5 Sectional forces in Bridge Girder K12 August 2019

K12 is chosen as the preferred option, and the latest results from the files ShipCollision_K12_06 and K12_07_PROD_load_combinations_bridge_direct_expected_max are shown below.

Ship coll	**N**	**Mz**	**My**	**T**	**Vz**	**Vy**
Mz+	51	**5876**	346	64	-13	48
Mz-	-50	-5838	252	-92	-16	-44

ULS 3	**N**	**Mz**	**My**	**T**	**Vz**	**Vy**
Mz+	6	**2439**	-47	144	-12	11
Mz-	30	-2680	801	51	-22	-11

Units: meter and MN

Figure 5-1 Maximal forces for K12

The SLS condition with no tension in the joint is governing for prestressing between the steel girder and the abutment.

Tendons c/c 600 mm both in plates and bulkheads give space for about 170 tendons.

It is chosen to have 54 tendons 6-19 in the webs and 48 in the bottom slab. In top slab 48 tendons 6-22 for partly counteracting the permanent My moment. (6-19 means 19 strands 0.6 in diameter)

Total compression from prestressing is 536 MN after losses.

Below is shown the steel stresses in the joint for the SLS combinations. (sig P =-119 are compression stress from the tendons).

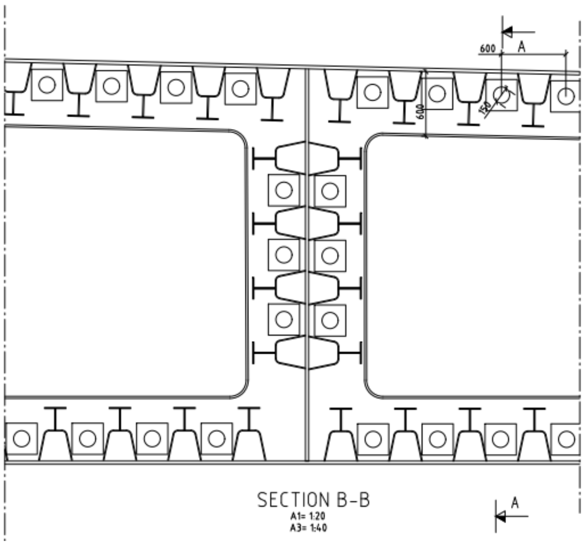
SLS	**N**	**Mz**	**My**	**sig P**	**sig N**	**sig Mz**	**sig My**	**sum MPa**
N+	39	-228	426	-141	10	8	70	-52
N-	-34	183	-51	-141	-9	7	8	-135
Mz+	4	1524	-80	-141	1	57	13	-70
Mz-	**19**	**-1675**	451	-141	5	62	74	**0**
My+	**8**	**-428**	698	-141	2	16	114	-8
My-	3	572	-281	-141	1	21	46	-73

Figure 5-2 SLSl forces and stresses.

The ALS capacity for Mz is about 8200 MNm, (1.4 x collision load).

6 Changes to Details in the end Section.

The end section is reinforced with T-stiffeners against the end plate, which has got manholes between the webs. The openings are provided with stiffening plates all around.



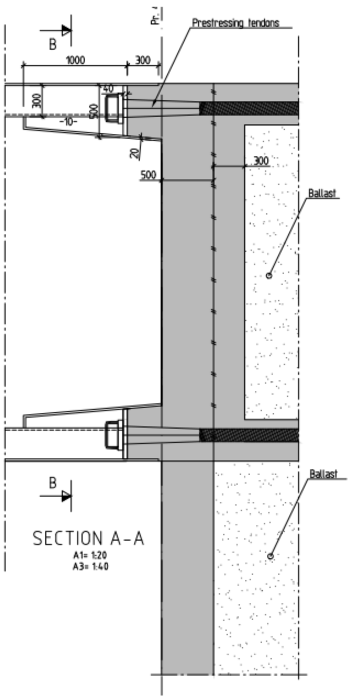


Figure 6-1 Details end section

7 Conclusion

The proposed design as shown in chapter 3 with the modifications shown in chapter 6, is found usable for transfer of forces from the floating bridge to the north abutment.

Concept development, floating bridge
E39 Bjørnafjorden

Appendix K – Enclosure 5

10205546-13-NOT-086
Column design

MEMO

PROJECT	Concept development, floating bridge E39 Bjørnafjorden	DOCUMENT CODE	10205546-13-NOT-086
CLIENT	Statens vegvesen	ACCESSIBILITY	Restricted
SUBJECT	Column design	PROJECT MANAGER	Svein Erik Jakobsen
TO	Statens vegvesen	PREPARED BY	Espen Tuveng
COPY TO		RESPONSIBLE UNIT	AMC

SUMMARY

Two different column geometries are used. One “long” column for floating bridge high part, axis 3-8, and a “short” column for floating bridge low part, axis 9-. The columns are identical for K11, K12, K13 and K14.

The columns have a rectangular section at the interface between pontoon and bridge girder. There is a transition at the bottom and top of the columns from a rectangular section to an 8-sided section used for the middle part of the columns.

A simplified screening of ULS and ALS combinations have been performed. The checks are based on elastic capacity.

Columns have sufficient capacity to withstand ULS combinations.

Ship impact will result in plastic deformations of the columns. Plate thickness can alternatively be increased from 25 mm to 40 mm for the columns to absorb more energy during an impact. Another alternative is to increase the size of the narrow middle part of the columns. This will increase the column ship impact capacity significantly, but will also increase wind drag.

1	24.05.2019	Final issue	E. Tuveng	P. N. Larsen	S. E. Jakobsen
0	29.03.2019	Status 2 issue	E. Tuveng	P. N. Larsen	S. E. Jakobsen
REV.	DATE	DESCRIPTION	PREPARED BY	CHECKED BY	APPROVED BY

1 Column properties

Two different column geometries are used. One “long” column for floating bridge high part, axis 3-8, and a “short” column for floating bridge low part, axis 9-. The column properties are identical for K11, K12, K13 and K14, only the length varies.

The columns are designed as quadratic or rectangular sections. The middle part of the columns has chamfered corners and is narrower than the top and bottom. This is done to improve wind drag, and to give the columns a more aesthetic appearance. The transition piece from a rectangular section to a chamfered section with 8-sides is designed with triangular pieces. The transition to a chamfered and narrower section is unfavorable when transferring loads through the column. From a structural design point of view, the chamfering and narrowing can be removed to increase the load bearing capacity of the columns.

Column geometry is shown in Figure 1-1 and is tabulated in Table 1-1.
Section properties are presented in Table 1-2. Section capacity calculated according to NS-EN 1993-1-1 [1], section 6 are presented in Table 1-3.

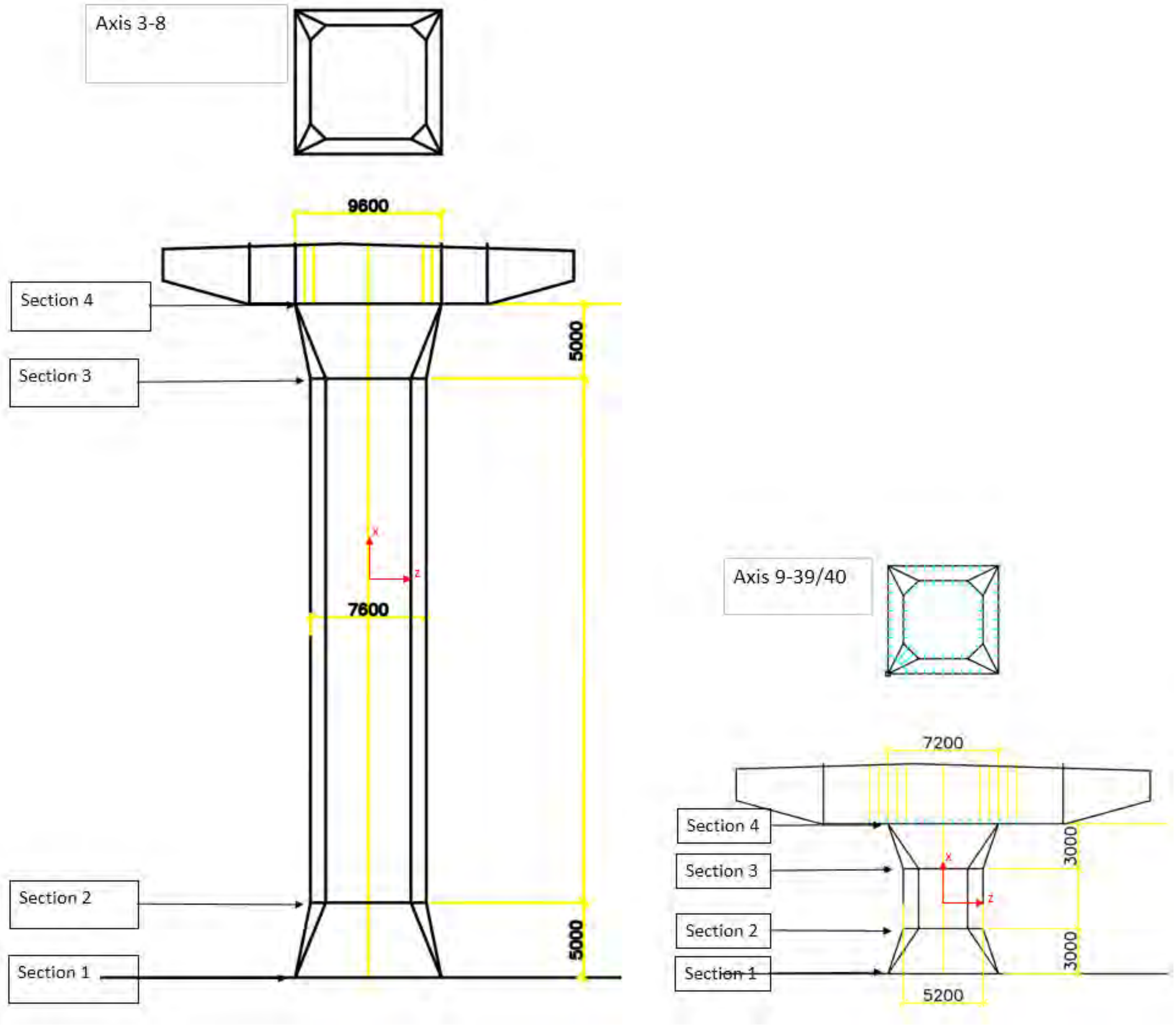


Figure 1-1 Column axis 3-8 (left) and axis 9- (right)

Table 1-1 Column geometry

Section		Section name	Overall dimensions for section		
			L (y-axis, N-S dir) [m]	W (z-axis, E-W dir) [m]	t (skin plate) [mm]
Bottom	Long column - section 1	L1	8	8	25
|	Long column - section 2	L2	7.6	7.6	25
|	Long column - section 3	L3	7.6	7.6	25
Top	Long column - section 4	L4	9.6	9.6	25
Bottom	Short column - section 1	S1	8	8	25
|	Short column - section 2	S2	6	5.2	25
|	Short column - section 3	S3	6	5.2	25
Top	Short column - section 4	S4	8	7.2	25

Table 1-2 Column section properties

Section name	A_x [m^2]	A_y [m^2]	A_z [m^2]	I_x [m^4]	I_y [m^4]	I_z [m^4]	W_y [m^3]	W_z [m^3]	2*t*AE [m^3]
L1	1.280	0.640	0.640	20.170	13.650	13.650	3.396	3.396	5.120
L2	1.122	0.608	0.608	17.280	10.120	10.120	2.650	2.650	4.621
L3	1.122	0.608	0.608	17.280	10.120	10.120	2.650	2.650	4.621
L4	1.536	0.768	0.768	34.950	23.590	23.590	4.895	4.895	7.373
S1	1.280	0.640	0.640	20.170	13.650	13.650	3.396	3.396	5.120
S2	0.802	0.480	0.416	6.804	3.398	4.164	1.297	1.379	2.496
S3	0.802	0.480	0.416	6.804	3.398	4.164	1.297	1.379	2.496
S4	1.216	0.640	0.576	17.190	10.780	12.630	2.979	3.142	4.608

N_{Rd} is calculated according to section 6.2.4 of NS-EN 1993-1-1 [1].

V_{Rd} is calculated according to section 6.2.6 of NS-EN 1993-1-1 [1].

M_{Rd} is calculated according to section 6.2.5 of NS-EN 1993-1-1 [1].

$M_{T,Rd}$ is based on Bredt's 1st formula.

Table 1-3 Column section capacities

Section name	N_{Rd} [MN]	$V_{y,pl,Rd}$ [MN]	$V_{z,pl,Rd}$ [MN]	$M_{y,Rd}$ [MNm]	$M_{z,Rd}$ [MNm]	$M_{T,Rd}$ [MNm]
L1	488.7	141.1	141.1	1 296.7	1 296.7	1 117.4
L2	428.4	134.0	134.0	1 011.8	1 011.8	1 007.9
L3	428.4	134.0	134.0	1 011.8	1 011.8	1 007.9
L4	586.5	169.3	169.3	1 869.0	1 869.0	1 611.8
S1	488.7	141.1	141.1	1 296.7	1 296.7	1 117.4
S2	306.3	105.8	91.7	495.2	526.5	542.4
S3	306.3	105.8	91.7	495.2	526.5	542.4
S4	464.3	141.1	127.0	1 137.4	1 199.7	1 005.1

1.1 Plates and stiffenening system

For columns at axis 3-8, the plate thickness is 25 mm (optionally 40 mm). The plates are stiffened by horizontal T-profiles with dimension 1000 x 300 x 10.0 x 20.0 mm, and vertical bulb-profiles with dimension BF 400 x 14.0 mm. The T-profiles have a center distance of 3000 mm. Bulb-profiles have a center distance of 600 mm.

For columns at axis 9-, the plate thickness is 25 mm (optionally 40 mm). The plates are stiffened by horizontal T-profiles with dimension 1000 x 300 x 10.0 x 20.0 mm, and vertical bulb-profiles with dimension BF 400 x 14.0 mm. The T-profiles have a center distance of 3000 mm. Bulb-profiles have a center distance of 600 mm. The column is shown in Figure 1-2.

The stiffener dimensions are chosen so that buckling is not limiting to the capacity of the columns. A buckling check utilizing Stipla DNV-RP-C201 [2] has been performed. A summary where yield stress 420 MPa / 1.1 = 381 MPa is applied is shown on the next page. As expected, the yield check for the plate show full utilization. Buckling control show remaining capacity.

The optional 40 mm plate thickness is added to increase the column capacity for an eccentric ship impact where torsion is the dominant force.

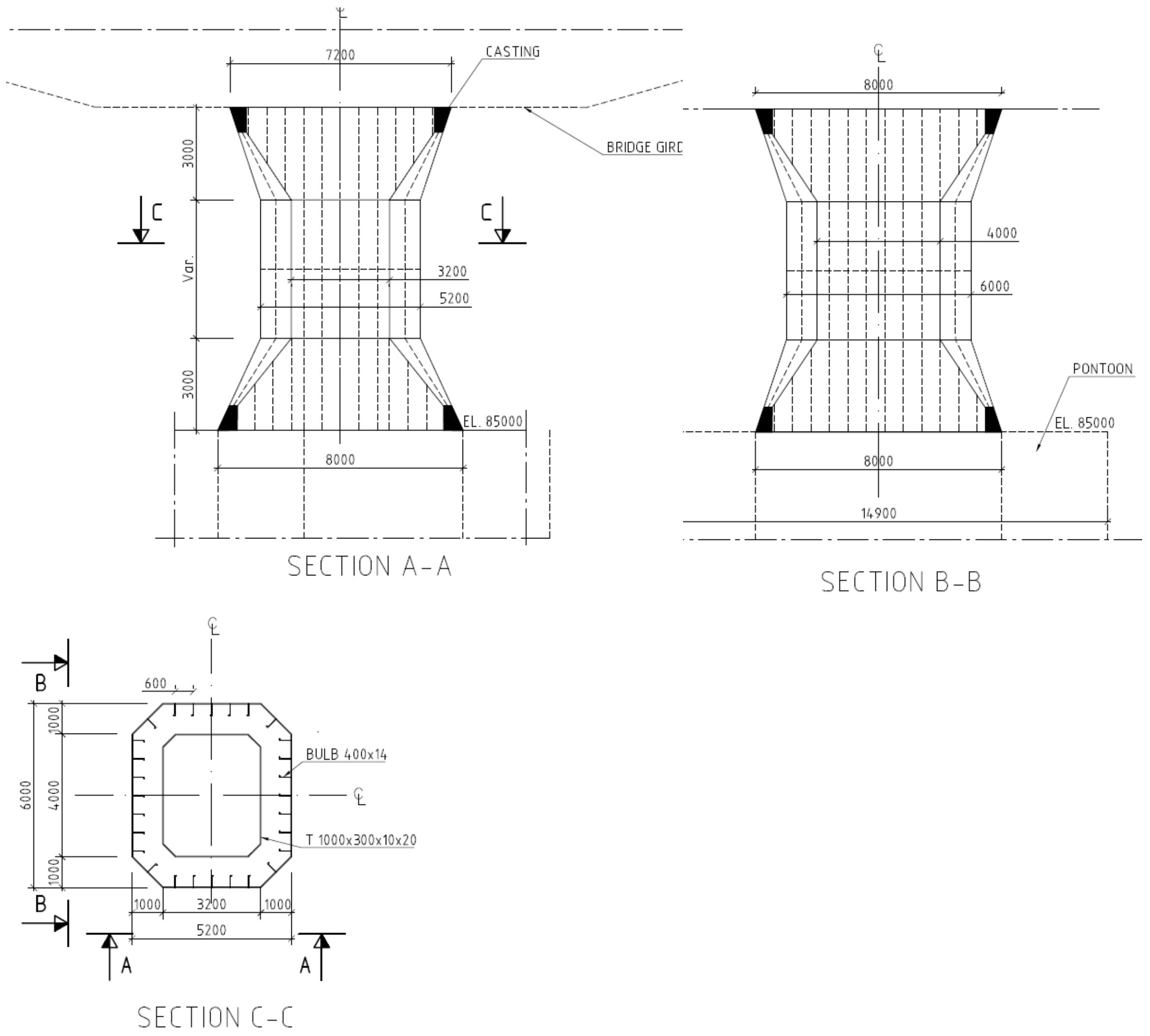
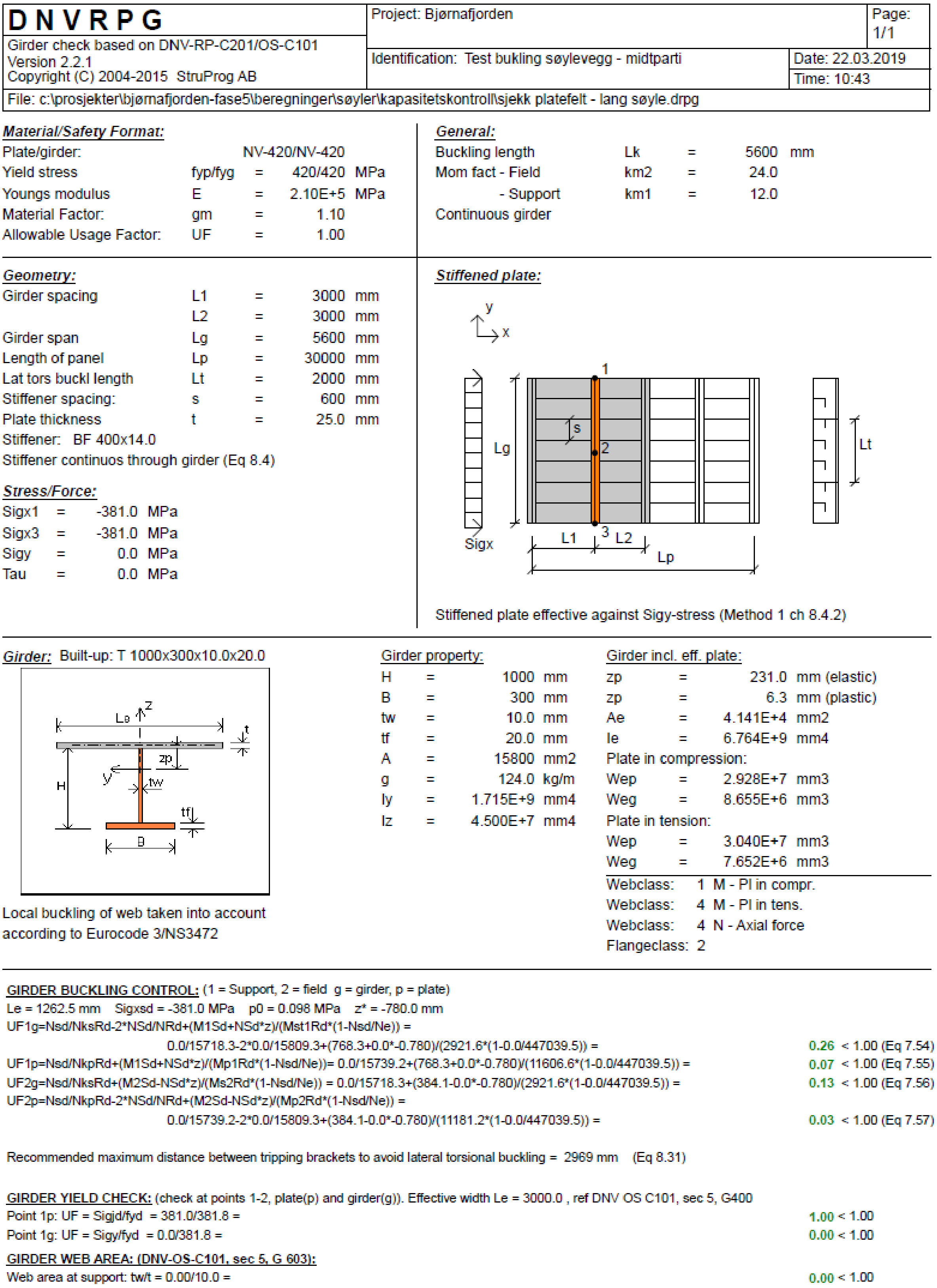


Figure 1-2 Column axis 9-



DNVRPG
Girder check based on DNV-RP-C201/OS-C101
Version 2.2.1
Copyright (C) 2004-2015 StruProg AB

Project: Bjørnafjorden
Page: 1/1
Identification: Test bukling søylevegg - midtparti
Date: 22.03.2019
Time: 10:43

File: c:\prosjekter\bjørnafjorden-fase5\beregninger\søyler\kapasitetskontroll\sjekk platefelt - lang søyle.drpg

