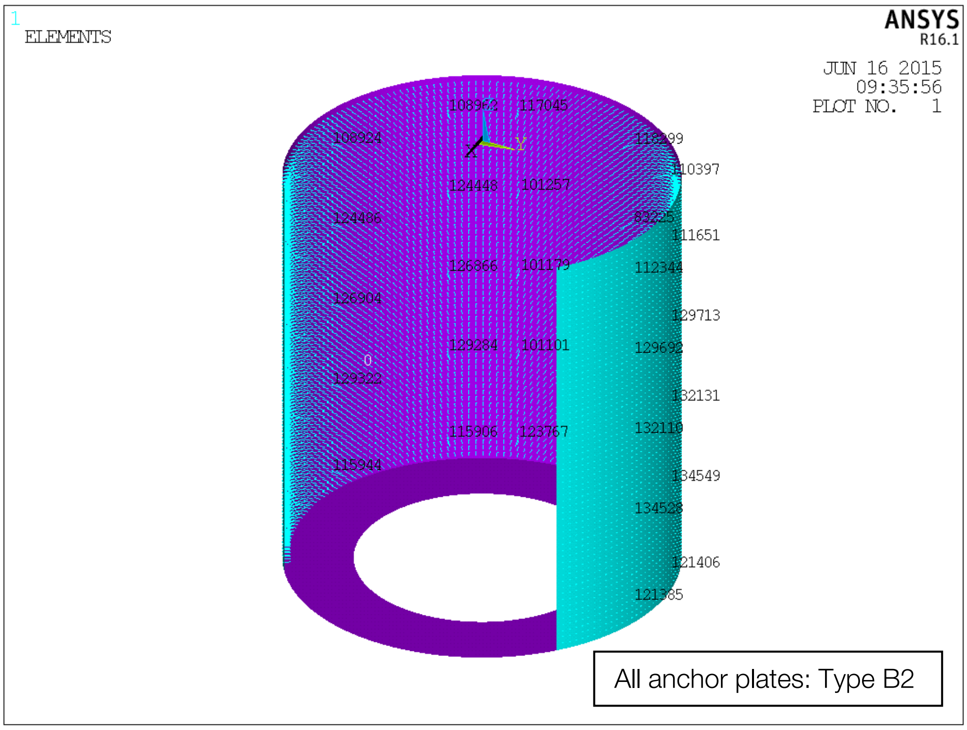


Fig. 6-2: Node numbering of anchor plates, Numerical model No. 1a (2) (examplary)

6.1.3 Displacements of anchor plates – cylindrical part of the liner – at LOCA

Numerical model No. 1a

- The following table indicates the displacements of the anchor plates of numerical model No. 1a, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	121444	101101	83069	121444
Value	0,44	0,00	0,01	0,44

Numerical model No. 1b

- The following table indicates the displacements of the anchor plates of numerical model No. 1b, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	121444	101101	83069	121444
Value	0,44	0,00	0,01	0,44

Numerical model No. 1c

- The following table indicates the displacements of the anchor plates of numerical model No. 1c, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	81778	99392	99316	81778
Value	0,45	0,00	0,01	0,45

Numerical model No. 1d

- The following table indicates the displacements of the anchor plates of numerical model No. 1d, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	116392	97967	86676	116392
Value	0,44	0,00	0,01	0,44

Numerical model No. 1e

- The following table indicates the displacements of the anchor plates of numerical model No. 1e, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	110714	96251	96407	110714
Value	0,44	0,00	0,01	0,44

Numerical model No. 1f

- The following table indicates the displacements of the anchor plates of numerical model No. 1f, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	129322	87572	105448	129322
Value	0,44	0,00	0,01	0,44

Numerical model No. 1g

- The following table indicates the displacements of the anchor plates of numerical model No. 1g, global polar coordinate system, LOCA

Anchor plates type B2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	123729	105604	87416	123729
Value	0,44	0,00	0,01	0,44

Numerical model No. 1h

- The following table indicates the displacements of the anchor plates of numerical model No. 1h, global polar coordinate system, LOCA

Anchor plates type A2:

All anchor plates are calculated as anchor plates A2.