Material/Safety Format:
Plate/girder: NV-420/NV-420
Yield stress fyp/fyg = 420/420 MPa
Youngs modulus E = 2.10E+5 MPa
Material Factor: gm = 1.10
Allowable Usage Factor: UF = 1.00

General:
Buckling length Lk = 5600 mm
Mom fact - Field km2 = 24.0
- Support km1 = 12.0
Continuous girder

Geometry:
Girder spacing L1 = 3000 mm
L2 = 3000 mm
Girder span Lg = 5600 mm
Length of panel Lp = 30000 mm
Lat tors buckl length Lt = 2000 mm
Stiffener spacing: s = 600 mm
Plate thickness t = 25.0 mm
Stiffener: BF 400x14.0
Stiffener continuos through girder (Eq 8.4)

Stress/Force:
Sigx1 = -381.0 MPa
Sigx3 = -381.0 MPa
Sigy = 0.0 MPa
Tau = 0.0 MPa

Stiffened plate:

Stiffened plate effective against Sigy-stress (Method 1 ch 8.4.2)

Girder: Built-up: T 1000x300x10.0x20.0

Local buckling of web taken into account
according to Eurocode 3/NS3472

Girder property:
H = 1000 mm
B = 300 mm
tw = 10.0 mm
tf = 20.0 mm
A = 15800 mm2
g = 124.0 kg/m
Iy = 1.715E+9 mm4
Iz = 4.500E+7 mm4

Girder incl. eff. plate:
zp = 231.0 mm (elastic)
zp = 6.3 mm (plastic)
Ae = 4.141E+4 mm2
Ie = 6.764E+9 mm4
Plate in compression:
Wep = 2.928E+7 mm3
Weg = 8.655E+6 mm3
Plate in tension:
Wep = 3.040E+7 mm3
Weg = 7.652E+6 mm3

Webclass: 1 M - Pl in compr.
Webclass: 4 M - Pl in tens.
Webclass: 4 N - Axial force
Flangeclass: 2

GIRDER BUCKLING CONTROL: (1 = Support, 2 = field g = girder, p = plate)
Le = 1262.5 mm Sigxsd = -381.0 MPa p0 = 0.098 MPa z* = -780.0 mm
UF1g=Nsd/NksRd-2*NSd/NRd+(M1Sd+NSd*z)/(Mst1Rd*(1-Nsd/Ne)) =
0.0/15718.3-2*0.0/15809.3+(768.3+0.0*-0.780)/(2921.6*(1-0.0/447039.5)) = 0.26 < 1.00 (Eq 7.54)
UF1p=Nsd/NkpRd+(M1Sd+NSd*z)/(Mp1Rd*(1-Nsd/Ne))= 0.0/15739.2+(768.3+0.0*-0.780)/(11606.6*(1-0.0/447039.5)) = 0.07 < 1.00 (Eq 7.55)
UF2g=Nsd/NksRd+(M2Sd-NSd*z)/(Ms2Rd*(1-Nsd/Ne)) = 0.0/15718.3+(384.1-0.0*-0.780)/(2921.6*(1-0.0/447039.5)) = 0.13 < 1.00 (Eq 7.56)
UF2p=Nsd/NkpRd-2*NSd/NRd+(M2Sd-NSd*z)/(Mp2Rd*(1-Nsd/Ne)) =
0.0/15739.2-2*0.0/15809.3+(384.1-0.0*-0.780)/(11181.2*(1-0.0/447039.5)) = 0.03 < 1.00 (Eq 7.57)

Recommended maximum distance between tripping brackets to avoid lateral torsional buckling = 2969 mm (Eq 8.31)

GIRDER YIELD CHECK: (check at points 1-2, plate(p) and girder(g)). Effective width Le = 3000.0 , ref DNV OS C101, sec 5, G400
Point 1p: UF = Sigjd/fyd = 381.0/381.8 = 1.00 < 1.00
Point 1g: UF = Sigy/fyd = 0.0/381.8 = 0.00 < 1.00

GIRDER WEB AREA: (DNV-OS-C101, sec 5, G 603):
Web area at support: tw/t = 0.00/10.0 = 0.00 < 1.00

2 Forces from global analysis

Input for capacity checks of the columns are based on the following global analysis results presented in Table 2-1 and Table 2-2.

Table 2-1 Global analysis, ULS

Bridge	Revision	Date
K11	07	20.03.2019
K12	05	20.03.2019
K13	06	20.03.2019
K14	06	20.03.2019

Table 2-2 Global analysis, ALS - Ship impact

Bridge	Revision	Date
K11	07	20.03.2019
K12	05	20.03.2019
K13	06	20.03.2019
K14	06	20.03.2019

3 Capacity check

The capacity is checked with a linear summation of the utilization for each load component according to NS-EN 1993-1-1 [1], section 6.2.1 (7). The check is elastic.

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} < 1.0 \quad (3.1)$$

Shear capacity $V_{Pl,Rd}$ is calculated according to section 6.2.6 [1], and reduced due to torsion according to 6.2.7 (9).

$$V_{pl,T,Rd} = \left[1 - \frac{\tau_{t,Ed}}{\left({}^{f_y}/_{\sqrt{3}}\right)/\gamma_{M0}}\right] \quad (3.2)$$

The shear force can according to section 6.2.8 (2) be ignored for combinations of moment and shear if $V_{Ed} < 0.5 * V_{pl,T,Rd}$.

3.1 Material properties

Steel with quality S420N [3] have been used for all parts.

Density: 7850 tonne/m^3

3.2 Material factors

Material factors according to NS-EN 1993-2 [4] have been used.

ULS: $\gamma_{M0} = 1.1$

ALS: $\gamma_{M0} = 1.0$

4 ULS capacity check

From “envelopes” results, the following combinations have been checked:

- Min N
- Min M longit
- Min M transv
- Min T
- Min V longit
- Min V transv
- Max N
- Max M longit
- Max M transv
- Max T
- Max V longit
- Max V transv

From “expmax” results, the following combinations have been checked:

- Worst
- Case 1
- Case 2
- Case 3
- Case 4

ULS 2 and ULS 3 combinations have been checked for both “envelopes” and “expmax”.

The columns are divided in several elements, and forces are reported at the node for each element. Column section properties corresponding to the elevation of the column are used when checking the capacity. See example in Table 4-1 below.

Table 4-1 Correlation column properties and global analysis section forces

			Min N					
			N	**M longit**	**M transv**	**T**	**V longit**	**V transv**
Chosen section			**MN**	**MNm**	**MNm**	**MNm**	**MN**	**MN**
	tag	**z**						
L1	**A3 bottom**	**3.5**	-33.6536	7.938879	2.287161	2.550667	-0.0747	-0.40694
L2		**9.196115**	-33.0566	4.428309	2.980319	2.550667	-0.08579	-0.41371
L2		**9.196115**	-33.0566	4.428309	2.980319	2.550667	-0.08579	-0.41371
L2		**14.89223**	-32.459	1.727235	3.346456	2.550666	-0.04387	-0.5342
L2		**14.89223**	-32.459	1.727235	3.346456	2.550666	-0.04387	-0.5342
L2		**20.58835**	-31.8602	-1.32955	3.606427	2.550666	-0.0487	-0.5389
L2		**20.58835**	-31.8602	-1.32955	3.606427	2.550666	-0.0487	-0.5389
L2		**26.28446**	-31.2614	-4.41417	3.889151	2.550666	-0.05259	-0.54362
L3		**26.28446**	-31.2614	-4.41417	3.889151	2.550666	-0.05259	-0.54362
L3		**31.98058**	-30.6638	-7.5256	4.192842	2.550666	-0.05566	-0.54836
L3		**31.98058**	-30.6638	-7.5256	4.192842	2.550666	-0.05566	-0.54836
L3		**37.67669**	-30.0651	-11.1199	4.312051	2.550665	0.012458	-0.71298
L3		**37.67669**	-30.0651	-11.1199	4.312051	2.550665	0.012458	-0.71298
L3		**43.37281**	-29.4675	-15.196	4.243019	2.550671	0.010589	-0.71774
L3		**43.37281**	-29.4675	-15.196	4.243019	2.550671	0.010589	-0.71774
L4	**A3 top**	**49.06892**	-28.8669	-17.2417	4.205392	2.550672	0.00983	-0.72011

A summary of utilizations is presented in Table 4-2.

Table 4-2 ULS results summary

	Max utilization	
Bridge / combination	**Axis 3-8**	**Axis 9-**
K11_envelopes_ULS2	0.18	0.26
K11_envelopes_ULS3	0.38	0.42
K11_expmax_ULS2	0.26	0.35
K11_expmax_ULS3	0.65	0.59
K12_envelopes_ULS2	0.19	0.22
K12_envelopes_ULS3	0.37	0.32
K12_expmax_ULS2	0.27	0.27
K12_expmax_ULS3	0.58	0.51
K13_envelopes_ULS2	0.24	0.30
K13_envelopes_ULS3	0.43	0.43
K13_expmax_ULS2	0.34	0.38
K13_expmax_ULS3	0.63	0.61
K14_envelopes_ULS2	0.28	0.33
K14_envelopes_ULS3	0.50	0.42
K14_expmax_ULS2	0.35	0.38
K14_expmax_ULS3	0.72	0.60
MAX	**0.72**	**0.61**

Maximum utilization observed is 0.72. This occurs for K14_expmax_ULS3. A more detailed summary for this concept and combination is shown in Table 4-3. The “Worst” combination is triggering the maximum utilization.

Table 4-3 Capacity check - K14_expmax_ULS3

Worst		**Case1**		**Case2**		**Case3**		**Case4**		$V_{y,max,Ed}/V_{pl,Rd}$	$V_{z,max,Ed}/V_{pl,Rd}$
Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**		
0.72	0.67	0.46	0.45	0.57	0.54	0.54	0.49	0.71	0.65	0.07	0.09
0.60	0.58	0.49	0.48	0.55	0.53	0.49	0.48	0.52	0.50	0.07	0.14

Investigating further, we see that it is a L3 section near the top of the column that has the highest utilization. The section has relatively large longitudinal- and transversal moments.

Table 4-4 Capacity check - K14_expmax_ULS3 Worst – Axis 3

Column properties			**Utilization Worst**		**Forces**					
					N	**M longit**	**M transv**	**T**	**V longit**	**V transv**
Column section	**tag**	**z**	**Min**	**Max**	**MN**	**MNm**	**MNm**	**MNm**	**MN**	**MN**
L1	A3 bottom	3.5	0.15	0.10	-30.0	-60.2	-52.0	-79.7	-9.1	-4.8
L2		9.1	0.27	0.22	-29.5	-76.6	-128.3	-79.7	-9.1	-4.8
L2		14.7	0.34	0.29	-29.0	-94.1	-180.4	-79.7	-9.2	-5.1
L2		20.3	0.41	0.36	-28.4	-116.3	-232.7	-79.7	-9.3	-5.1
L2		25.9	0.49	0.43	-27.9	-139.8	-285.3	-79.7	-9.3	-5.1
L3		31.6	0.56	0.51	-27.4	-166.6	-337.8	-79.7	-9.3	-5.1
L3		37.2	0.64	0.59	-26.8	-195.1	-390.5	-79.7	-9.4	-5.5
L3		**42.8**	**0.72**	**0.67**	**-26.3**	**-224.6**	**-443.3**	**-79.7**	**-9.3**	**-5.4**
L4	A3 top	48.4	0.42	0.39	-25.7	-239.5	-469.7	-79.7	-9.3	-5.4

For all checked combinations, ULS capacity is sufficient for the current column design. Based on the results, there is no basis for claiming that one bridge concept is favorable with regards to column design. There will be stress concentrations at the transition between top/bottom and middle part of the columns (4-sided to 8-sided).

ULS column forces are also checked in a finite element model (FEM). Results show overall acceptable stress level. The analysis is documented in memo 10205546-13-NOT-099 [5].

5 ALS capacity check

The forces are extracted from a time-series analysis with centric and eccentric ship collision from revision and date as shown in Table 2-2.

The capacity has been checked using the methodology explained in chapter 3. The check is elastic. Ship impact forces are significant and there will be plastic deformations in the column, therefore an elastic check is not that relevant. The intention here is to screen the ship impact forces and to evaluate how the columns can handle the impact forces. Further work has been done to evaluate the columns ability to absorb energy from a ship impact. The columns have been run with both implicit and explicit finite element analysis with non-linear material properties. This is documented in Appendix J [6] and memo 10205546-13-NOT-099 [5]. The conclusion from the analyzes is that the column capacity can be increased considerably by using 40 mm plate thickness instead of 25 mm. A plate thickness of 40 mm can take approximately 50% of the ship impact energy. Another alternative for increasing the structural capacity is to increase the size of the narrow mid-section of the columns so that the walls are straight. This is an even more effective way of increasing the structural capacity. The downside will be increased wind drag and possibly a less aesthetic column.

Table 5-1 K11 - Ship impact

Bottom	**Capacity check (3.1)**			**Shear capacity check (3.2)**		
	0 deg	**30 deg**	**60 deg**	**0 deg**	**30 deg**	**60 deg**
K11_A3	1.09	1.57	1.86	OK	Fail	Fail
K11_A4	1.02	1.50	1.83	OK	Fail	Fail
K11_A5	0.94	1.38	1.66	OK	Fail	Fail
K11_A10	0.47	0.63	0.78	OK	Fail	Fail
K11_A20	0.31	0.40	0.51	OK	Fail	Fail
K11_A30	0.32	0.43	0.36	OK	Fail	Fail
Top						
K11_A3	0.07	0.08	0.08	OK	Fail	Fail
K11_A4	0.06	0.07	0.13	OK	OK	Fail
K11_A5	0.07	0.10	0.12	OK	OK	Fail
K11_A10	0.11	0.15	0.16	OK	Fail	Fail
K11_A20	0.19	0.24	0.29	OK	Fail	Fail
K11_A30	0.21	0.25	0.20	OK	Fail	Fail

Not all columns have been checked. A pattern can however be seen from the checked columns. It is expected that the results for columns not checked will be similar to the results found for checked columns.

A limited number of columns have been checked for K12 and K13. The forces does not vary much between K11, K12, K13 and K14. It is expected that the results will be similar to the results shown for K11 and K14.

Table 5-2 K12 - Ship impact

Bottom	**Capacity check NS-EN 1993-1-1 6.2.1 (6.2)**			**Shear capacity check**		
	0 deg	**30 deg**	**60 deg**	**0 deg**	**30 deg**	**60 deg**
K12_A3	1.10	1.56	1.87	OK	Fail	Fail
K12_A10	0.48	0.63	0.83	OK	Fail	Fail
Top						
K12_A3	0.07	0.08	0.09	OK	Fail	Fail
K12_A10	0.11	0.15	0.17	OK	Fail	Fail

Table 5-3 K13 - Ship impact

Bottom	**Capacity check NS-EN 1993-1-1 6.2.1 (6.2)**			**Shear capacity check**		
	0 deg	**30 deg**	**60 deg**	**0 deg**	**30 deg**	**60 deg**
K13_A3	1.06	1.52	1.79	OK	Fail	Fail
K13_A10	0.45	0.61	0.77	OK	Fail	Fail
Top						
K13_A3	0.07	0.08	0.09	OK	Fail	Fail
K13_A10	0.12	0.16	0.18	OK	Fail	Fail

Table 5-4 K14 - Ship impact

Bottom	**Capacity check NS-EN 1993-1-1 6.2.1 (6.2)**			**Shear capacity check**		
	0 deg	**30 deg**	**60 deg**	**0 deg**	**30 deg**	**60 deg**
K14_A3	1.08	1.58	1.86	OK	Fail	Fail
K14_A4	1.04	1.49	1.84	OK	Fail	Fail
K14_A5	0.98	1.36	1.60	OK	Fail	Fail
K14_A10	0.46	0.62	0.79	OK	Fail	Fail
K14_A20	0.31	0.44	0.51	OK	Fail	Fail
K14_A30	0.29	0.43	0.35	OK	Fail	Fail
Top						
K14_A3	0.07	0.08	0.09	OK	Fail	Fail
K14_A4	0.07	0.07	0.11	OK	OK	Fail
K14_A5	0.08	0.10	0.14	OK	OK	Fail
K14_A10	0.12	0.15	0.17	OK	Fail	Fail
K14_A20	0.19	0.26	0.28	OK	Fail	Fail
K14_A30	0.19	0.27	0.21	OK	Fail	Fail

For the long columns at axis A3-A5, there is large moment about longitudinal- and transversal- axis. The moment is primarily at the bottom of the columns. Very little moment at the top of the columns. Large torsional forces causes the shear capacity check to fail for most of the columns. Their ability to absorb energy from a ship impact without a structural collapse is documented in Appendix J and memo 10205546-13-NOT-099 [5].

5.1 Weight calculation

Table 5-5 Properties for weight calculation

Column	**Part**	Height [m]	Weight [tonne]
Long	Upper	5	53.5
Long	Middle	Varies	Varies
Long	Lower	5	47.3
Short	Upper	3	25.5
Short	Middle	Varies	Varies
Short	Lower	3	27.0

The total weight of the columns for each of the bridge concepts are presented in Table 5-6. Slightly different column lengths cause the difference in weight between concepts.

If the option of using 40 mm plate thickness instead of 25 mm, the weight will increase with approximately 35 %. A straight column without the narrow mid section will increase the weight by approximately 28 %.

Table 5-6 Total column weight [tonne]

K11	**K12**	**K13**	**K14**
5 095.1	5 095.1	4 857.1	4 967.3

6 Summary

The columns as designed now can handle the ULS forces with 25 a mm skin plate.

The overall picture from a simplified screening is that the moment is likely to be handled by plastic redistribution of forces at the column top and bottom. With 25 mm plate thickness, the low columns are unable to absorb the current magnitude of energy from a ship impact. To absorb 50% of the ship impact energy, the plate thickness must be increased to 40 mm. This will increase the weight of the columns by 35%. Alternatively, the geometry can be changed by widening the narrow part of the column. This is more effective than just to increase the plate thickness, but wind drag will increase and the columns may appear less aesthetic. See Appendix J [6] and memo 10205546-13-NOT-099 [5] for detailed results from the FEM analyzes.

For ULS and ALS, no significant difference between columns for bridge K11, K12, K13 and K14 has been observed. If the column structural capacity is increased by widening the narrow part of the columns, wind drag will increase. This is unfavorable for K11 as it is more sensitive to wind forces than the other concepts.

Weight for the columns differs little between concepts. Column design is identical for all concepts.

7 References

[1] CEN, NS-EN 1991-1-1 Eurocode 1: Actions on structures. Part 1-1: General actions. Densities, self-weight, imposed loads of buildings, 2002+NA:2008.

[2] DNV-GL, Recommended practice DNV-RP-C201, Buckling strength of plated structures, Oslo: DNV-GL, 2010.

[3] CEN, "NS-EN 10025-3; Hot rolled products of structural steels. Part 3: Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels," 2004.

[4] CEN, *NS-EN 1993-2:2006+NA:2009 Eurocode 3: Design of steel structures, Part 2 Steel Bridges,* 2009.

[5] AMC, "10205546-13-NOT-099 : FEM analysis of bridge girder and column," 24.05.2019.

[6] AMC, "SBJ-32-C5-AMC-27-RE-110 : Appendix J: Ship collision Rev. 0," 24.05.2019.

[7] StruProg AB, "Stipla DNV-RP-C201, ver 2.2," 2014.

Concept development, floating bridge
E39 Bjørnafjorden

Appendix K – Enclosure 6

10205546-13-NOT-087
Design of pontoons

MEMO

PROJECT	Concept development, floating bridge E39 Bjørnafjorden	DOCUMENT CODE	10205546-13-NOT-087
CLIENT	Statens vegvesen	ACCESSIBILITY	Restricted
SUBJECT	Design of pontoons	PROJECT MANAGER	Svein Erik Jakobsen
TO	Statens vegvesen	PREPARED BY	Frode Fløtten / Andreas Landa
COPY TO		RESPONSIBLE UNIT	AMC

SUMMARY

The structural layout and strength assessment of the pontoons for the low bridge part of the Bjørnafjorden floating bridge is performed. The strength assessment is based on simplified and conservative load assumptions. The pontoon structure assessment has been performed for Ultimate limit state (ULS) and Accidental limit state (ALS). Fatigue limit state (FLS) has not been evaluated in this document, but will be evaluated in Appendix I.

The proposed structural dimensions show acceptable utilization both with regards to maximum allowable stress level and minimum scantling requirements and buckling utilization, for both ULS and ALS conditions. The results are presented in section 4.5, 5.5 and 6. The structural net scantling weight for the “base case” pontoon without mooring lines is 705 ton for a displacement of 3710 m^3, and the structural weight for the “base case” pontoon with mooring lines is 934 Ton for a displacement of 5565 m^3. These pontoons will be used for all concepts.

The splash zone has been calculated based on 100-year coupled motions taken from the global analysis, in addition to the largest wave over 100 years. The extent of the splash zone has been found to be 6.5m starting from the top of the pontoon. The duplex steel will be placed in this area. The splash zone is based on vertical movement from environmental loads with a return period of 100 years. This seems to be too conservative considered the 100 year wave height shall be divided by 3 according to DNVGL-OS-C101, ref. /3/. In next stage of the project a movement with a lower return period should be considered for determination of the splash zone.

Compared to revision 0 of this document the tank plan has been updated. The changes are assumed to have no negative effect on the pontoon structural capacity. In addition, the steel quality has been changed from NV36 to NV42 which will increase the reported margins against buckling failure.

1	24.05.2019	Final issue	A. Landa	P. N. Larsen	S. E. Jakobsen
0	29.03.2019	Status 2 issue	F. Fløtten	P. N. Larsen	S. E. Jakobsen
REV.	DATE	DESCRIPTION	PREPARED BY	CHECKED BY	APPROVED BY

Table of Contents

1 Introduction

This memo describes the structural analyses performed for two pontoons for the low bridge part of the Bjørnafjorden floating bridge. The structural layout and dimensions have been established for one pontoon without mooring lines and for one pontoon with supports for mooring lines, the dimensions is shown in Table 2-1 and Table 2-2. The pontoons are dimensioned for operating conditions (ULS) and for accidental filling of pontoon compartments (ALS). An conservative approach to loads have been used where external sea pressure is set to top of the pontoons with relevant load factors for ULS and ALS limit states.

2 Design Basis

2.1 General description

The pontoons have a “Circtangel” shape i.e. a rectangle with half cylinders at each end in the transverse bridge girder direction and with flat bottom and top plate.

The outer shell plates, inner transverse- and longitudinal bulkheads are reinforced with bulb stiffeners. Additional structural strength is provided by web-frames in the bridge girder longitudinal direction.

Table 2-1 Pontoon dimensions for low bridge section with a pontoon distance of 125 m. Pontoon without mooring lines

Length in X-direction [m]	Width in X-direction [m]	Radius [m]	Draft [m]	Freeboard [m]	Total height [m]	Displacement [m^3]
53.0	14.9	7.45	5.0	3.5	8.5	3710

Table 2-2 Pontoon dimensions for low bridge section with a pontoon distance of 125 m. Pontoon with mooring lines

Length in X-direction [m]	Width in X-direction [m]	Radius [m]	Draft [m]	Freeboard [m]	Total height [m]	Displacement [m^3]
53.0	14.9	7.45	7.5	3.5	11.0	5565

2.2 Design rules

The bridge as a whole will be designed according to the following standards:

- N400 Bruprosjektering
- NS-EN 1990 Basis of structural design
- NS-EN 1991 Eurocode 1 Actions on structures
- NS-EN 1993 Eurocode 3 Design of steel structures

For the pontoons the following offshore codes apply:

- DNVGL-OS-C101 Design of Offshore Steel Structures, general - LRFD design)

- DNVGL-OS-C103 Structural design of column stabilised units – LRFD method
- DNVGL-RP-C201 Buckling strength of plated structures
- DNVGL-RP-C202 Buckling strength of shells
- DNVGL-RP-C203 Fatigue design of offshore steel structures
- DNVGL-RP-C205 Environmental conditions and environmental loads

The regulations are based on N400, Eurocode and offshore regulations, in that order.

2.3 Material properties

The following steel material grades are used in the pontoon design and is according to Eurocode.

Steel material grade S355 for material thickness $t \leq 40$ mm

Modulus of Elasticity	$2.10 \cdot 10^{11}$ N/m^2
Poisson`s Ratio	0.3
Thermal Expansion Coefficient	$1.6 \cdot 10^{-5}\ {}^0C^{-1}$
Density	7850 kg/m^3
Acceleration of gravity	9.81 m/s^2
Yield Strength f_y	355 N/mm^2
Tensile Strength f_u	470 N/mm^2

Steel material grade S420 for material thickness $t \leq 40$ mm

Modulus of Elasticity	$2.10 \cdot 10^{11}$ N/m^2
Poisson`s Ratio	0.3
Thermal Expansion Coefficient	$1.2 \cdot 10^{-5}\ {}^0C^{-1}$
Density	7850 kg/m^3
Acceleration of gravity	9.81 m/s^2
Yield Strength f_y	420 N/mm^2
Tensile Strength f_u	520 N/mm^2

Steel material grade 25CR super duplex (SDSS) for material thickness $t \leq 40$ mm

Modulus of Elasticity	$2.10 \cdot 10^{11}$ N/m^2
Poisson`s Ratio	0.3
Thermal Expansion Coefficient	$1.2 \cdot 10^{-5}\ {}^0C^{-1}$
Density	7850 kg/m^3
Acceleration of gravity	9.81 m/s^2
Yield Strength f_y	550 N/mm^2
Tensile Strength f_u	800 N/mm^2

2.4 Units

Units of the S.I. (System International) metric system are used.

Table 2-3 Units

Description	Unit	Symbol
Length	Metre	m
Mass	Kilogram Tonne	Kg T (tonne), 1 T = 1000 kg
Force	Newton	N
Pressure	Pascal	Pa = N/m^2

2.5 Analysis tools

The SESAM software package supported by DNV GL Software has been used for the analyses performed for the pontoons:

GeniE	Pre-processor for concept design and analysis of offshore structures
HydroD	Pre-processor for hydrostatic and hydrodynamic analysis
Sestra	Finite element analysis solver
Xtract	Post-processor for presentation, animation and reporting of results from finite element analyses

For the plate buckling calculations performed the STIPLA software by StruProg AB has been utilized.

2.6 Coordinate system

The pontoon structural model uses right-handed coordinate system which is oriented as follows:

- The X-axis is parallel with the bridge girder direction
- The Y-axis is transverse to the bridge girder direction
- The Z-axis is in the vertical direction and pointing upwards

The origin of the coordinate axis system is taken at:

- The longitudinal centre line of the pontoon
- The transverse centre line of the pontoon
- The bottom plate of the pontoon

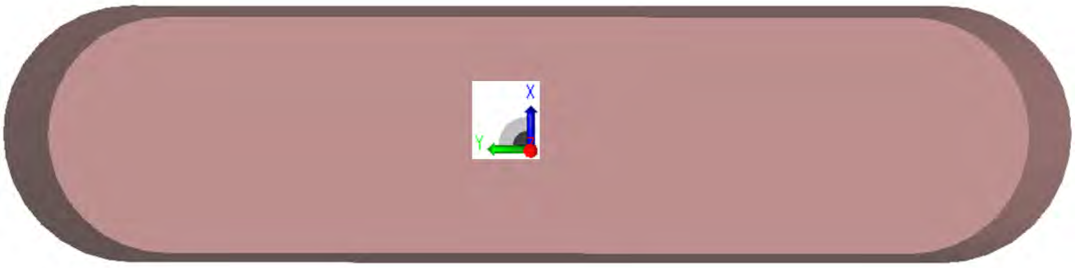


Figure 2-1 Local coordinate system for the pontoons

2.7 Special provisions for plating and stiffeners

The requirements for minimum scantlings are taken from DNVGL-OS-C101, ref./3/.

2.7.1 Minimum plate thickness

The thickness of plates should not be less than:

$$t = \frac{14.3 \cdot t_0}{\sqrt{f_{yd}}} \ (mm)$$

Where:

f_{yd} = design yield strength f_y/γ_M , f_y is the minimum yield stress

t_0 = 7.0 mm for primary structural elements, and 5.0 mm for secondary elements

γ_M = 1.10 material factor for steel

2.7.2 Bending of plating

The thickness of plating subjected to lateral pressure shall not be less than:

$$t = \frac{15.8 \cdot k_a \cdot s \cdot \sqrt{p_d}}{\sqrt{\sigma_{pd1} \cdot k_{pp}}} \ (mm)$$

Where:

k_a = correction factor for aspect ratio of plate field

= $(1.1 – 0.25\ s/l)^2$

= maximum 1.0 for s/l = 0.4

= maximum 0.72 for s/l = 1.0

s = stiffener spacing (m), measured along the plating

p_d = design pressure (kN/m^2)

σ_{pd1} = design bending stress (N/mm^2), taken as the smaller of

- $1.3(f_{yd} – \sigma_{jd})$, and
- $f_{yd} = f_y/\gamma_M$

σ_{jd} = equivalent stress for in-plane membrane stress:

$$\sigma_{jd} = \sqrt{\sigma_{xd}^2 + \sigma_{yd}^2 - \sigma_{xd}\sigma_{yd} + 3\tau_d^2}$$

k_{pp} = fixation parameter for plate

= 1.0 for clamped edges

= 0.5 for simply supported edges

2.7.3 Stiffeners

The minimum section modulus for stiffeners subjected to lateral pressure shall not be less than:

$$Z_s = \frac{l^2 s p_d}{k_m \sigma_{pd2} k_{ps}} 10^6 \ (mm^3), minimum \ 15 \cdot 10^3 \ (mm^3)$$

Where:

l = stiffener span (m)

k_m =bending moment factor

σ_{pd2} = design stress (N/mm^2)

= $f_{yd} - \sigma_{jd}$

k_{ps} = fixation parameter for stiffeners

= 1.0 if at least one end is clamped

= 0.9 if both ends are simply supported

2.8 Environmental data

The environmental conditions applied are based on “Design Basis Bjørnafjorden” ref./1/.

- Significant wave height H_S = 2.1 m for 100 year return period

- Maximum wave height (approx.) $H_{max} \approx 1.86 H_S = 1.86 \cdot 2.1$ m = 3.91 m for 100 year return period

2.9 Corrosion allowance

The pontoons will be provided with several corrosion reduction measures, such as passive galvanic cathodic protection for steel surfaces permanently submerged, all steel surfaces in the tidal and splash zone to be of super duplex steel and all other external and internal surfaces will be treated with special coating system and no corrosion allowance is considered in the structural strength assessment of the pontoons.

2.10 Splash zone

The extent of the splash zone is defined in “Design Basis, Bjørnafjorden floating bridges” ref./1/ and in DNVGL-OS-C101 ref./3/.

The splash zone height is calculated according to DNVGL-OS-C101 and the following equations:

The upper limit of the splash zone (SZ_U) is calculated by:

$$SZ_U = U_1 + U_2 + U_3 + U_4 + U_5$$

Where:

U_1 = 60 % of 1/3rd of the maximum wave height H_{max}

U_2 = highest astronomical tide level (not applicable for floater structure)

U_3 = foundation settlement (not applicable)

U_4 = range of operation draught

U_5 = motion of structure

The lower limit of the splash zone (SZ_L) is calculated by:

$$SZ_L = L_1 + L_2 + L_3 + L + L_5$$

Where:

L_1 = 40 % of 1/3rd of the maximum wave height H_{max}

L_2 = lowest astronomical tide (not applicable for floater structure)

L_3 = range of operating draught

L_4 = motions of the structure

The motion of the structure is taken from the global analysis. Coupled heave and roll motion is used. The motions are shown in Table 2-4, and it is seen that the 100-year return periods give the largest amplitudes and is hence used in the calculations of the splash zone.

Table 2-4 Combined motions, heave and roll

	Amplitude [m]	
	K12	K14
100-year combined wind/wave	2.29	1.96
1-year wind/wave w/traffic	0.55	0.50

The upper limit of the splash zone (SZ_U) is then:

$U_1 = 1/3 \cdot 0.60 \cdot H_{max} = 1/3 \cdot 0.6 \cdot 3.91\text{m} = 0.78$ m

U_2 – not applicable

U_3 – not applicable

U_4 – not applicable

$U_5 = D_{amplitude} = 2.29$ m

$$SZ_U = U_1 + U_2 + U_3 + U_4 + U_5 = 0.78m + 2.29m = 3.07\ m \text{ above SWL}$$

The lower limit of the splash zone (SZ_L) is then:

$L_1 = 1/3 \cdot 0.40 \cdot H_{max} = 1/3 \cdot 0.4 \cdot 3.91\text{m} = 0.52$ m

L_2 – not applicable

L_3 – not applicable

$L_4 = D_{amplitude} = 2.29$ m

$$SZ_L = L_1 + L_2 + L_3 + L + L_5 = 0.52 + 2.29 = 2.81\ m \text{ below SWL}$$

According to “Design Basis, Bjørnafjorden floating bridges” ref. /1/ an addition of ΔH = 30 cm shall be added to the calculated splash zone.

SZ_{U_total} = 3.07 m + 0.15 m = 3.22 m Upper limit above SWL

SZ_{L_total} = 2.81 m + 0.15 m = 2.96 m Lower limit below SWL

The pontoon draft at static condition is 5.0 m measured from the pontoon bottom and upwards. Total extent of the calculated splash zone is 6.18 m. However, to avoid having 300mm with stainless steel between the upper limit of the splash zone and the top plate of the pontoon, the super duplex part is used all the way to the top of the pontoon. Hence; the extent of the splash zone is 6.5m.

Figure 2-2 Extent of splash zone

3 Calculation method

3.1 Loads

The external loads are considered in a simplified and conservative way. The loads from the bridge girder and column will be counteracted by the buoyancy of the pontoon. The only external load applied to the pontoons is sea pressure and mooring line tension, since the pontoon will not experience severe freeboard exceedance in 100-year condition will this be a conservative approach. The sea pressure consists of a static part and a dynamic part. The static pressure is applied from the pontoon bottom up to the Stillwater line (SWL). The dynamic part is applied from the SWL up to pontoon top plate. The static and dynamic part of the sea pressure is combined with relevant ULS and ALS load factors.

3.1.1 ULS loads – external sea pressure

External sea pressure is calculated in the following way for load case ULS1 and ULS2:

$$P_{ULS} = \delta \cdot g \cdot (D \cdot 1.2 + (T - D) \cdot 1.6)$$

Where

δ = 1025 kg/m^3

g = 9.81 m/s^2

D = draught

T = pontoon height

SWL = Stillwater line

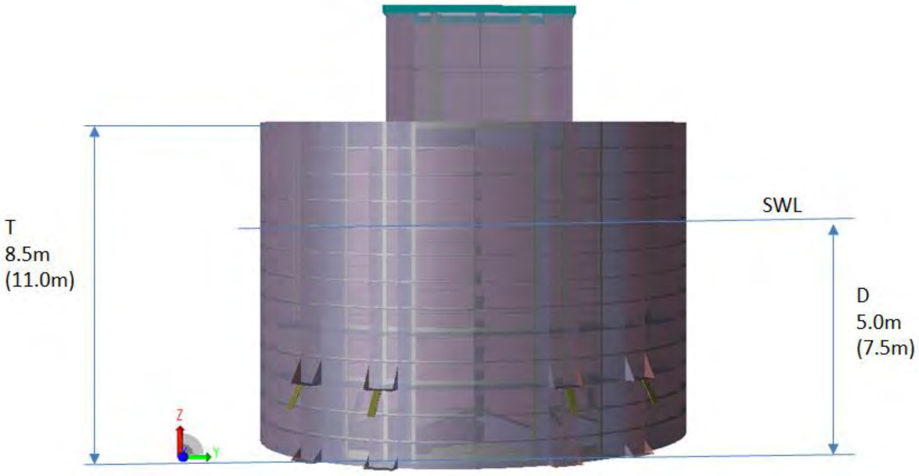


Figure 3-1 frontal view of pontoon with height definitions

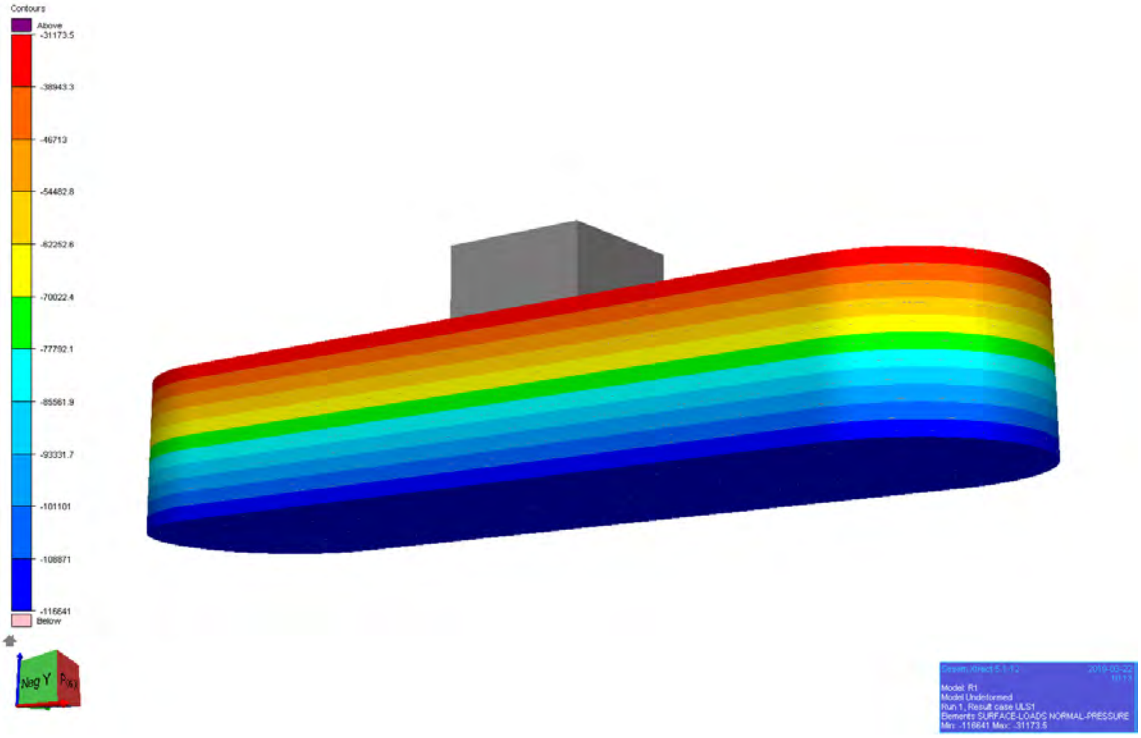


Figure 3-2 Verification of applied external pressure for load case "ULS1" for "base case" pontoon without mooring lines

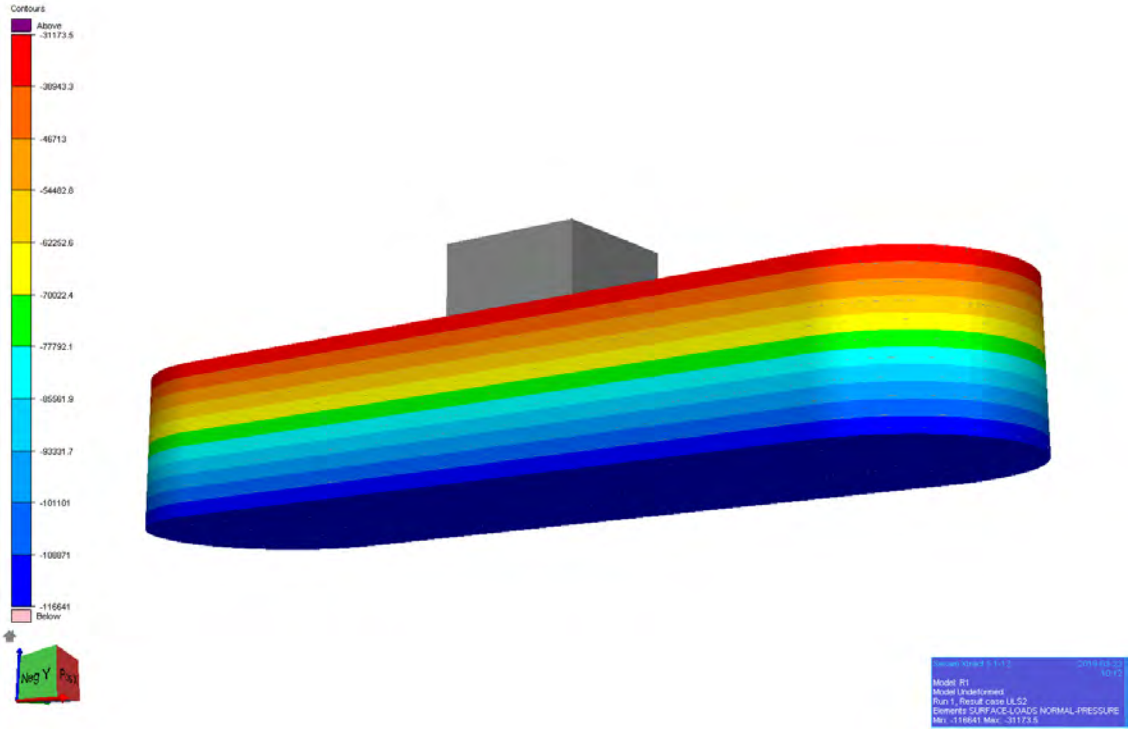


Figure 3-3 Verification of applied external pressure for load case "ULS2" for "base case" pontoon without mooring lines

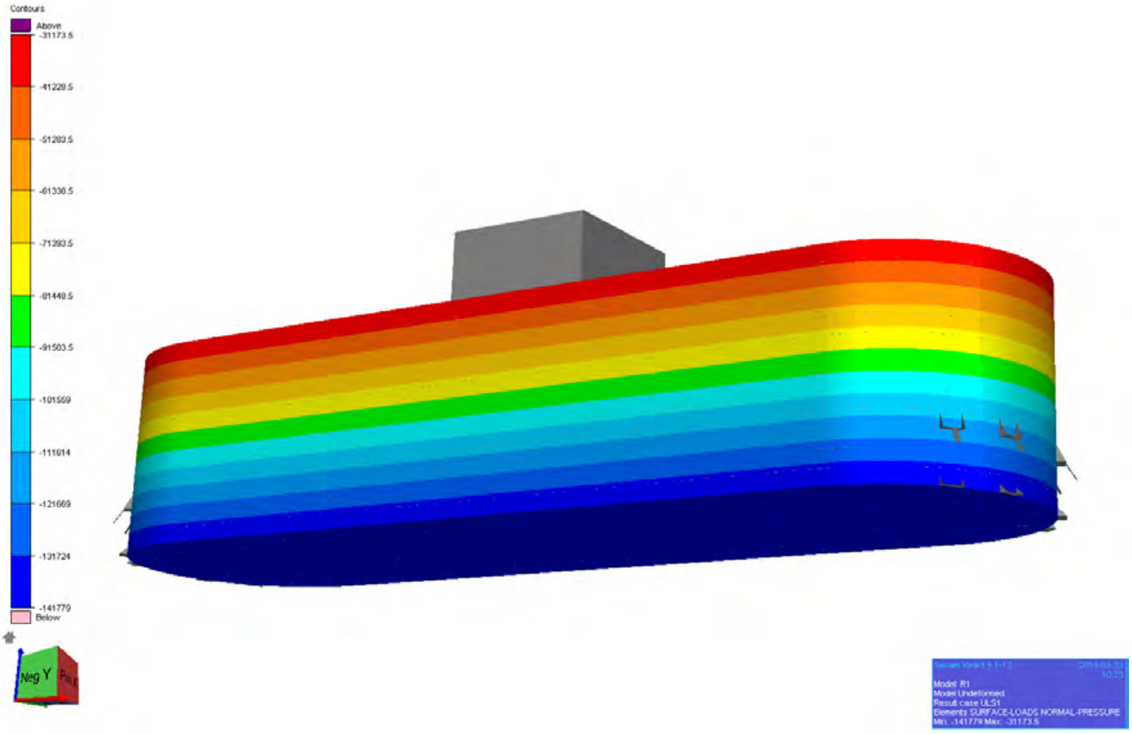


Figure 3-4 Verification of applied external pressure for load case "ULS1" for "base case" pontoon with mooring lines