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	117722	123839	137776	117722
Value	-0,44	0,00	-0,01	-0,44

Numerical model No. 1i

- The following table indicates the displacements of the anchor plates of numerical model No. 1i, global polar coordinate system, LOCA

Anchor plates type A1 and A2:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	57215	57215	58345	57215
Value	0,00	0,15	-0,03	-0,15

6.1.4 Displacements of headed studs – cylindrical part of the liner – at LOCA

The complete results of the analysises are not represented in Appendix A; due to the numerousness of headed studs in the model this would go beyond the scope.

Numerical model No. 1a

- The following table indicates the displacements of the headed studs of numerical model No. 1a, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,15	-0,22	0,00
MAX Value	0,44	0,15	0,22	0,44

Numerical model No. 1b

- The following table indicates the displacements of the headed studs of numerical model No. 1b, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,57	-0,22	0,00
MAX Value	0,44	0,57	0,25	0,66

Numerical model No. 1c

- The following table indicates the displacements of the headed studs of numerical model No. 1c, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,32	-0,30	0,00
MAX Value	0,45	0,28	0,26	0,52

Numerical model No. 1d

- The following table indicates the displacements of the headed studs of numerical model No. 1d, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,15	-0,22	0,00
MAX Value	0,44	0,15	0,23	0,44

Numerical model No. 1e

- The following table indicates the displacements of the headed studs of numerical model No. 1e, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,60	-0,27	0,00
MAX Value	0,44	0,61	0,24	0,70

Numerical model No. 1f

- The following table indicates the displacements of the headed studs of numerical model No. 1f, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,55	-0,66	0,00
MAX Value	0,44	0,55	0,66	0,77

Numerical model No. 1g

- The following table indicates the displacements of the headed studs of numerical model No. 1g, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,66	-0,73	0,00
MAX Value	0,44	0,66	0,73	0,78

Numerical model No. 1h

- The following table indicates the displacements of the headed studs of numerical model No. 1h, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-0,56	-0,09	0,00
MAX Value	-0,44	0,57	0,09	0,66

Numerical model No. 1i

- The following table indicates the displacements of the headed studs of numerical model No. 1i, global polar coordinate system, LOCA.

Headed studs:

Node	ux (mm)	uy (mm)	uz (mm)	usum (mm)
Maximum absolute values				
Node	any	any	any	any
MIN Value	0,00	-2,50	-1,61	-2,50
MAX Value	0,00	2,50	0,96	2,50

6.1.5 Forces of headed studs – cylindrical part of the liner – at LOCA

The complete results of the analysises are not represented in Appendix A; due to the numerousness of headed studs in the model this would go beyond the scope.

Numerical model No. 1a

- The following table indicates the forces of the headed studs of numerical model No. 1a, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-23,32	-21,52	-25,23
MAX Value	0,00	21,47	25,14

Numerical model No. 1b

- The following table indicates the forces of the headed studs of numerical model No. 1b, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-27,45	-35,19	-25,96
MAX Value	0,00	35,19	25,21

Numerical model No. 1c

- The following table indicates the forces of the headed studs of numerical model No. 1c, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-32,25	-26,81	-26,43
MAX Value	0,00	27,93	27,46

Numerical model No. 1d

- The following table indicates the forces of the headed studs of numerical model No. 1d, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-23,30	-21,49	-25,26
MAX Value	0,00	21,45	24,96

Numerical model No. 1e

- The following table indicates the forces of the headed studs of numerical model No. 1e, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-28,89	-35,84	-25,75
MAX Value	0,00	35,82	26,71

Numerical model No. 1f

- The following table indicates the forces of the headed studs of numerical model No. 1f, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-33,48	-34,93	-36,88
MAX Value	0,00	34,93	36,78

Numerical model No. 1g

- The following table indicates the forces of the headed studs of numerical model No. 1g, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-26,23	-36,86	-37,61
MAX Value	0,00	36,88	37,61

Numerical model No. 1h

- The following table indicates the forces of the headed studs of numerical model No. 1h, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-1,74	-35,16	-16,16
MAX Value	24,75	35,16	16,16

Numerical model No. 1i

- The following table indicates the forces of the headed studs of numerical model No. 1i, global polar coordinate system, LOCA.