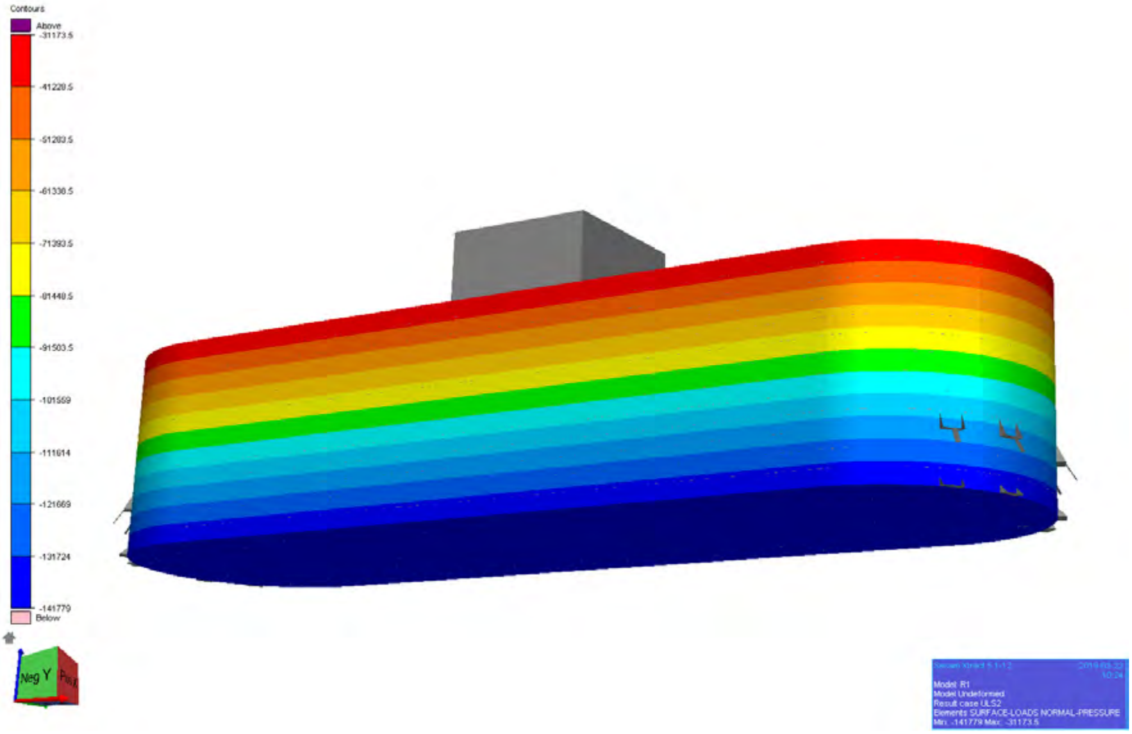


Figure 3-5 Verification of applied external pressure for load case "ULS2" for "base case" pontoon with mooring lines

3.1.2 External sea pressure at Stillwater draft (SWL)

External sea pressure is calculated in the following way for load case P_SWL at Stillwater level without load factors:

$$P_{SWL} = \delta \cdot g \cdot D$$

Where

$\delta = 1025\ kg/m^3$

$g = 9.81\ m/s^2$

D = draught

T = pontoon height

SWL = Stillwater line

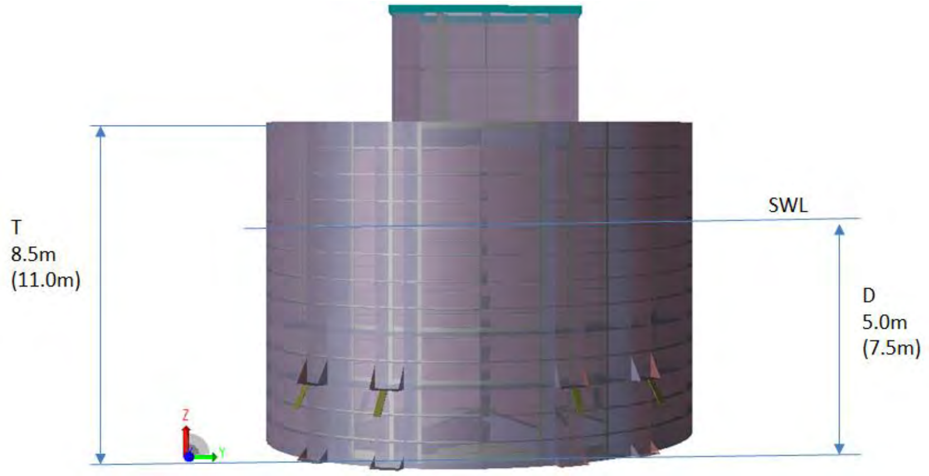


Figure 3-6 frontal view of pontoon with height definitions

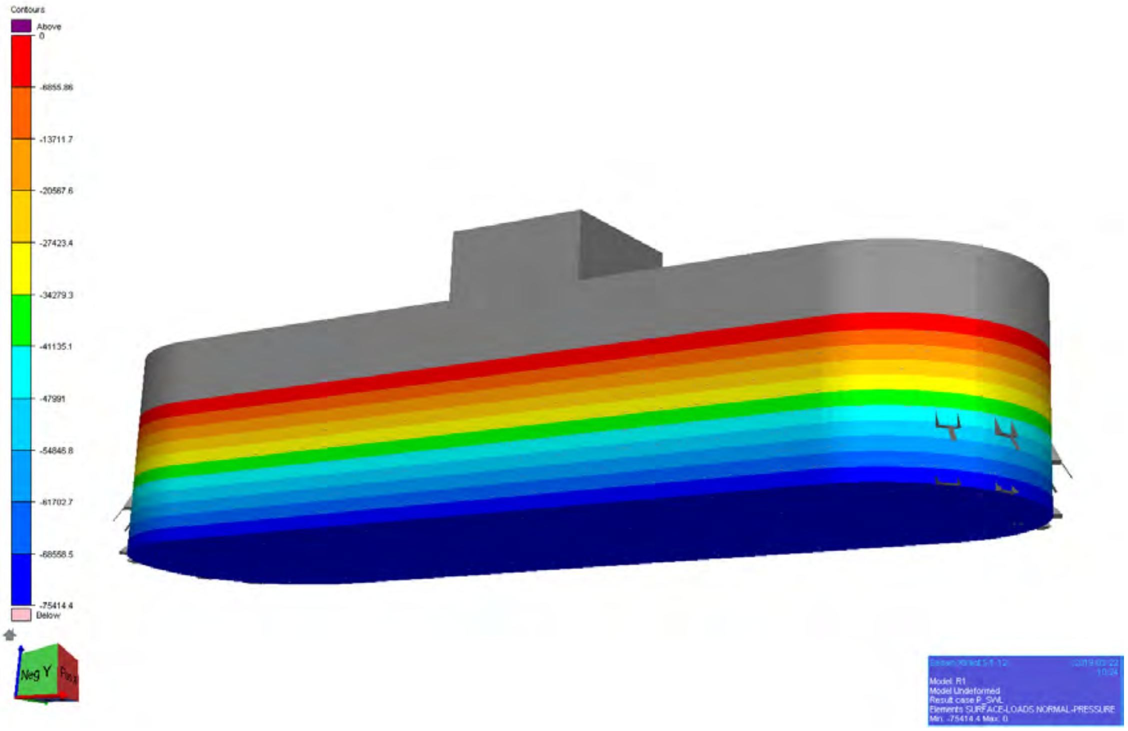


Figure 3-7 Verification of applied external pressure for load case "P_SWL" for "base case" pontoon with mooring lines

3.1.3 ULS loads – mooring line tension

Mooring line tension of 5620 kN has been used for the ULS assessment. There are assumed eight mooring lines per pontoon. A vertical angle of 40 degrees and a horizontal angle of 22.5 degrees and 45 degrees are used in the analysis. The mooring line tension for the operating condition is extracted from ref./2/. The following load cases uses the mooring line tension of 5620 kN multiplied with a load factor of 1.3; FL1ULS, FL2ULS, FL3ULS, FL4ULS, FL5ULS, FL6ULS, FL7ULS AND FL8ULS.

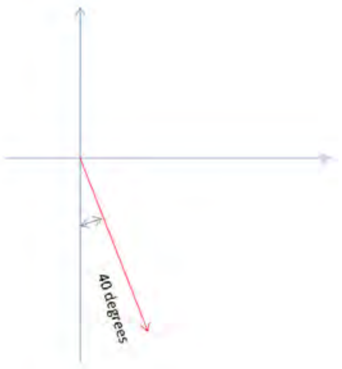


Figure 3-8 Vertical angle of mooring lines

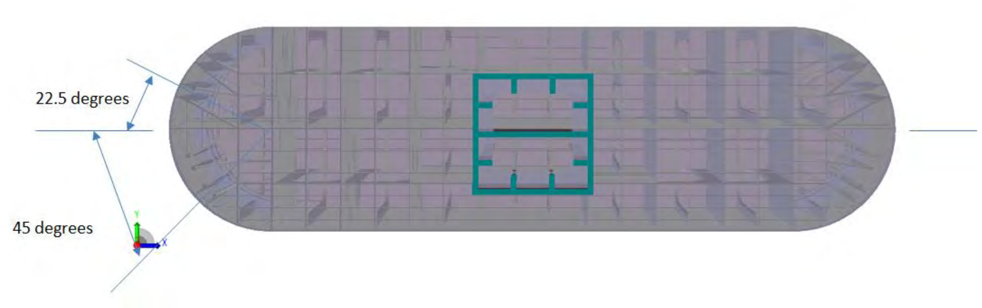


Figure 3-9 Horizontal angles of mooring lines

3.1.4 FLS loads

No fatigue assessment has been performed for the pontoons or the connection area between the pontoons and the columns.

3.1.5 ALS loads – external sea pressure

External sea pressure is calculated in the following way for load case ALSP25 where T = 8.5 m and 11.0 respectively:

$$P_{ALS} = \delta \cdot g \cdot (D \cdot 1.0 + (T - D) \cdot 1.0)$$

Where

$\delta = 1025\ \mathrm{kg/m^3}$

$g = 9.81\ \mathrm{m/s^2}$

D = draught

T = pontoon height

SWL = Stillwater line

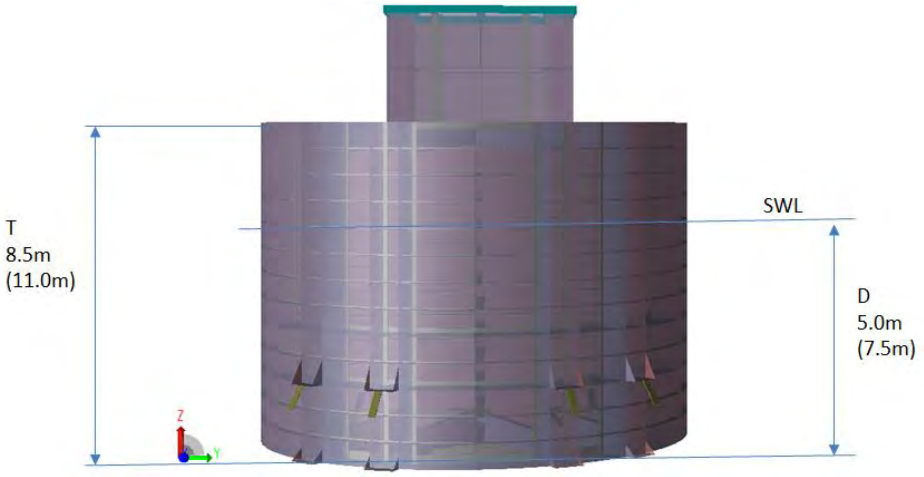


Figure 3-10 frontal view of pontoon with height definitions

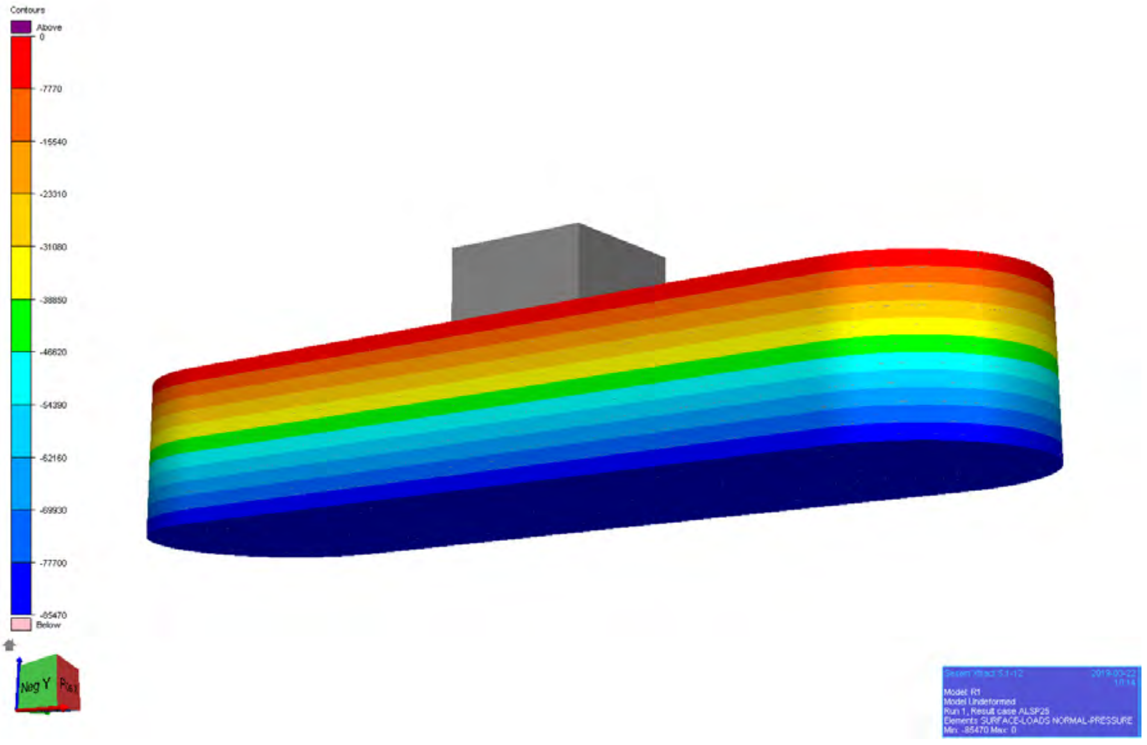


Figure 3-11 Verification of applied external pressure for load case "ALSP25" for "base case" pontoon without mooring lines

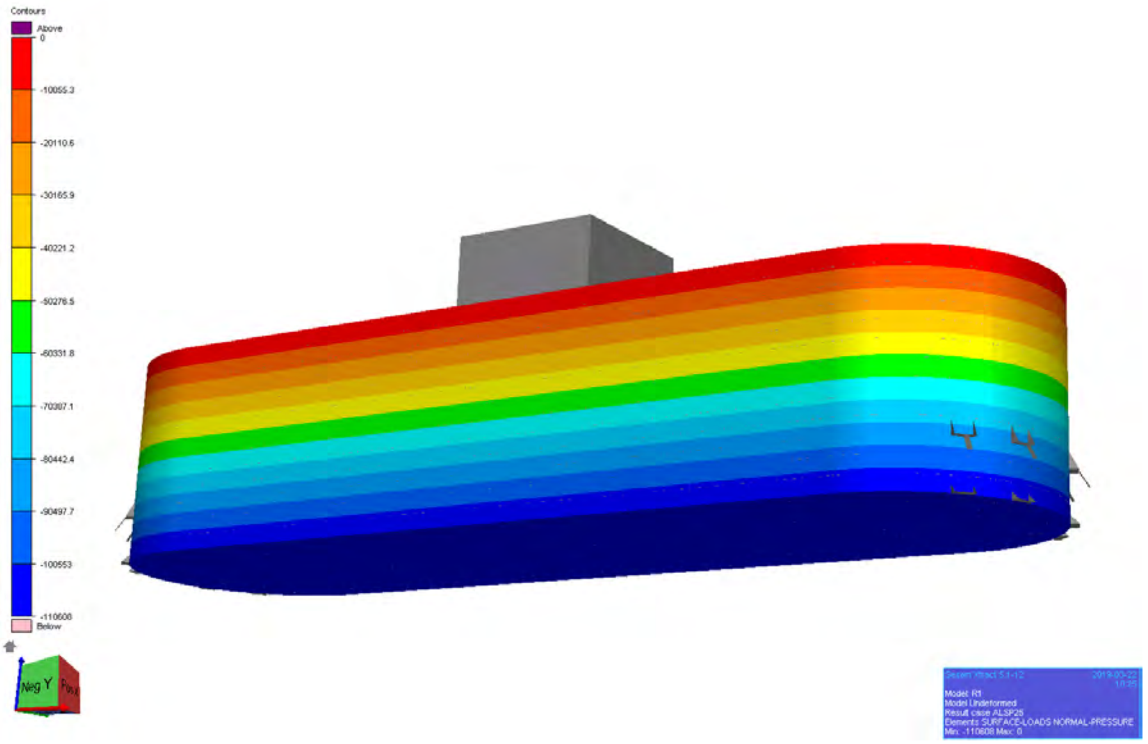


Figure 3-12 Verification of applied external pressure for load case "ALSP25" for "base case" pontoon with mooring lines

3.1.6 ALS loads – filling of pontoon compartments

The “base case” pontoon has been divided into 24 compartments as shown in Figure 3-13. Accidental filling of the pontoon compartments for ALS assessment of the pontoon structure has been considered in the ALS load combinations shown in section 3.1.8 and 3.1.9.

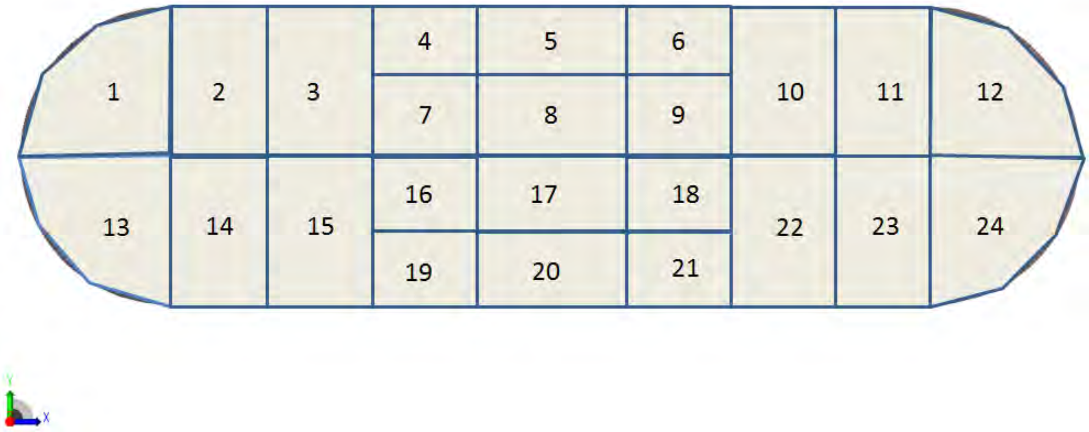


Figure 3-13 Pontoon compartments

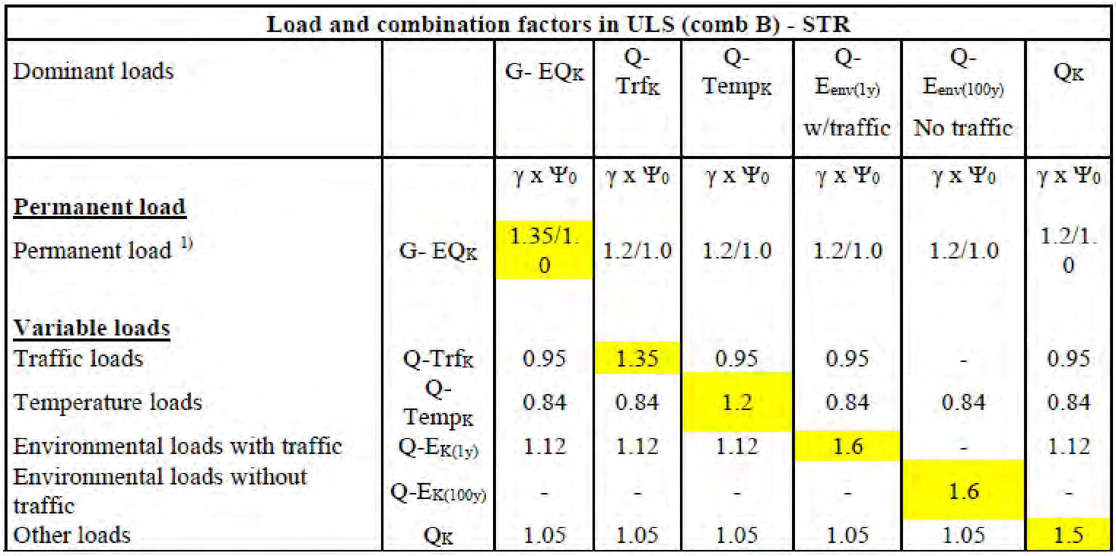
3.1.7 ALS loads – failure in mooring system

The maximum breaking strength (MBL) of one mooring line is combined with the operational mooring line tension for seven mooring lines. MBL = 15000 kN is considered, ref./2/. The same mooring line angles as used for the ULS assessment is used, ref section 3.1.3. The load cases FL1ALS, FL2ALS, FL3ALS, FL4ALS, FL5ALS, FL6ALS, FL7ALS and FL8ALS consist of the MBL of 15000 kN multiplied with a load factor of 1.25 (for one line) and the operation load which is 5620 kN is multiplied with a load factor of 1.3 (for seven lines).

3.1.8 Load combinations – “pontoon base case”

The load factors and load combinations for the pontoon without mooring lines is shown in Table 3-1 and Table 3-2.

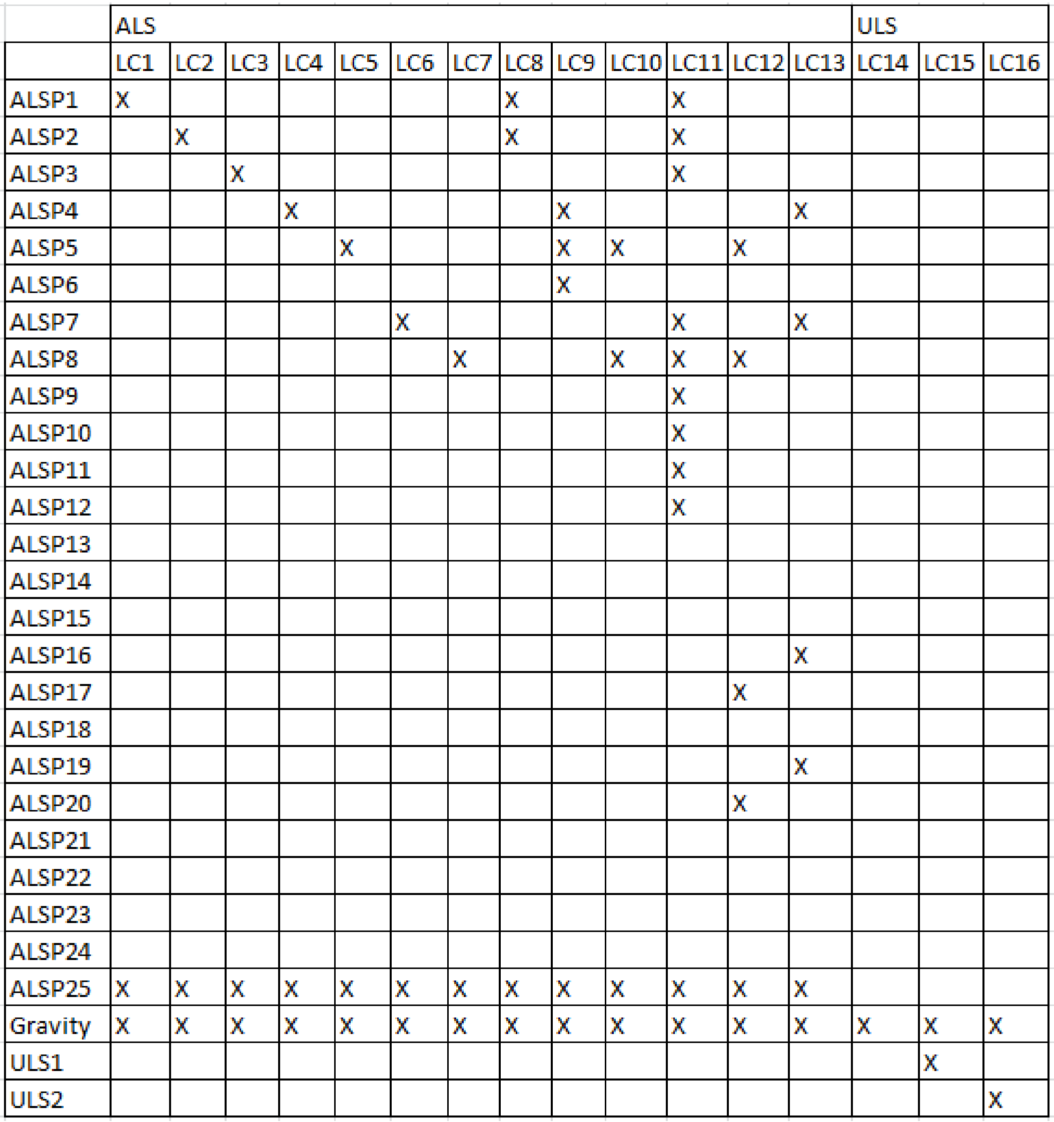
Table 3-1Load and combination factors for ULS



Load and combination factors in ULS (comb B) - STR

Dominant loads		G- EQ$_K$	Q- Trf$_K$	Q- Temp$_K$	Q- E$_{env(1y)}$ w/traffic	Q- E$_{env(100y)}$ No traffic	Q$_K$
		γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0
Permanent load							
Permanent load [1)]	G- EQ$_K$	1.35/1.0	1.2/1.0	1.2/1.0	1.2/1.0	1.2/1.0	1.2/1.0
Variable loads							
Traffic loads	Q-Trf$_K$	0.95	1.35	0.95	0.95	-	0.95
Temperature loads	Q-Temp$_K$	0.84	0.84	1.2	0.84	0.84	0.84
Environmental loads with traffic	Q-E$_{K(1y)}$	1.12	1.12	1.12	1.6	-	1.12
Environmental loads without traffic	Q-E$_{K(100y)}$	-	-	-	-	1.6	-
Other loads	Q$_K$	1.05	1.05	1.05	1.05	1.05	1.5

Table 3-2 Load combinations for pontoon without mooring lines



	ALS													ULS		
	LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8	LC9	LC10	LC11	LC12	LC13	LC14	LC15	LC16
ALSP1	X							X			X					
ALSP2		X						X			X					
ALSP3			X								X					
ALSP4				X					X				X			
ALSP5					X				X	X		X				
ALSP6									X							
ALSP7						X					X		X			
ALSP8							X			X	X	X				
ALSP9											X					
ALSP10											X					
ALSP11											X					
ALSP12											X					
ALSP13																
ALSP14																
ALSP15																
ALSP16													X			
ALSP17												X				
ALSP18																
ALSP19													X			
ALSP20												X				
ALSP21																
ALSP22																
ALSP23																
ALSP24																
ALSP25	X	X	X	X	X	X	X	X	X	X	X	X	X			
Gravity	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ULS1															X	
ULS2																X

3.1.9 Load combinations – “pontoon with mooring lines”

The load factors and load combinations for the pontoon without mooring lines is shown in Table 3-3, Table 3-4 and Table 3-5. The load factor for mooring line loads is 1.25*MBL for ALS condition and 1.3*(mooring line 100 year operating tension) for the ULS condition.

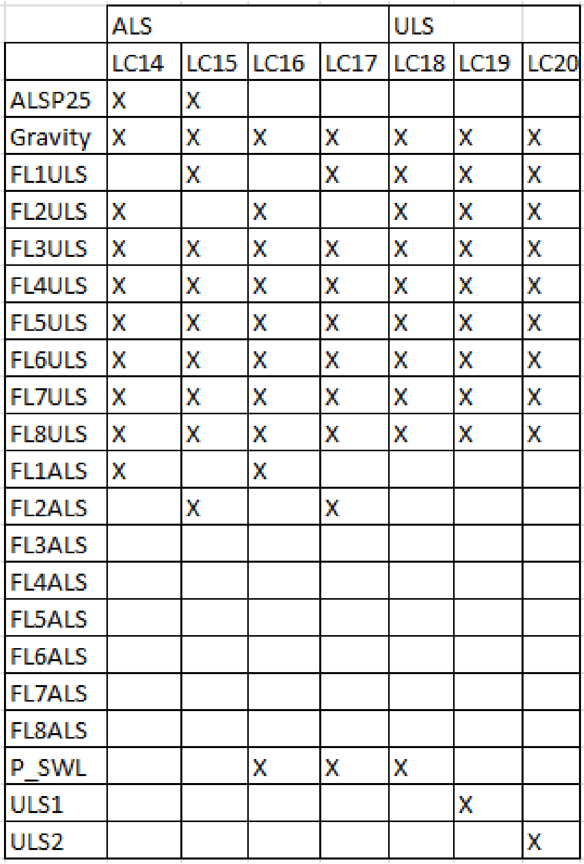
Table 3-3Load and combination factors for ULS

Load and combination factors in ULS (comb B) - STR							
Dominant loads		G- EQ$_K$	Q- Trf$_K$	Q- Temp$_K$	Q- E$_{env(1y)}$ w/traffic	Q- E$_{env(100y)}$ No traffic	Q$_K$
		γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0	γ x Ψ_0
Permanent load							
Permanent load $^{1)}$	G- EQ$_K$	1.35/1.0	1.2/1.0	1.2/1.0	1.2/1.0	1.2/1.0	1.2/1.0
Variable loads							
Traffic loads	Q-Trf$_K$	0.95	1.35	0.95	0.95	-	0.95
Temperature loads	Q-Temp$_K$	0.84	0.84	1.2	0.84	0.84	0.84
Environmental loads with traffic	Q-E$_{K(1y)}$	1.12	1.12	1.12	1.6	-	1.12
Environmental loads without traffic	Q-E$_{K(100y)}$	-	-	-	-	1.6	-
Other loads	Q$_K$	1.05	1.05	1.05	1.05	1.05	1.5

Table 3-4 Load combinations for pontoon with mooring lines

	ALS												
	LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8	LC9	LC10	LC11	LC12	LC13
ALSP1	X							X			X		
ALSP2		X						X			X		
ALSP3			X								X		
ALSP4				X					X				X
ALSP5					X				X	X		X	
ALSP6									X				
ALSP7						X					X		X
ALSP8							X			X	X	X	
ALSP9											X		
ALSP10											X		
ALSP11											X		
ALSP12											X		
ALSP13													
ALSP14													
ALSP15													
ALSP16													X
ALSP17												X	
ALSP18													
ALSP19													X
ALSP20												X	
ALSP21													
ALSP22													
ALSP23													
ALSP24													
ALSP25	X	X	X	X	X	X	X	X	X	X	X	X	X
Gravity	X	X	X	X	X	X	X	X	X	X	X	X	X
P_SWL													
ULS1													
ULS2													

Table 3-5 Load combinations for pontoon with mooring lines



	ALS				ULS		
	LC14	LC15	LC16	LC17	LC18	LC19	LC20
ALSP25	X	X					
Gravity	X	X	X	X	X	X	X
FL1ULS		X		X	X	X	X
FL2ULS	X		X		X	X	X
FL3ULS	X	X	X	X	X	X	X
FL4ULS	X	X	X	X	X	X	X
FL5ULS	X	X	X	X	X	X	X
FL6ULS	X	X	X	X	X	X	X
FL7ULS	X	X	X	X	X	X	X
FL8ULS	X	X	X	X	X	X	X
FL1ALS	X		X				
FL2ALS		X		X			
FL3ALS							
FL4ALS							
FL5ALS							
FL6ALS							
FL7ALS							
FL8ALS							
P_SWL			X	X	X		
ULS1						X	
ULS2							X

3.1.10 Material factors

The material factors considered in the analyses are γ_{M2} = 1.10 for the ULS strength check and γ_{M2} = 1.00 for the ALS strength check.

3.2 Acceptance criteria

The allowable stress limit for yield assessment is as follows:

- ULS: $\sigma_{Allowable}$ = 355/1.1 MPa = 322 MPa for steel quality S355
- ULS: $\sigma_{Allowable}$ = 550/1.1 MPa = 500 MPa for steel quality SDSS
- ALS: $\sigma_{Allowable}$ = 355/1.0 MPa = 355 MPa for steel quality S355
- ALS: $\sigma_{Allowable}$ = 550/1.0 MPa = 550 MPa for steel quality SDSS

For buckling and scantling assessment the material factor for ULS condition is γ_m = 1.1 and for ALS condition the material factor γ_m = 1.0 is used. With allowable utilisation of 1.0.

4 FE analysis – pontoon base case

4.1 Description of FE model

A finite element model is made of the "base case" pontoon without mooring lines using DNVGL Sesam Software GeniE. A combination of 2nd order beam elements and plate elements has been used. The mesh size is set to 500 mm.

4.2 Applied loads

The considered ULS load cases for the "pontoon base case" are shown in Figure 4-1 and Figure 4-2 and consist of only external sea pressure as described in section 3.1.1 and 3.1.3. The considered ALS load combinations for the "pontoon base case" are shown in Figure 4-3 through Figure 4-15 and is described in section 3.1.6 and 3.1.7.

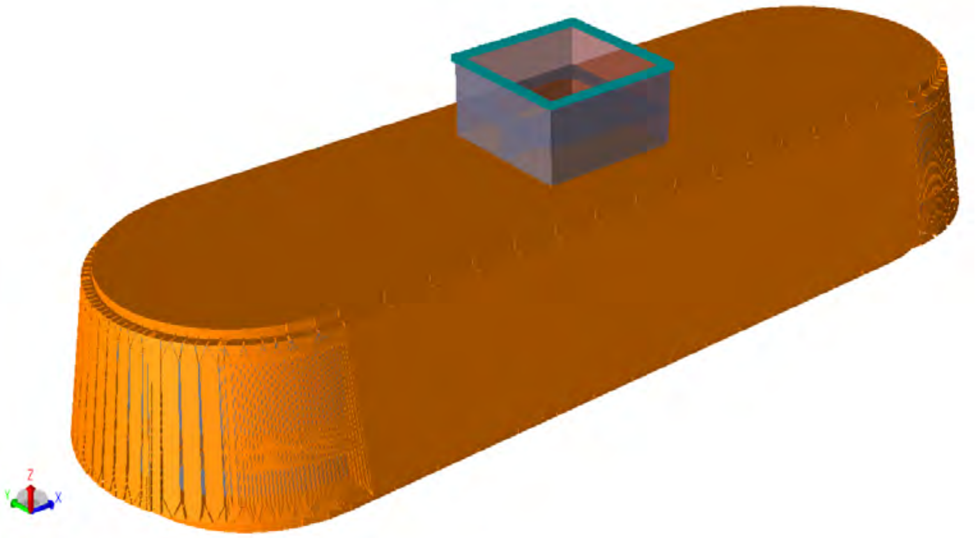


Figure 4-1 Load case "ULS1"

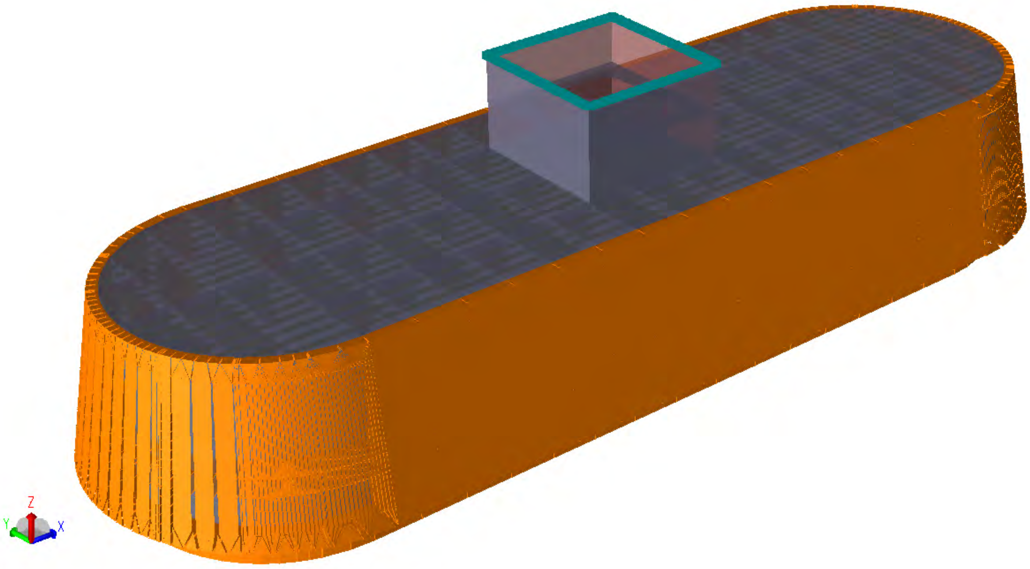


Figure 4-2 Load case "ULS2"

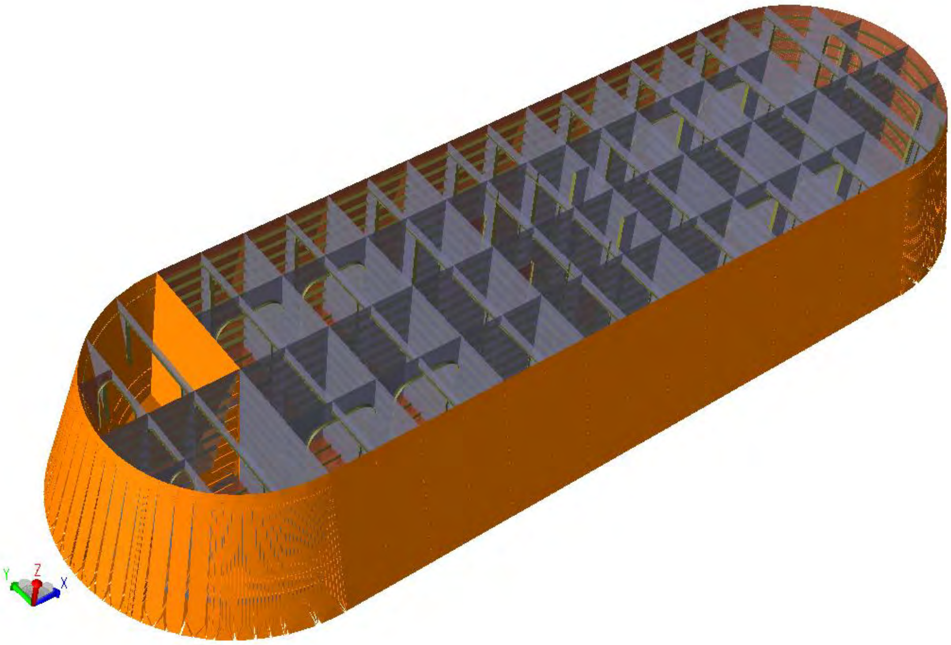


Figure 4-3 ALS load combination "LC1"

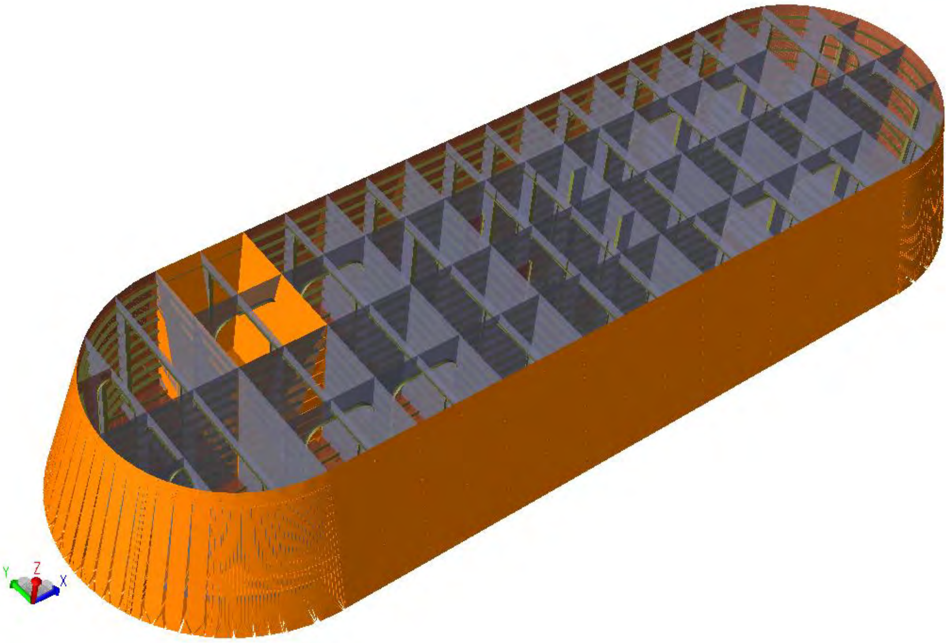


Figure 4-4 ALS load combination "LC2"

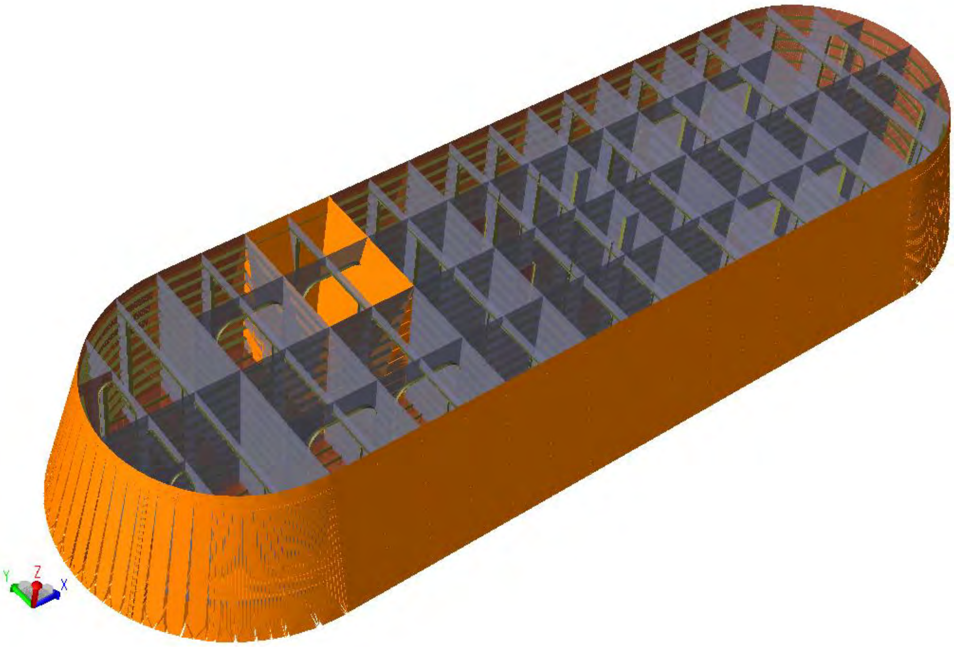


Figure 4-5 ALS load combination "LC3"

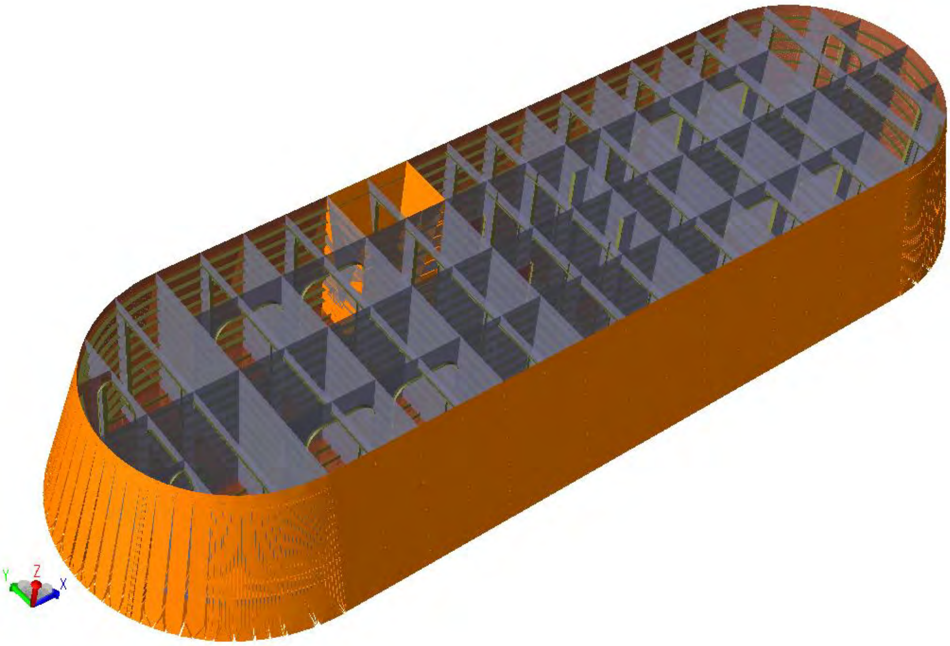


Figure 4-6 ALS load combination "LC4"