Headed studs:

	Fx (kN)	Fy (kN)	Fz (kN)
Total values			
MIN Value	-32,60	-49,19	-41,34
MAX Value	41,30	49,20	47,49

6.2 Stresses, strains and displacements of numerical model

6.2.1 Results of cylindrical part of the liner at LOCA

Numerical model No. 1a

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1a, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
259,3	287,8

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0132	0,0209
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0014	0,0015
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0118	0,0194

Displacements of liner [mm]	
u_x (min - max)	
-0,35	5,81
u_y (min - max)	
-0,24	0,24
u_z (min - max)	
-0,35	0,35

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,15	0,15
u_z (min - max)	
-0,22	0,22
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,01

Numerical model No. 1b

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1b, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
259,3	298,1

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0192	0,0286
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0015	0,0015
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0178	0,0271

Displacements of liner [mm]	
u_x (min - max)	
-0,47	7,79
u_y (min - max)	
-0,77	0,77
u_z (min - max)	
-0,35	0,36

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,57	0,57
u_z (min - max)	
-0,22	0,25
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,01

Numerical model No. 1c

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1c, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
259,3	295,1

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0160	0,0255
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0014	0,0015
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0146	0,0240

Displacements of liner [mm]	
u_x (min - max)	
-0,45	11,69
u_y (min - max)	
-0,43	0,38
u_z (min - max)	
-0,45	0,43

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,45
u_y (min - max)	
-0,32	0,28
u_z (min - max)	
-0,30	0,26
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,45
u_y (min - max)	
0,00	0,00
u_z (min - max)	
0,00	0,01

Numerical model No. 1d

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1d, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
259,3	287,8

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0132	0,0209
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0014	0,0015
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0118	0,0194

Displacements of liner [mm]	
u_x (min - max)	
-0,35	5,79
u_y (min - max)	
-0,24	0,24
u_z (min - max)	
-0,34	0,35

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,15	0,15
u_z (min - max)	
-0,22	0,23
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,01

Numerical model No. 1e

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1e, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top,\ bot}$
259,3	298,0

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top,\ bot}$
0,0199*	0,0298
$epel,eqv_{mid}$	$epel,eqv_{top,\ bot}$
0,0015	0,0016
$eppl,eqv_{mid}$	$eppl,eqv_{top,\ bot}$
0,0185	0,0282

Displacements of liner [mm]	
u_x (min - max)	
-0,50	8,01
u_y (min - max)	
-0,78	0,78
u_z (min - max)	
-0,42	0,38

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,60	0,61
u_z (min - max)	
-0,27	0,24
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,01

*This value exceeds the admissible strain and it is caused by the specific form of the liner sheet and the buckle with a sharp edge at this point. This edge generates extreme strains in a very small area, which are not realistic.

Numerical model No. 1f

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1f, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
259,2	311,0

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0228*	0,0359
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0015	0,0016
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0213	0,0343

Displacements of liner [mm]	
u_x (min - max)	
-0,55	8,53
u_y (min - max)	
-0,75	0,75
u_z (min - max)	
-0,93	0,93

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,55	0,55
u_z (min - max)	
-0,66	0,66
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
0,00	0,01

*This value exceeds the admissible strain and it is caused by the specific form of the liner sheet and the buckle with a sharp edge at this point. This edge generates extreme strains in a very small area, which are not realistic.

Numerical model No. 1g

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1g, LOCA

Stresses von Mises [N/mm²]	
s,eqv$_{mid}$	s,eqv$_{top, bot}$
259,3	286,1

Strains von Mises [-]	
epto,eqv$_{mid}$	epto,eqv$_{top, bot}$
0,0221*	0,0349
epel,eqv$_{mid}$	epel,eqv$_{top, bot}$
0,0014	0,0015
eppl,eqv$_{mid}$	eppl,eqv$_{top, bot}$
0,0210	0,0336

Displacements of liner [mm]	
u_x (min - max)	
-0,57	8,23
u_y (min - max)	
-0,80	0,79
u_z (min - max)	
-1,00	1,00

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
-0,66	0,66
u_z (min - max)	
-0,73	0,73
Displacements of anchors B2 [mm]	
u_x (min - max)	
0,00	0,44
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,01

*This value exceeds the admissible strain and it is caused by the specific form of the liner sheet and the buckle with a sharp edge at this point. This edge generates extreme strains in a very small area, which are not realistic.