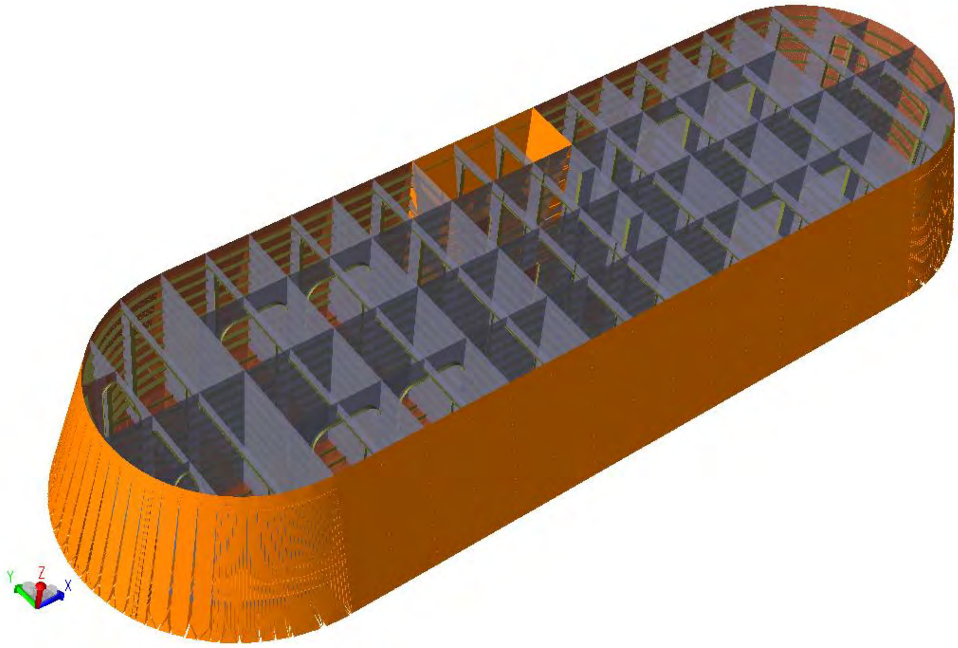


Figure 4-7 ALS load combination "LC5"

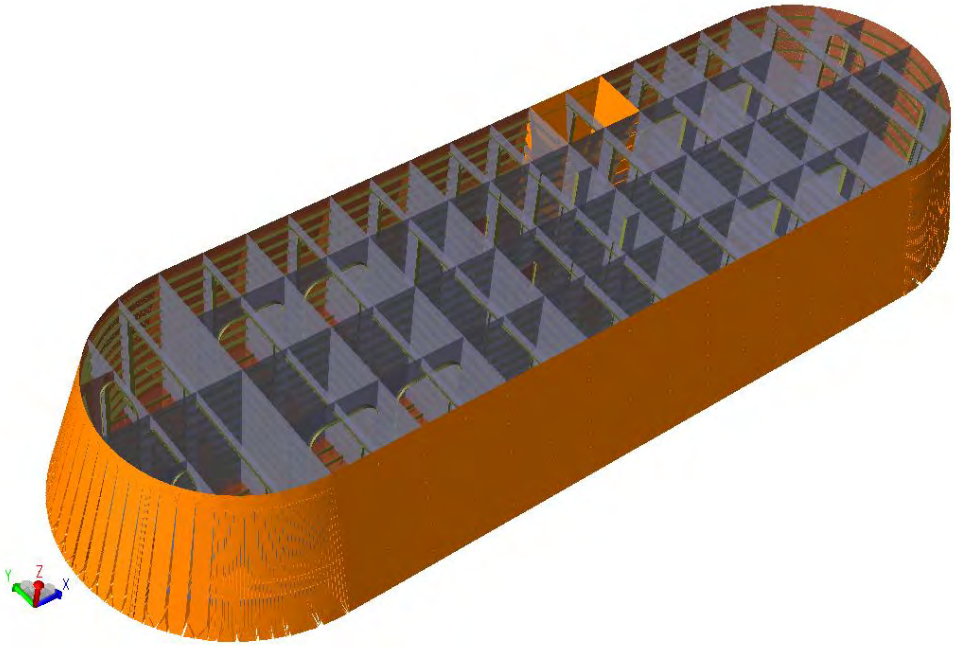


Figure 4-8 ALS load combination "LC6"

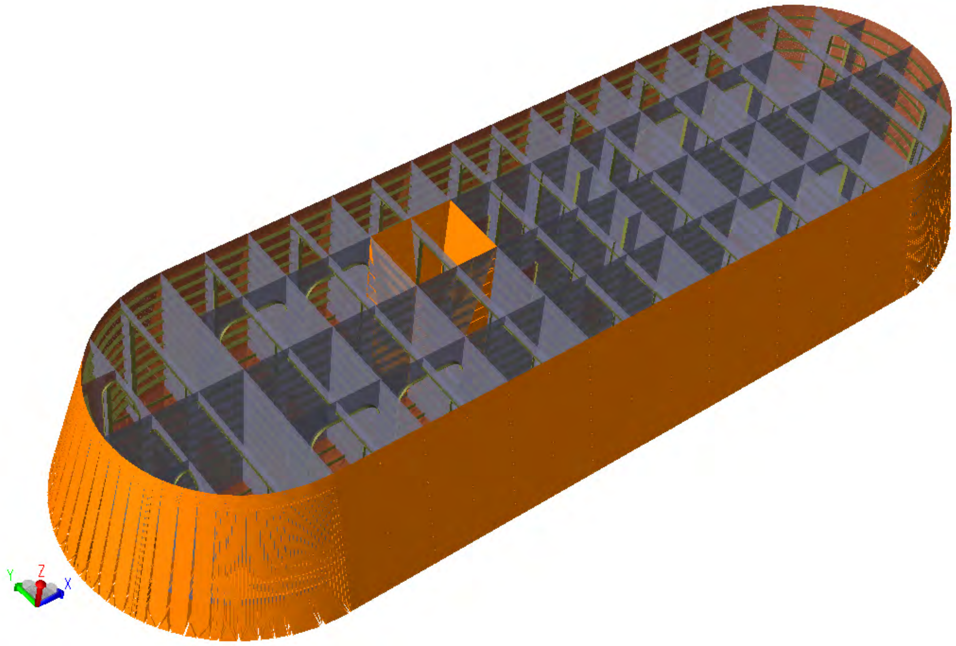


Figure 4-9 ALS load combination "LC7"

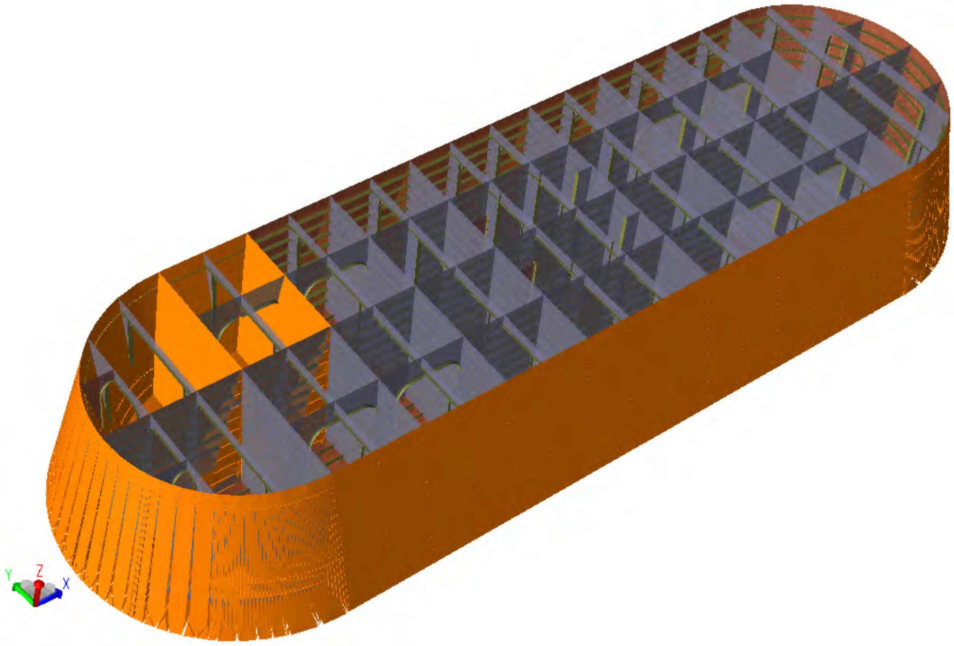


Figure 4-10 ALS load combination "LC8"

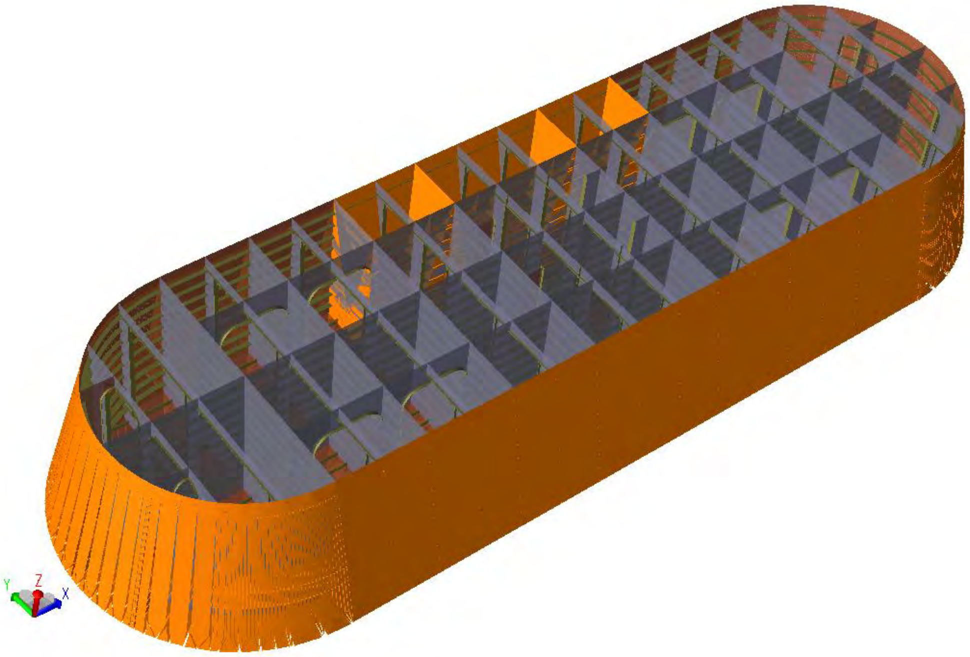


Figure 4-11 ALS load combination "LC9"

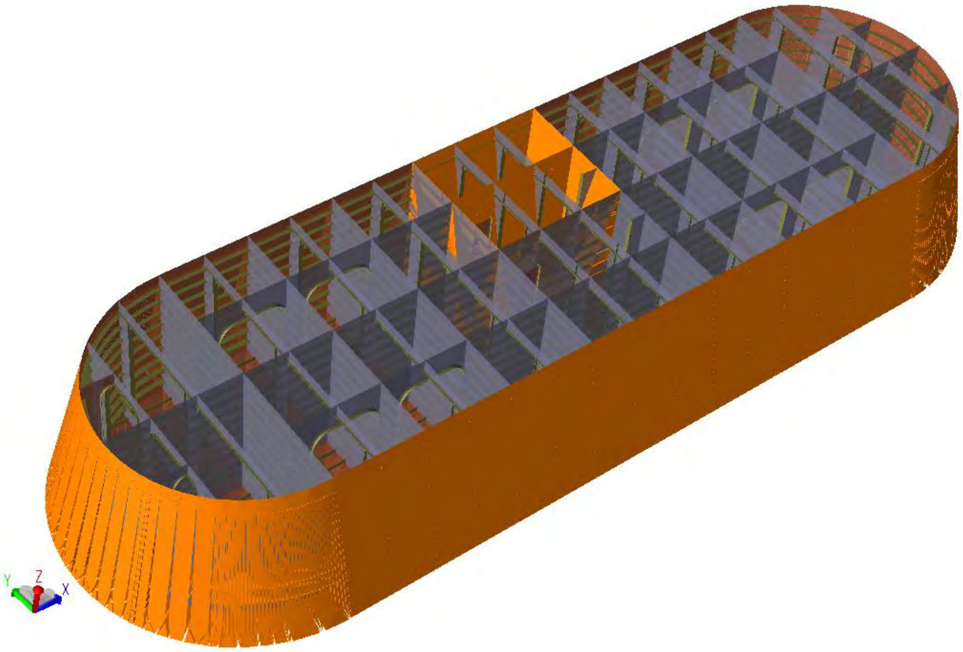


Figure 4-12 ALS load combination "LC10"

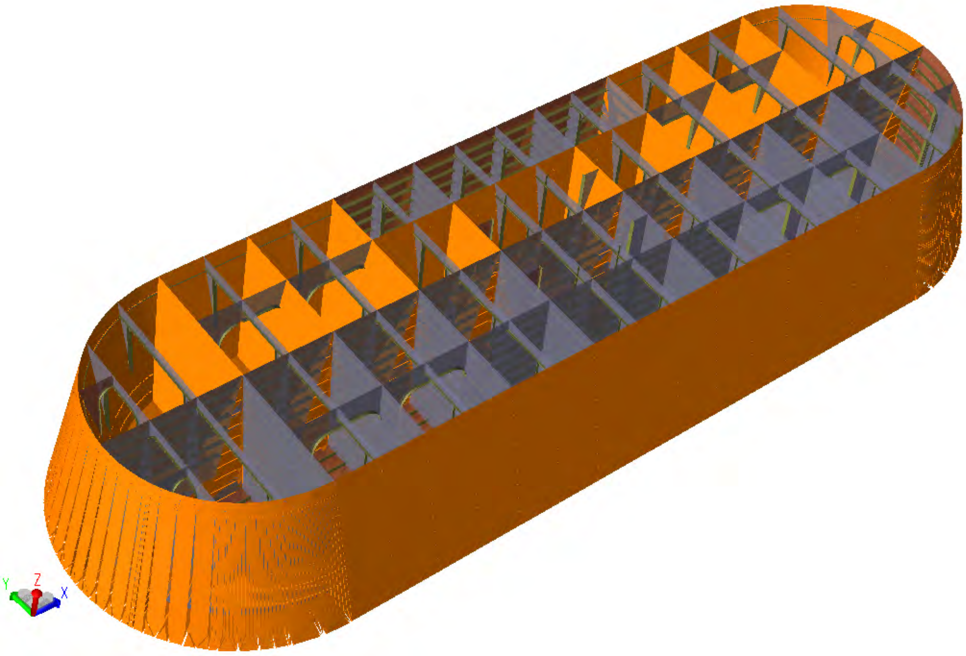


Figure 4-13 ALS load combination "LC11"

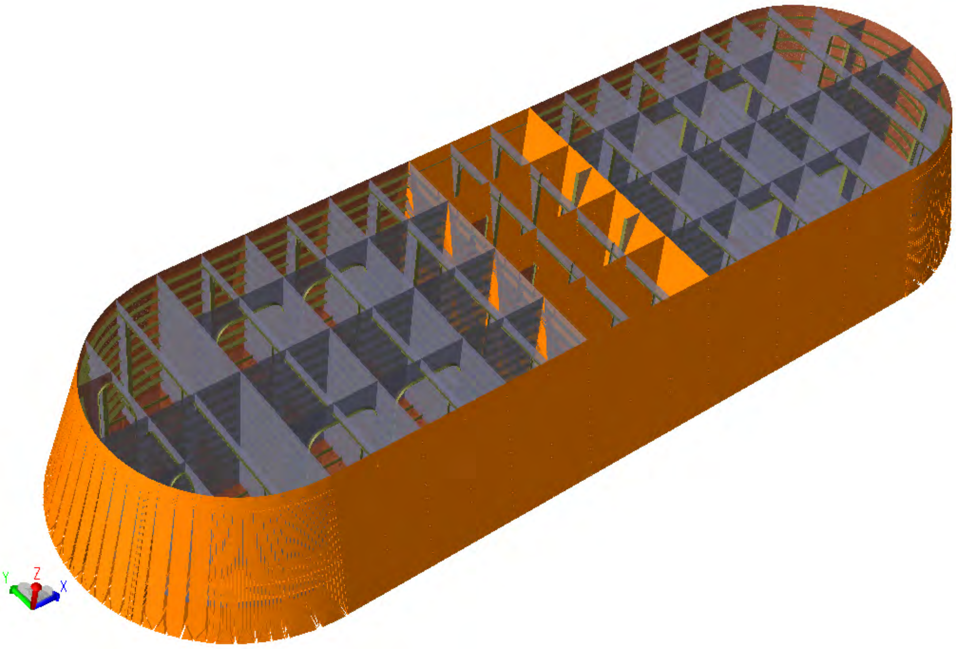


Figure 4-14 ALS load combination "LC12"

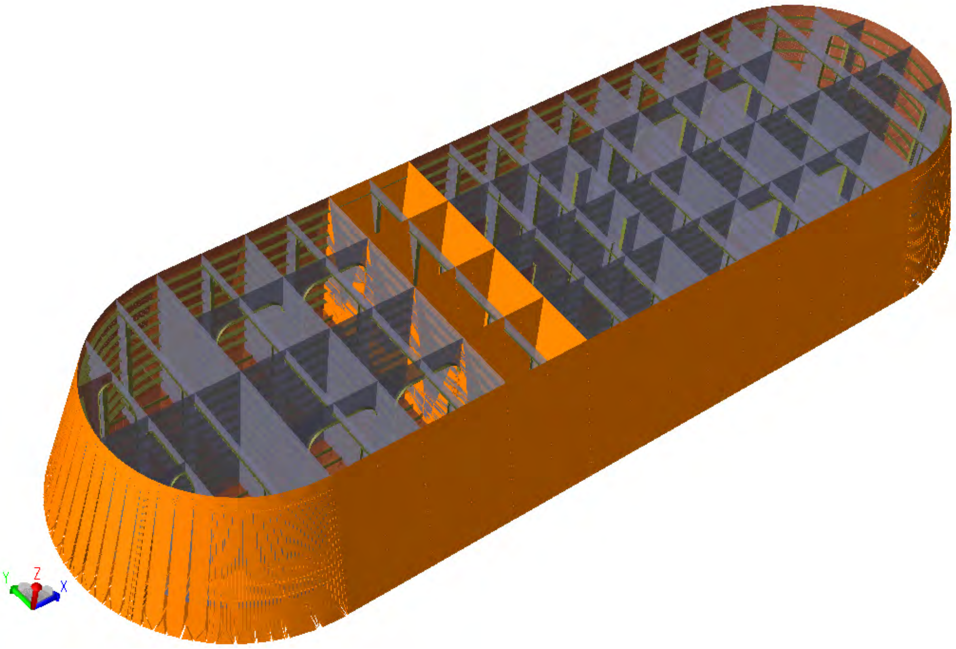


Figure 4-15 ALS load combination "LC13"

4.3 Boundary conditions

The boundary conditions are applied to the lower part of the column and are shown in Figure 4-16. All degrees of freedom are fixed.

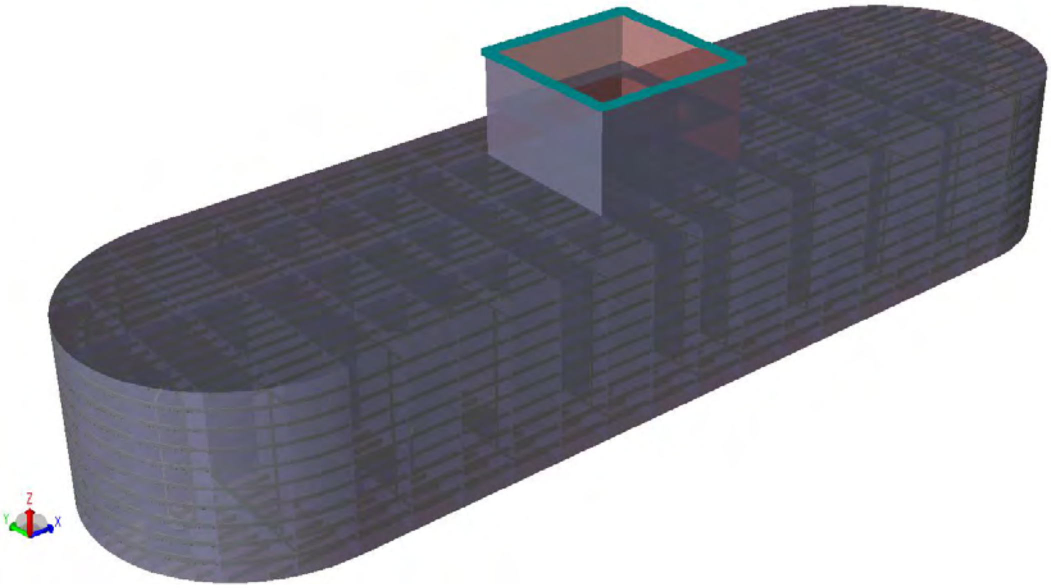


Figure 4-16 Boundary condition

4.4 Material dimensions

The plate thicknesses and stiffener dimensions used for the "pontoon base case" is shown in Figure 4-17 through Figure 4-27

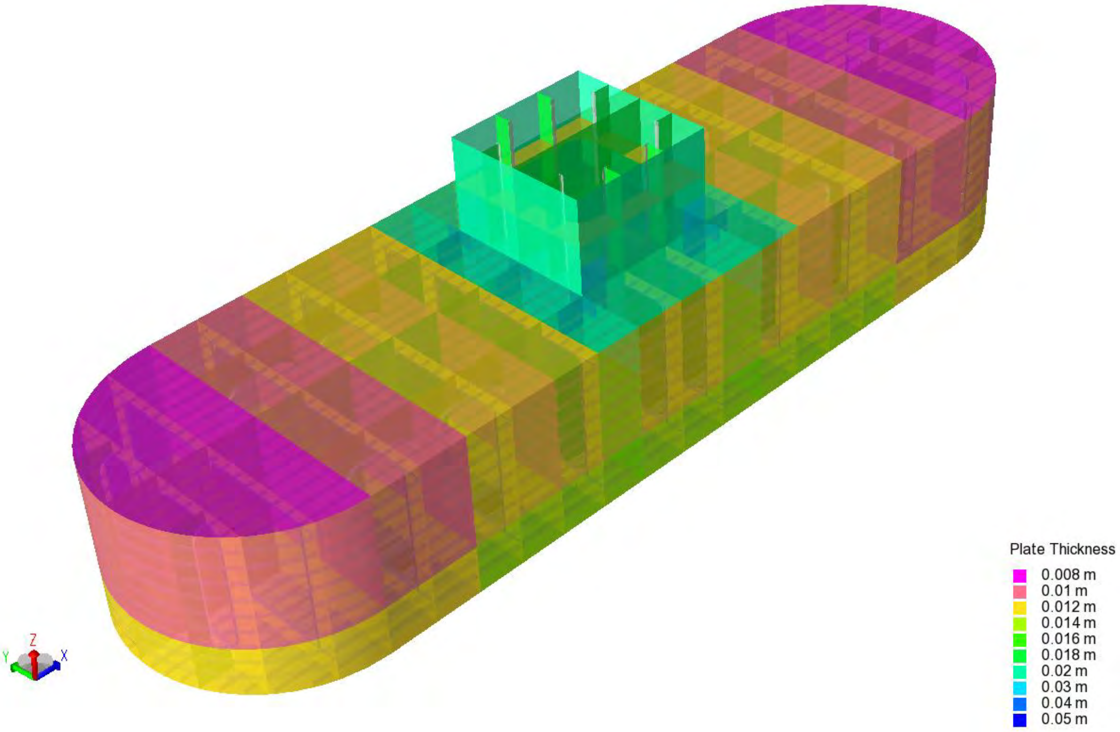


Figure 4-17 Material thicknesses [m]