Numerical model No. 1h

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1h, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
260,1	303,5

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0211*	0,0320
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0015	0,0016
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0196	0,0304

Displacements of liner [mm]	
u_x (min - max)	
-7,67	0,46
u_y (min - max)	
-0,78	0,78
u_z (min - max)	
-0,20	0,20

Displacements headed studs [mm]	
u_x (min - max)	
-0,44	0,00
u_y (min - max)	
-0,56	0,57
u_z (min - max)	
-0,09	0,09
Displacements of anchors A2 [mm]	
u_x (min - max)	
-0,44	0,00
u_y (min - max)	
0,00	0,00
u_z (min - max)	
-0,01	0,00

*This value exceeds the admissible strain and it is caused by the specific form of the liner sheet and the buckle with a sharp edge at this point. This edge generates extreme strains in a very small area, which are not realistic.

Numerical model No. 1i

- The following figures indicate the total membrane and membrane and bending stresses of the liner sheets of numerical model No. 1i, LOCA

Stresses von Mises [N/mm²]	
s,eqv_{mid}	$s,eqv_{top, bot}$
285,3	298,6

Strains von Mises [-]	
$epto,eqv_{mid}$	$epto,eqv_{top, bot}$
0,0251*	0,0298
$epel,eqv_{mid}$	$epel,eqv_{top, bot}$
0,0015	0,0015
$eppl,eqv_{mid}$	$eppl,eqv_{top, bot}$
0,0236	0,0282

Displacements of liner [mm]	
u_x (min - max)	
-0,74	1,96
u_y (min - max)	
-5,21	5,21
u_z (min - max)	
-4,56	3,55

Displacements headed studs [mm]	
u_x (min - max)	
0,00	0,00
u_y (min - max)	
-2,50	2,49
u_z (min - max)	
-1,61	0,96
Displacements of anchors A1, A2 [mm]	
u_x (min - max)	
0,00	0,00
u_y (min - max)	
-0,12	0,15
u_z (min - max)	
-0,03	0,01

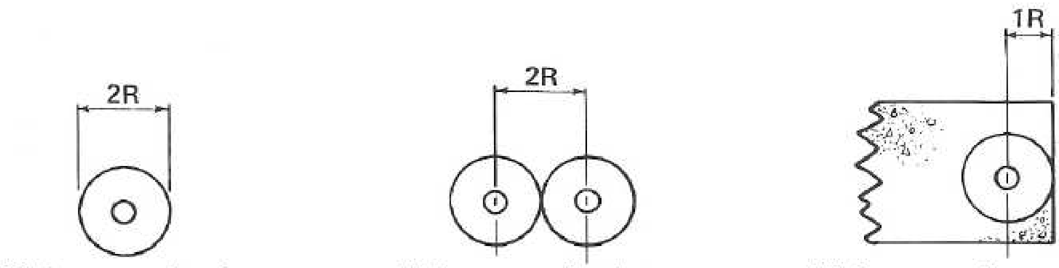
*This value exceeds the admissible strain and it is caused by the specific form of the liner sheet with a sharp edge at this point. This edge generates extreme strains in a very small area, which are not realistic.

6.3 Analysis of headed studs at LOCA

6.3.1 Verification of anchor spacing of headed studs

The following table indicates the spacing for full tension capacity development of stock size headed anchors; anchor spacing (R) in Inches [C 08], table 6:

Anchor Size	Normal Weight Concrete			Sand Lightweight Concrete			All Lightweight Concrete		
	3000 psi	4000 psi	5000 psi	3000 psi	4000 psi	5000 psi	3000 psi	4000 psi	5000 psi
1/4 x 2 11/16	1.535 in.	1.330 in.	1.190 in.	1.808 in.	1.566 in.	1.401 in.	2.047 in.	1.774 in.	1.587 in.
1/4 x 4 1/8	1.535	1.330	1.190	1.808	1.566	1.401	2.047	1.774	1.587
3/8 x 4 1/8	2.305	1.997	1.786	2.712	2.348	2.100	3.073	2.662	2.381
3/8 x 6 1/8	2.305	1.997	1.786	2.712	2.348	2.100	3.073	2.662	2.381
1/2 x 2 1/8	2.188	2.188	2.188	2.188	2.188	2.188	2.188	2.188	2.188
1/2 x 3 1/8	3.188	3.188	3.188	3.188	3.188	3.188	3.188	3.188	3.188
1/2 x 4 1/8	3.070	2.661	2.380	3.613	3.131	2.800	4.096	3.548	3.174
1/2 x 5 5/16	3.070	2.661	2.380	3.613	3.131	2.800	4.096	3.548	3.174
1/2 x 6 1/8	3.070	2.661	2.380	3.613	3.131	2.800	4.096	3.548	3.174
1/2 x 8 1/8	3.070	2.661	2.380	3.613	3.131	2.800	4.096	3.548	3.174
5/8 x 2 11/16	2.813	2.813	2.813	2.813	2.813	2.813	2.813	2.813	2.813
5/8 x 6 9/16	3.843	3.327	2.976	4.520	3.914	3.500	5.122	4.436	3.968
5/8 x 8 3/16	3.843	3.327	2.976	4.520	3.914	3.500	5.122	4.436	3.968
3/4 x 3 3/16	3.250	3.250	3.250	3.250	3.250	3.250	3.250	3.250	3.250
3/4 x 3 11/16	3.750	3.750	3.750	3.750	3.750	3.750	3.750	3.750	3.750
3/4 x 4 3/16	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250
3/4 x 5 3/16	5.250	3.992	3.571	5.250	5.250	5.250	5.250	5.250	5.250
3/4 x 6 3/16	4.610	3.992	3.571	5.424	4.697	4.201	6.147	5.323	4.761
3/4 x 7 3/16	4.610	3.992	3.571	5.424	4.697	4.201	6.147	5.323	4.761
3/4 x 8 3/16	4.610	3.992	3.571	5.424	4.697	4.201	6.147	5.323	4.761
7/8 x 3 11/16	3.813	3.813	3.813	3.813	3.813	3.813	3.813	3.813	3.813
7/8 x 4 3/16	4.313	4.313	4.313	4.313	4.313	4.313	4.313	4.313	4.313
7/8 x 5 3/16	5.313	5.313	5.313	5.313	5.313	5.313	5.313	5.313	5.313
7/8 x 6 3/16	5.377	4.657	4.167	6.313	6.313	4.901	6.313	6.313	6.313
7/8 x 7 3/16	5.377	4.657	4.167	6.326	5.479	4.901	7.169	6.210	5.555
7/8 x 8 3/16	5.377	4.657	4.167	6.326	5.479	4.901	7.169	6.210	5.555



Minimum spacing for single anchor = 2R

Minimum spacing between anchors = 2R

Minimum spacing, center of anchor to free edge = 1R

For headed studs with the dimension of ½ x 6 1/8” (13 x 150 mm) and a concrete of 5000 psi:
R: 2,38 in. = 60,5 mm ≤ 150 mm

The spacing of 150 mm between the studs is sufficient to develop the full tension capacity.

6.3.2 Verification of headed studs

Due to the load and support conditions and the pre-deformation of the containment liner, there arise forces in perpendicular direction (=longitudinal direction of the headed studs) which are assumed to be transferred into the headed studs. So the verification of the headed studs with the appropriate forces is listed in the following.

The following table indicates the design embedded tension capacities of stock size headed anchors; full shear cone area development [C 08], table 4:

(1.) Anchor Size	(2.) A.W. Length	Head Diameter	Head Thickness	Le (in.)	Ultimate Embedded Strength of Anchor (Pue) Kips	Tension Capacity (Puc)* — Kips (3.) f'c = 3000 psi NWT	(3.) f'c = 4000 psi NWT	(3.) f'c = 5000 psi NWT	(4.) f'c = 3000 psi SLWT	(4.) f'c = 4000 psi SLWT	(4.) f'c = 5000 psi SLWT	(5.) f'c = 3000 psi ALWT	(5.) f'c = 4000 psi ALWT	(5.) f'c = 5000 psi ALWT
¼ x 2 11/16	2 9/16	.500	.187	2⅜	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
¼ x 4⅛	4	.500	.187	3 13/16	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
⅜ x 4⅛	4	.750	.281											
⅜ x 6⅛	6	.750	.281	3 23/32	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96
				5 23/32	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96
½ x 2⅛	2	1.00	.312	1 11/16	10.60	3.75	4.33	4.84	3.18	3.68	4.11	2.81	3.25	3.63
½ x 3⅛	3	1.00	.312	2 11/16	10.60	8.20	9.46	10.58	6.97	8.04	8.99	6.15	7.10	7.94
½ x 4⅛	4	1.00	.312	3 11/16	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60
½ x 5 5/16	5 3/16	1.00	.312	4⅞	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60
½ x 6⅛	6	1.00	.312	5 11/16	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60
½ x 8⅛	8	1.00	.312	7 11/16	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60	10.60
⅝ x 2 11/16	2½	1.250	.312	2 3/16	16.56	6.22	7.18	8.00	5.29	6.10	6.80	4.65	5.39	6.00
⅝ x 6 9/16	6⅜	1.250	.312	6 1/16	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56
⅝ x 8 3/16	8	1.250	.312	7 11/16	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56	16.56
¾ x 3 3/16	3	1.250	.375	2⅝	23.86	8.41	9.71	10.86	7.15	8.25	9.23	6.31	7.28	8.15
¾ x 3 11/16	3½	1.250	.375	3⅛	23.86	11.31	13.05	14.60	9.61	11.09	12.41	8.48	9.79	10.95
¾ x 4 3/16	4	1.250	.375	3⅝	23.86	14.62	16.87	18.87	12.43	14.34	16.04	10.97	12.65	14.15
¾ x 5 3/16	5	1.250	.375	4⅝	23.86	22.48	23.86	23.86	19.11	22.05	23.86	16.86	19.46	21.76
¾ x 6 3/16	6	1.250	.375	5⅝	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86
¾ x 7 3/16	7	1.250	.375	6⅝	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86
¾ x 8 3/16	8	1.250	.375	7⅝	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86	23.86
⅞ x 3 11/16	3½	1.375	.375	3⅛	32.47	11.63	13.43	15.01	9.89	11.42	12.76	8.72	10.07	11.26
⅞ x 4 3/16	4	1.375	.375	3⅝	32.47	15.00	17.30	19.35	12.75	14.71	16.45	11.25	12.98	14.51
⅞ x 5 3/16	5	1.375	.375	4⅝	32.47	22.96	26.49	29.63	19.52	22.52	25.19	17.22	19.87	22.22
⅞ x 6 3/16	6	1.375	.375	5⅝	32.47	32.47	32.47	32.47	27.68	31.95	32.47	24.43	28.19	31.53
⅞ x 7 3/16	7	1.375	.375	6⅝	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47
⅞ x 8 3/16	8	1.375	.375	7⅝	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47	32.47

NOTES: (1.) Stock Anchor Sizes
(2.) A.W. — Length overall after welding to plate
(3.) NWT — Normal weight concrete (C = 1.0)
(4.) SLWT — Sand Lightweight Concrete (C = 0.85)
(5.) ALWT — All Lightweight Concrete (C = 0.75)
*Puc — From equation 5., Section 3.1 (where Puc > Pue, Pue controls.)

For headed studs with the dimension of ½ x 6 1/8" (13 x 150 mm) and a concrete of 5000 psi:
PUC: 10,60 kips = 47,2 kN ≥ 33,5 kN [6.1.5], respectively ≥ 41,3 kN.

The resulting tension force is less than the tension capacity of the headed stud.

The following table indicates the single reduction values for various edge distances in 5000 psi normal weight concrete [C 08], table 11:

Anchor Size	Radius N.W.C.(1.)	Tension Capacity (2.) Kips	Afc	Reduction To Tension Capacity (Kips) — Distance From Center Of Anchor To Free Edge (Inches) De: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1/4 x 2 11/16	1.190 in.	2.65	11.0	1.11	.58	0	0	0	0	0	0	0	0
1/4 x 4 1/8	1.190	2.65	11.0	1.11	.58	0	0	0	0	0	0	0	0
3/8 x 4 1/8	1.786	5.96	24.8	2.89	2.12	1.30	0	0	0	0	0	0	0
3/8 x 6 1/8	1.786	5.96	24.8	2.89	2.12	1.30	0	0	0	0	0	0	0
1/2 x 2 1/8	2.188	4.84	20.1	—	2.04	1.36	.59	0	0	0	0	0	0
1/2 x 3 1/8	3.188	10.58	44.0	—	5.19	4.26	3.25	2.17	1.00	0	0	0	0
1/2 x 4 1/8	2.380	10.60	44.1	—	4.46	3.42	2.32	0	0	0	0	0	0
1/2 x 5 5/16	2.380	10.60	44.1	—	4.46	3.42	2.32	0	0	0	0	0	0
1/2 x 6 1/8	2.380	10.60	44.1	—	4.46	3.42	2.32	0	0	0	0	0	0
1/2 x 8 1/8	2.380	10.60	44.1	—	4.46	3.42	2.32	0	0	0	0	0	0
5/8 x 2 11/16	2.813	8.00	33.3	—	3.81	2.98	2.07	.89	0	0	0	0	0
5/8 x 6 9/16	2.976	16.56	68.9	—	7.60	6.33	5.00	3.62	0	0	0	0	0
5/8 x 8 3/16	2.976	16.56	68.9	—	7.60	6.33	5.00	3.62	0	0	0	0	0
3/4 x 3 3/16	3.250	10.86	45.2	—	—	4.48	3.47	2.37	1.19	0	0	0	0
3/4 x 3 11/16	3.750	14.60	60.7	—	—	6.47	5.34	4.12	2.82	1.45	0	0	0
3/4 x 4 3/16	4.250	18.87	78.5	—	—	8.79	7.53	6.20	4.79	3.29	1.71	0	0
3/4 x 5 3/16	3.571	23.86	99.2	—	—	10.04	8.49	6.88	5.22	3.50	0	0	0
3/4 x 6 3/16	3.571	23.86	99.2	—	—	10.04	8.49	6.88	5.22	3.50	0	0	0
3/4 x 7 3/16	3.571	23.86	99.2	—	—	10.04	8.49	6.88	5.22	3.50	0	0	0
3/4 x 8 3/16	3.571	23.86	99.2	—	—	10.04	8.49	6.88	5.22	3.50	0	0	0
7/8 x 3 11/16	3.813	15.01	62.4	—	—	6.76	5.62	4.39	3.09	1.69	0	0	0
7/8 x 4 3/16	4.313	19.35	80.5	—	—	9.12	7.86	6.52	5.08	3.58	2.00	0	0
7/8 x 5 3/16	5.313	29.63	123.2	—	—	14.81	13.31	11.73	10.06	8.31	6.50	4.59	2.60
7/8 x 6 3/16	4.167	32.47	135.0	—	—	14.55	12.76	10.92	9.04	7.09	5.09	0	0
7/8 x 7 3/16	4.167	32.47	135.0	—	—	14.55	12.76	10.92	9.04	7.09	5.09	0	0
7/8 x 8 3/16	4.167	32.47	135.0	—	—	14.55	12.76	10.92	9.04	7.09	5.09	0	0

Notes: (1.) Radius Or R From Table 6., Section 4.6.
(2.) Tension Capacity Puc or Pue From Table 4., Section 4.5.

For headed studs with the dimension of ½ x 6 1/8" (13 x 150 mm) and a concrete of 5000 psi:
With a distance of 3 inch (=150/2) the reduction of the tension capacity of the headed stud is 0.

Shear capacities of stock size headed anchors

As described above for LOCA the **displacement limited loads** have to be considered and therefore only the displacements should be used for the analysis of the headed studs in plane direction of the liner.

Nuemrical models 1a – 1h:
As indicated in the table above [6.1.4], the maximum displacement of the headed studs is 0,45 mm (ux) perpendicular to the liner and 0,73 mm (uy, uz) in plane direction. This is far below the admissible displacement of 3 mm for abnormal loadcases [5.1.3].

Numerical model 1i:

As indicated in the table above [6.1.4], the maximum displacement of the headed studs is 2,50 mm (uy, uz) in plane direction. This is below the admissible displacement of 3 mm for abnormal loadcases [5.1.3].