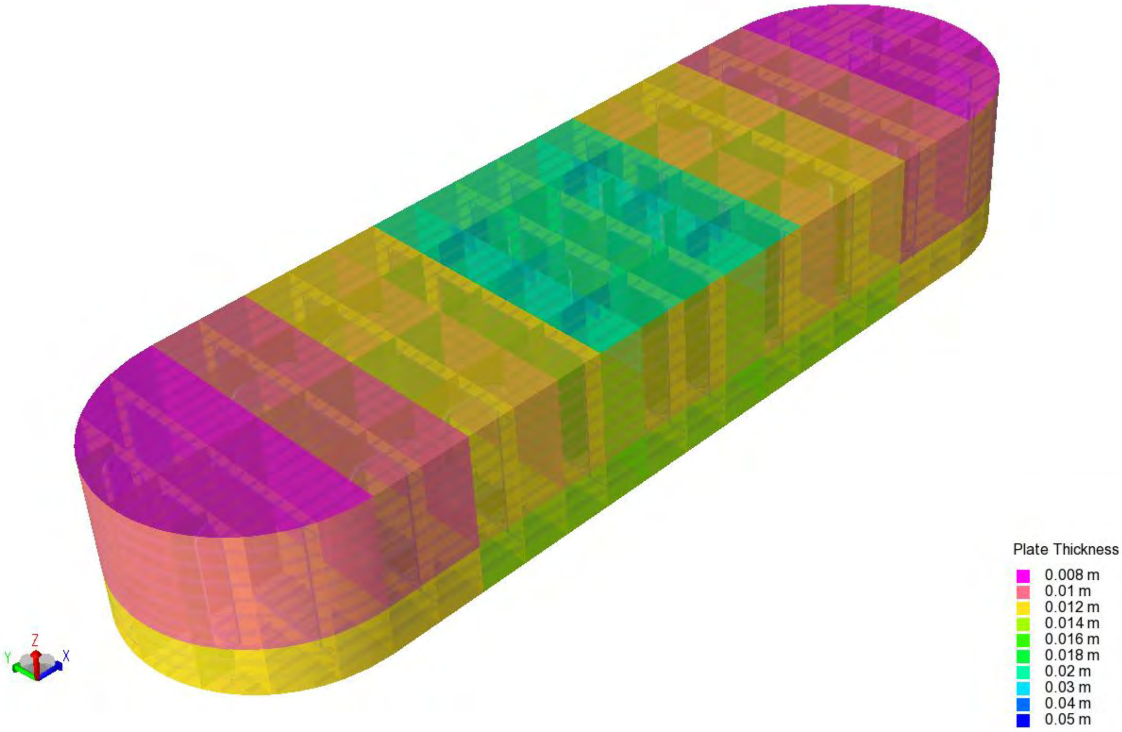


Figure 4-18 Material thicknesses [m]

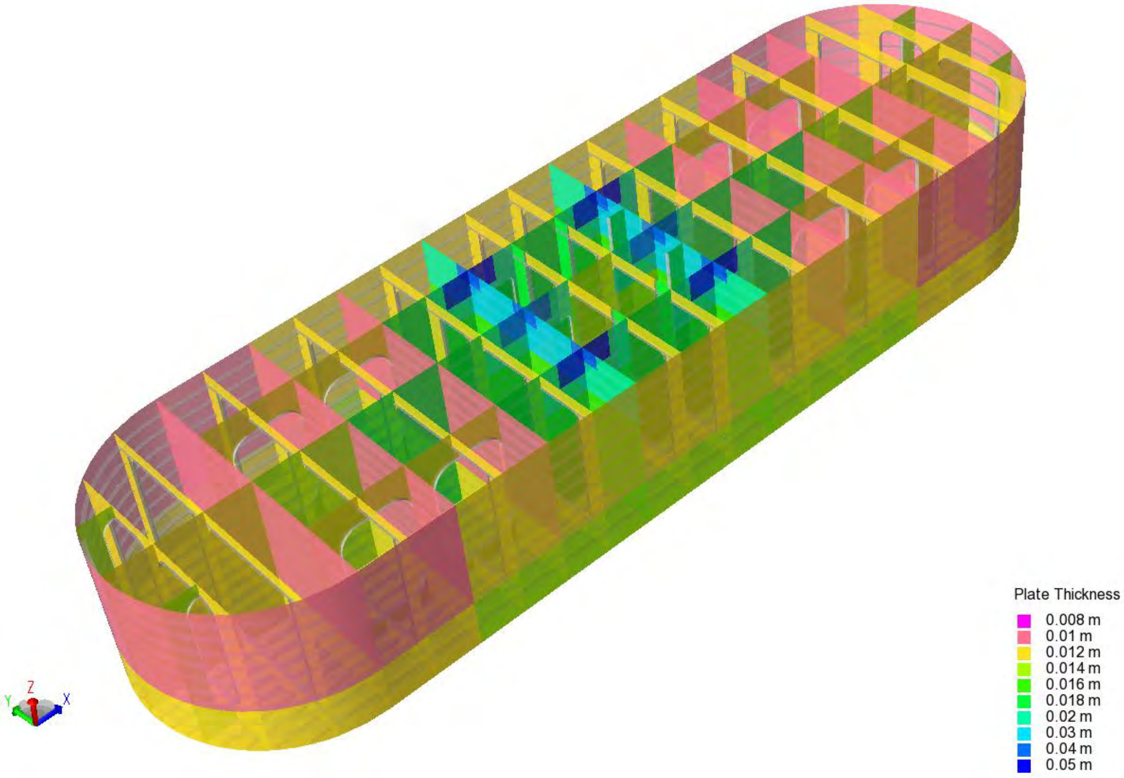


Figure 4-19 Material thicknesses [m]

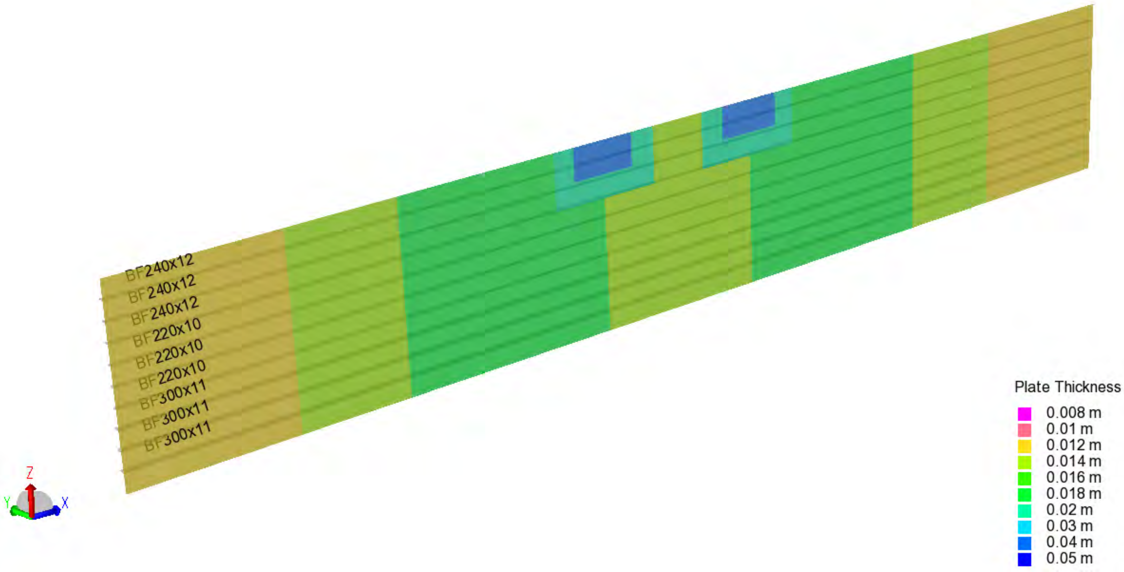


Figure 4-20 Material thicknesses [m] and section names, CL longitudinal bulkhead

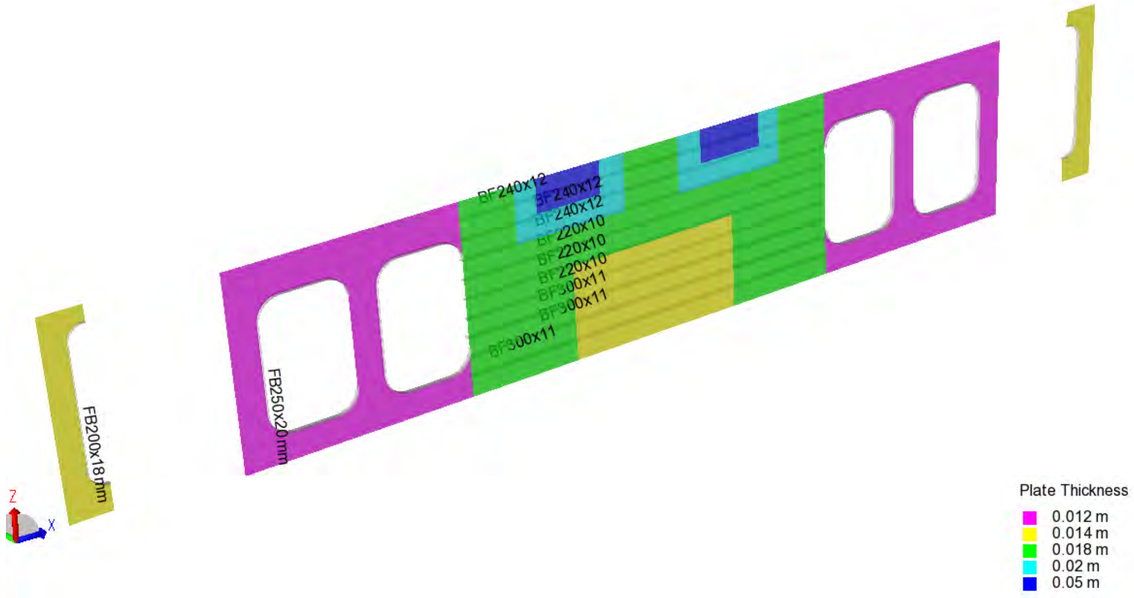


Figure 4-21 Material thicknesses [m] and section names, longitudinal bulkhead 4.0 m of CL

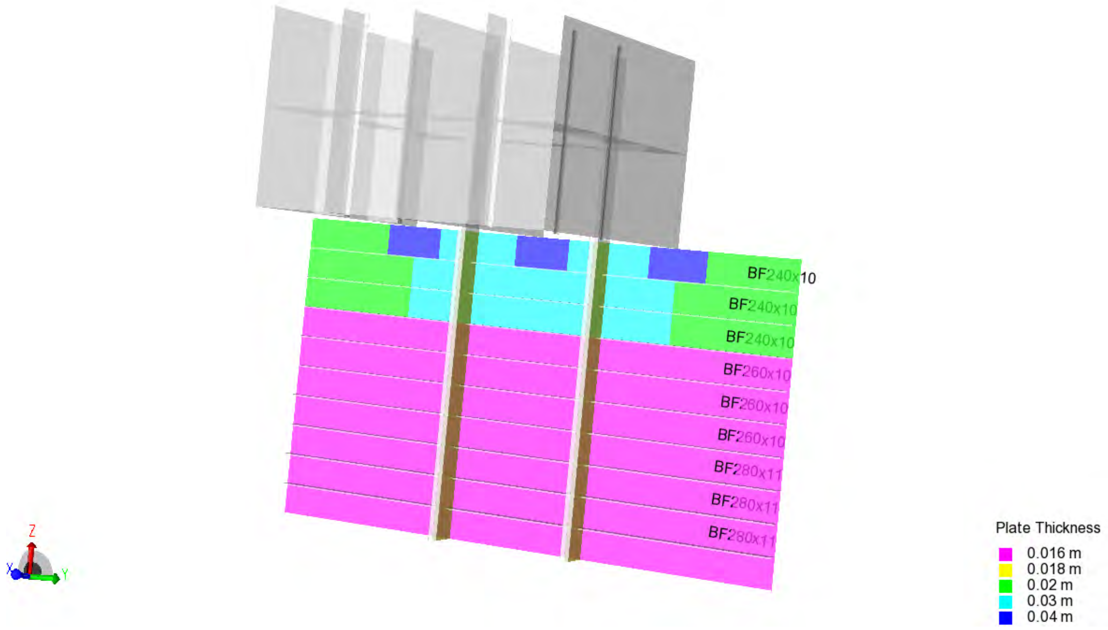


Figure 4-22 Material thicknesses [m] and section names, transverse bulkhead underneath column

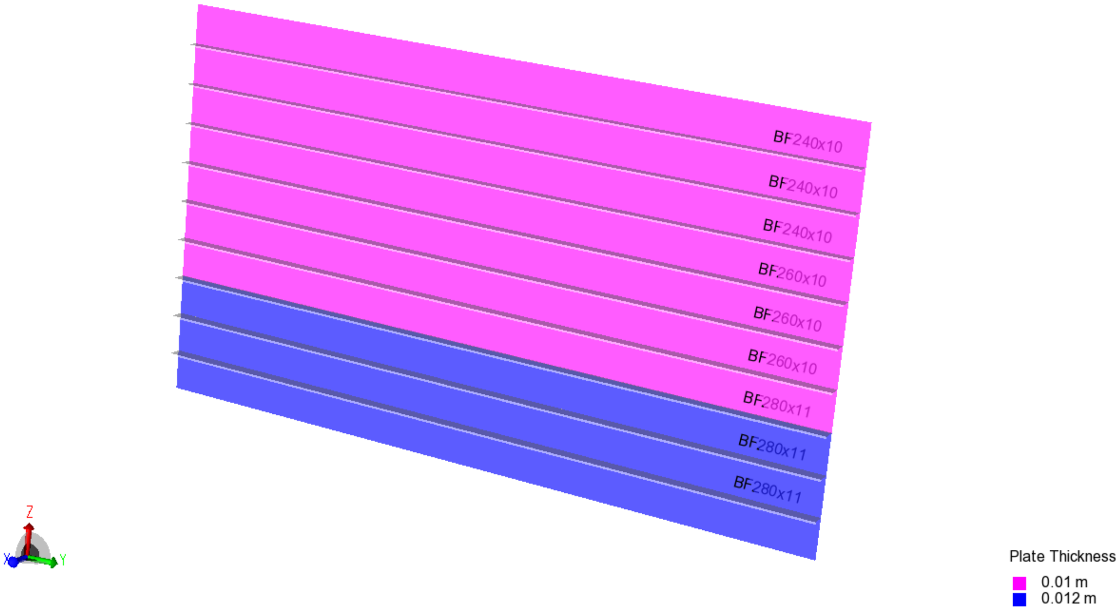


Figure 4-23 Material thicknesses [m] and section names, typical transverse bulkhead

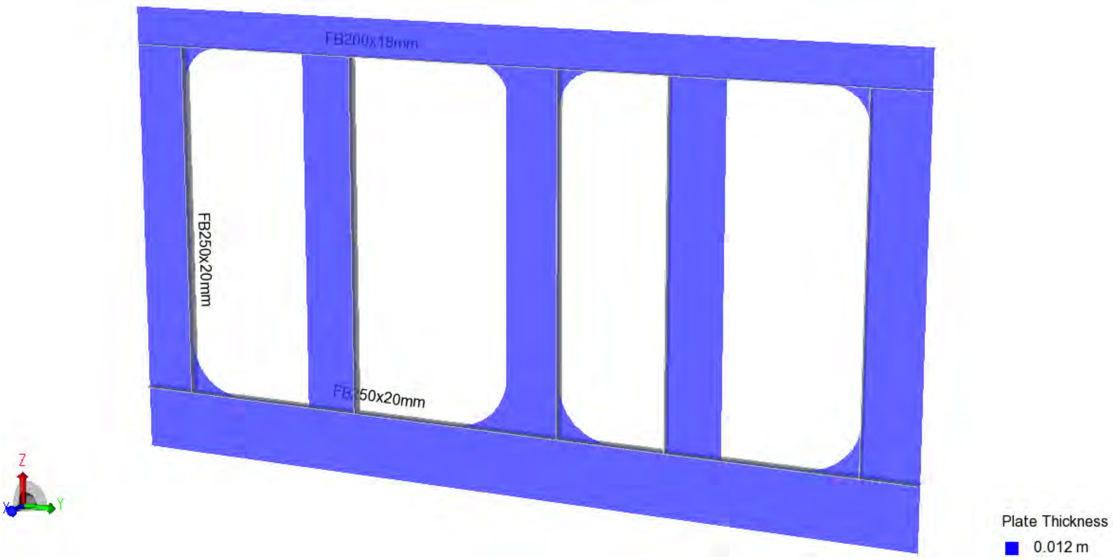


Figure 4-24 Material thicknesses [m] and section names, typical transverse web-frame

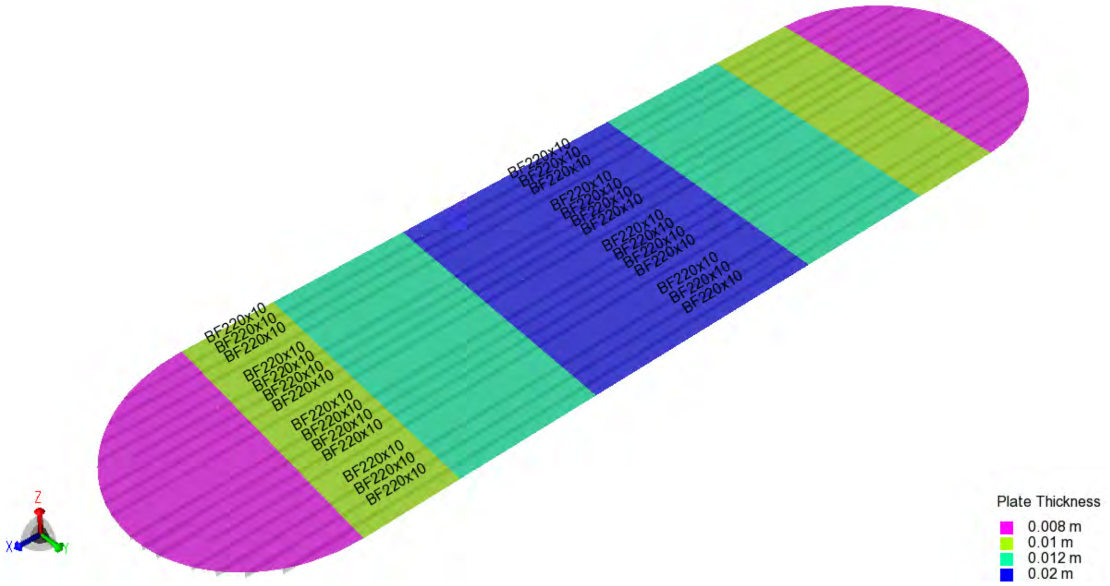


Figure 4-25 Material thicknesses [m] and section names, pontoon top plate

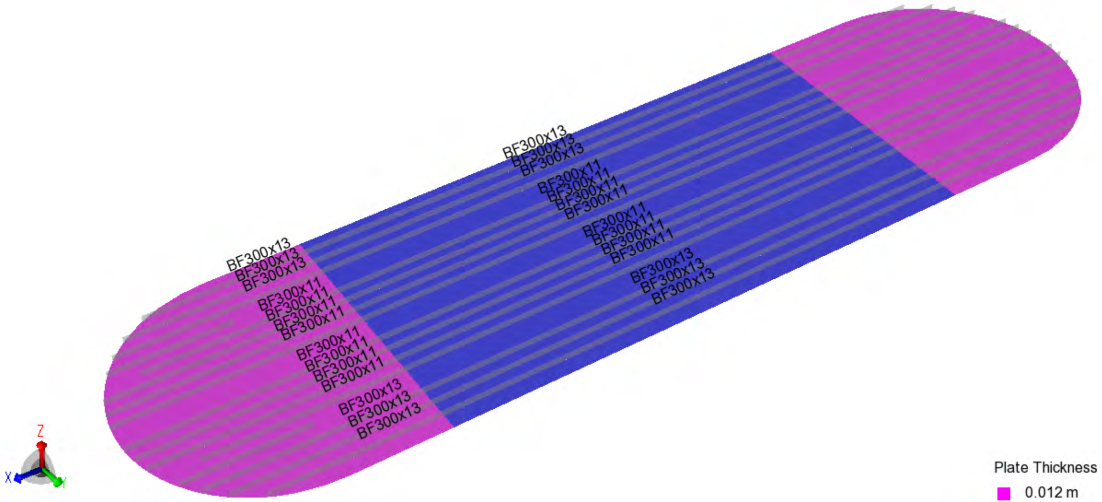


Figure 4-26 Material thicknesses [m] and section names, pontoon bottom plate

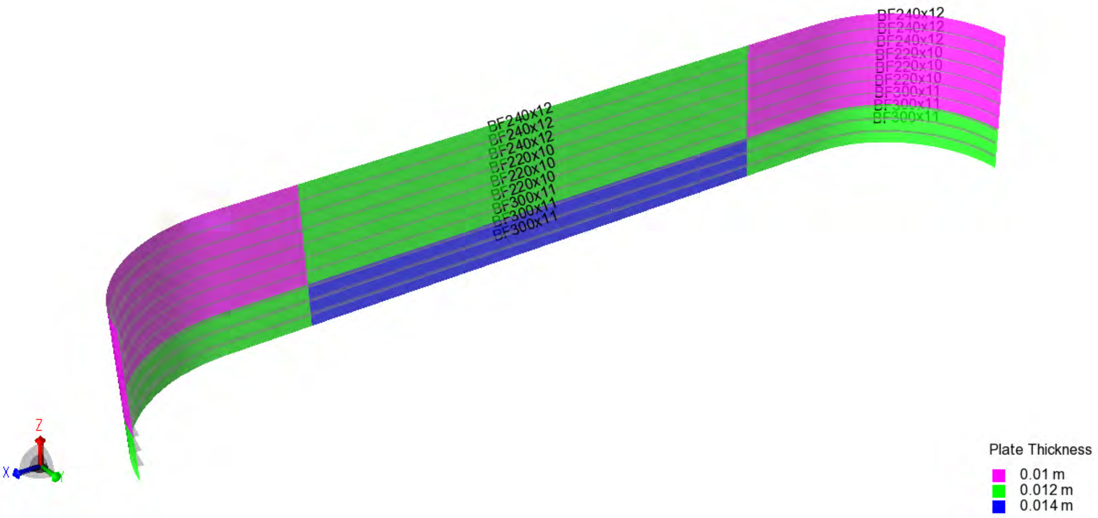


Figure 4-27 Material thicknesses [m] and section names, pontoon side shell

4.5 Results

Note that the steel quality has been changed from S355 to S420 after the analysis presented below was performed. Hence; the allowable stresses are somewhat higher compared to upper limit in the stress plots shown. In addition, the results presented in Table 4-1 will be conservative, the pontoons buckling capacity will be increased after increasing the yield strength.

Note that the thickness of the outer shell was changed after changed after the analyses were performed; the plate joint at elevation 2600mm was moved 600mm down. This was done to limit number of plate joints in the splash zone. The thickness change is assumed to have minimal effect on the results taken the stress levels presented in the following into account.

In addition the tank plan has been changed; the longitudinal bulkheads located 4000mm from centre line has been made watertight. The plate thickness of the bulkheads is similar as shown in Figure 4-21, i.e. 12mm. The centre line bulkhead is made non-watertight by introducing manholes. These changes are not assumed to have any negative effect on the structural strength of the pontoon. The pontoon will be more robust against collisions from striking vessels hitting the side of the pontoon with a small angle

4.5.1 Yield assessment

The yield assessment is based on scan of maximum von Mises membrane stresses for the ULS and ALS conditions respectively. Allowable stress limits are set according to the relevant limit state as follows:

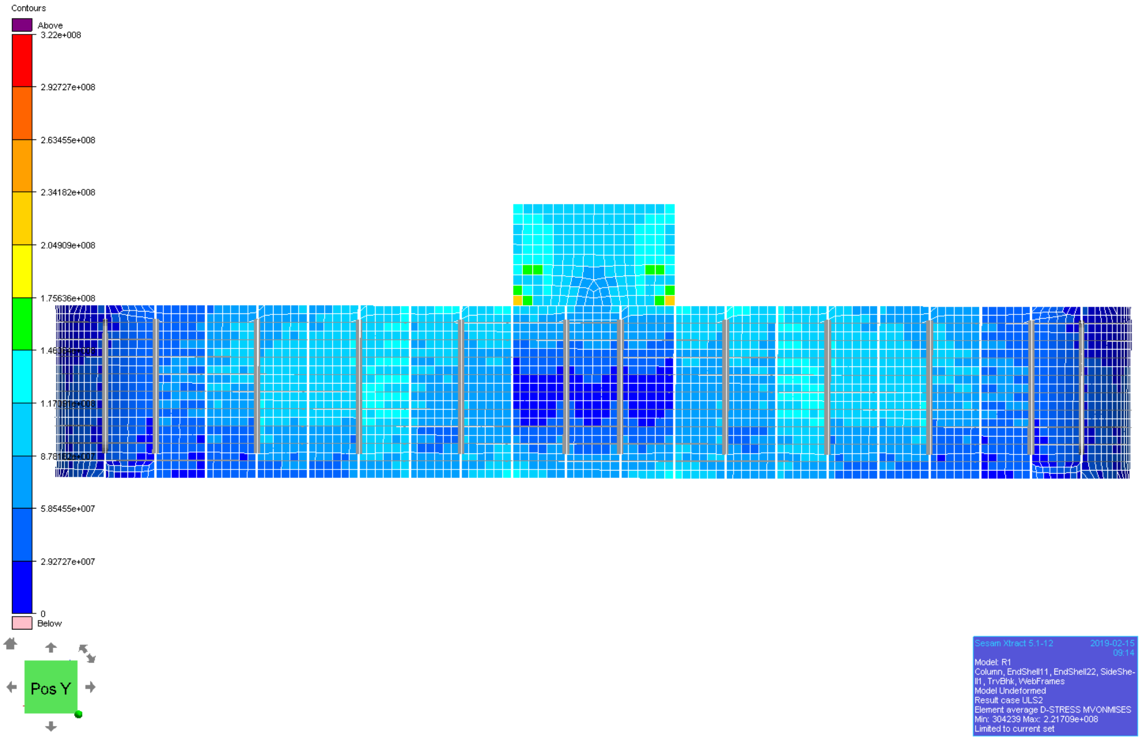
- ULS: $\sigma_{Allowable}$ = 355/1.1 MPa = 322 MPa for steel quality S355

- ULS: $\sigma_{Allowable}$ = 550/1.1 MPa = 500 MPa for steel quality SDSS

- ALS: $\sigma_{Allowable}$ = 355/1.0 MPa = 355 MPa for steel quality S355

- ALS: $\sigma_{Allowable}$ = 550/1.0 MPa = 550 MPa for steel quality SDSS

The yield assessment performed for the “pontoon base case” shows that the proposed structure scantling has sufficient strength. The results are shown in Figure 4-28 through Figure 4-41.



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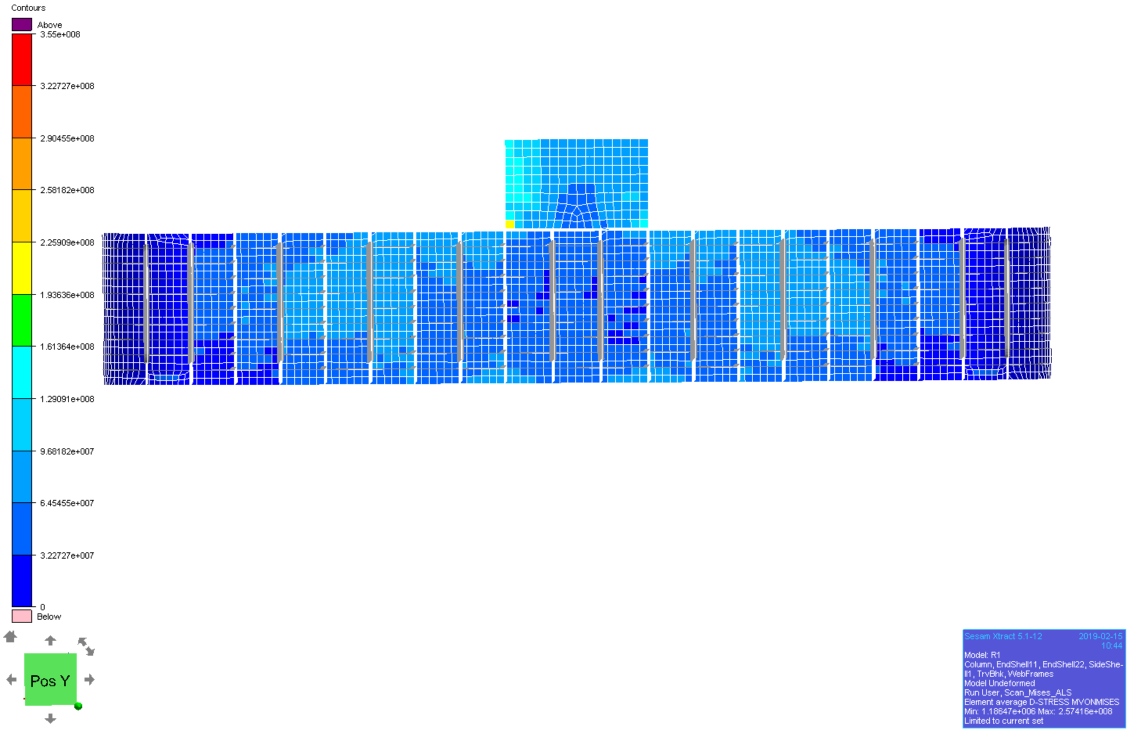
Column, EndShell11, EndShell22, SideShell1, TrvBhk, WebFrames
Model Undeformed
Result case ULS2
Element average D-STRESS MVONMISES
Min: 304239 Max: 2.21709e+008
Limited to current set

Figure 4-28 von Mises stresses for load case “ULS2” [N/m^2] outer side shell



Sesam Xtract 5.1-12 2019-02-15 10:44
Model: R1
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Model Undeformed
Run User, Scan_Mises_ALS
Element average D-STRESS MVONMISES
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Limited to current set

Figure 4-29 Scan of von Mises stresses for the ALS load combinations [N/m^2] outer side shell

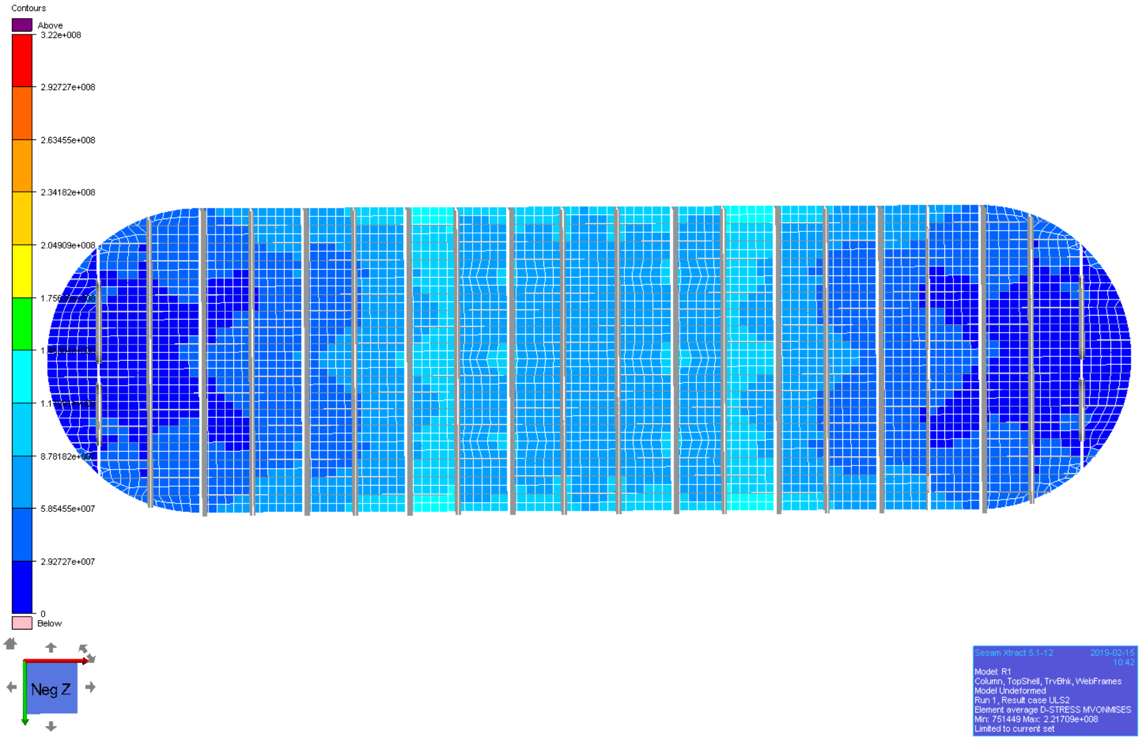


Figure 4-30 von Mises stresses for load case "ULS2" [N/m^2] outer top shell

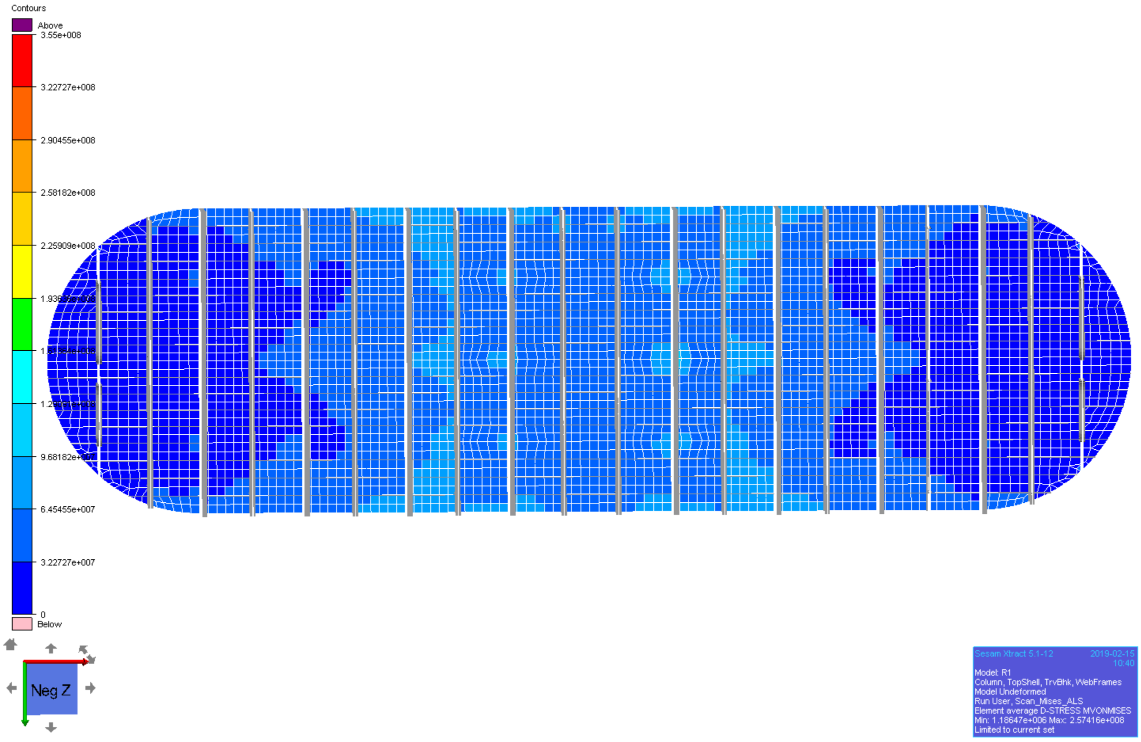
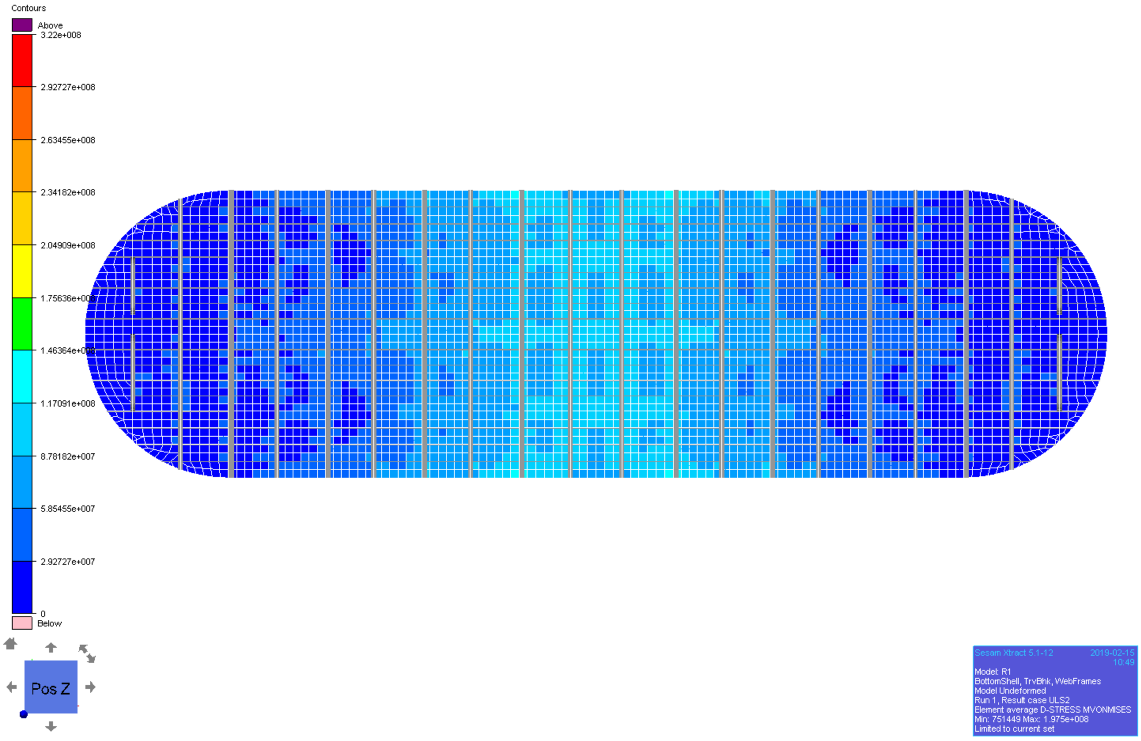


Figure 4-31 Scan of von Mises stresses for the ALS load combinations [N/m^2] outer top shell



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Sesam Xtract 5.1-12          2019-02-15
                                  10:49
Model: R1
BottomShell, TrvBhk, WebFrames
Model Undeformed
Run 1, Result case ULS2
Element average D-STRESS MVONMISES
Min: 751449 Max: 1.975e+008
Limited to current set
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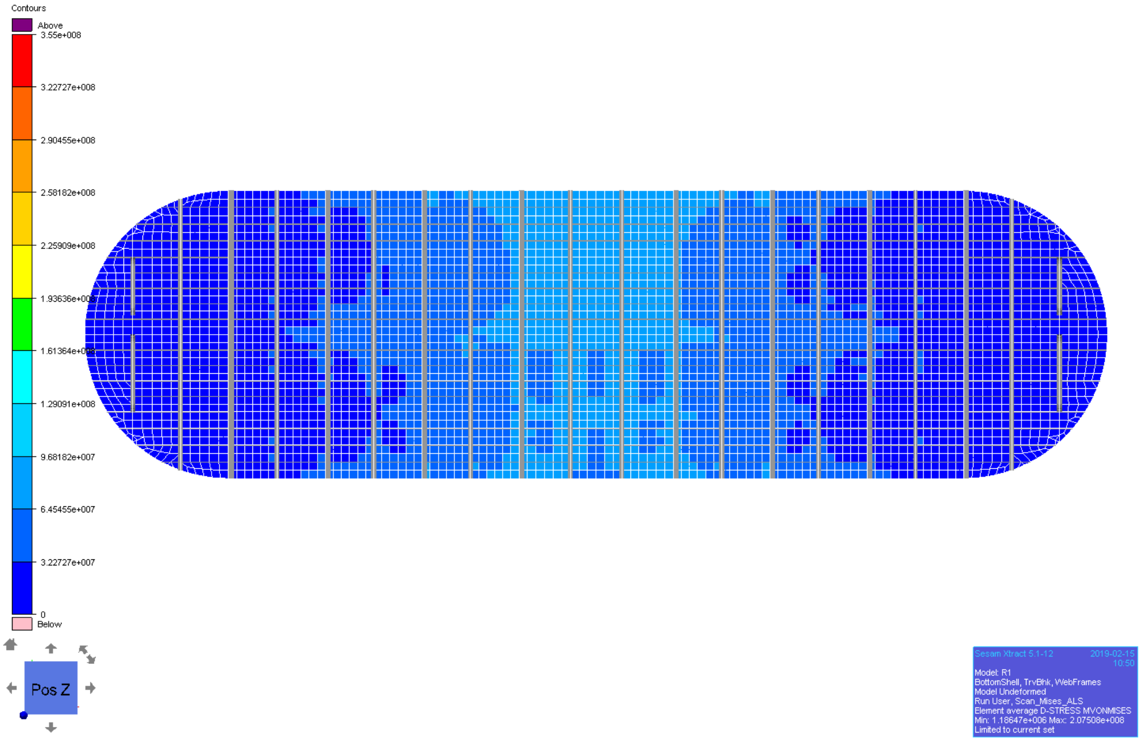
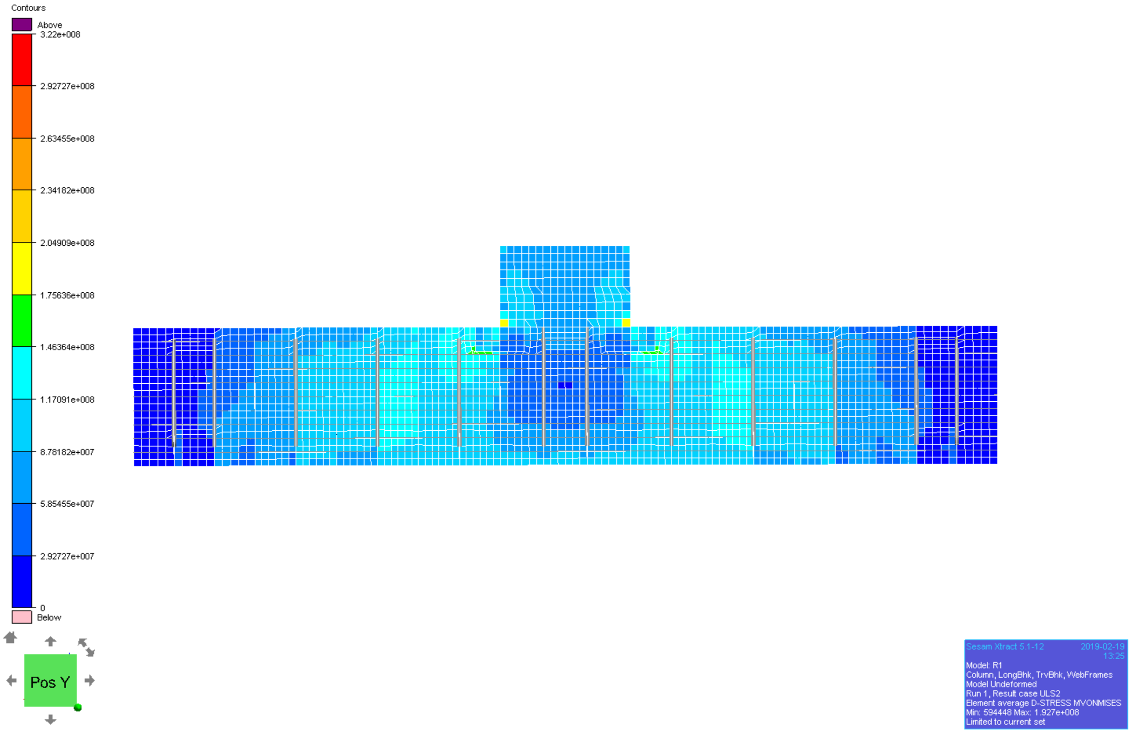
Figure 4-32 von Mises stresses for load case "ULS2" [N/m^2] outer bottom shell



```
Sesam Xtract 5.1-12          2019-02-15
                                  10:50
Model: R1
BottomShell, TrvBhk, WebFrames
Model Undeformed
Run User, Scan_Mises_ALS
Element average D-STRESS MVONMISES
Min: 1.18647e+006 Max: 2.07508e+008
Limited to current set
```

Figure 4-33 Scan of von Mises stresses for the ALS load combinations [N/m^2] outer bottom shell



```
Sesam Xtract 5.1-12          2019-02-19
                                  13:25
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run 1, Result case ULS2
Element average D-STRESS MVONMISES
Min: 594448 Max: 1.927e+008
Limited to current set
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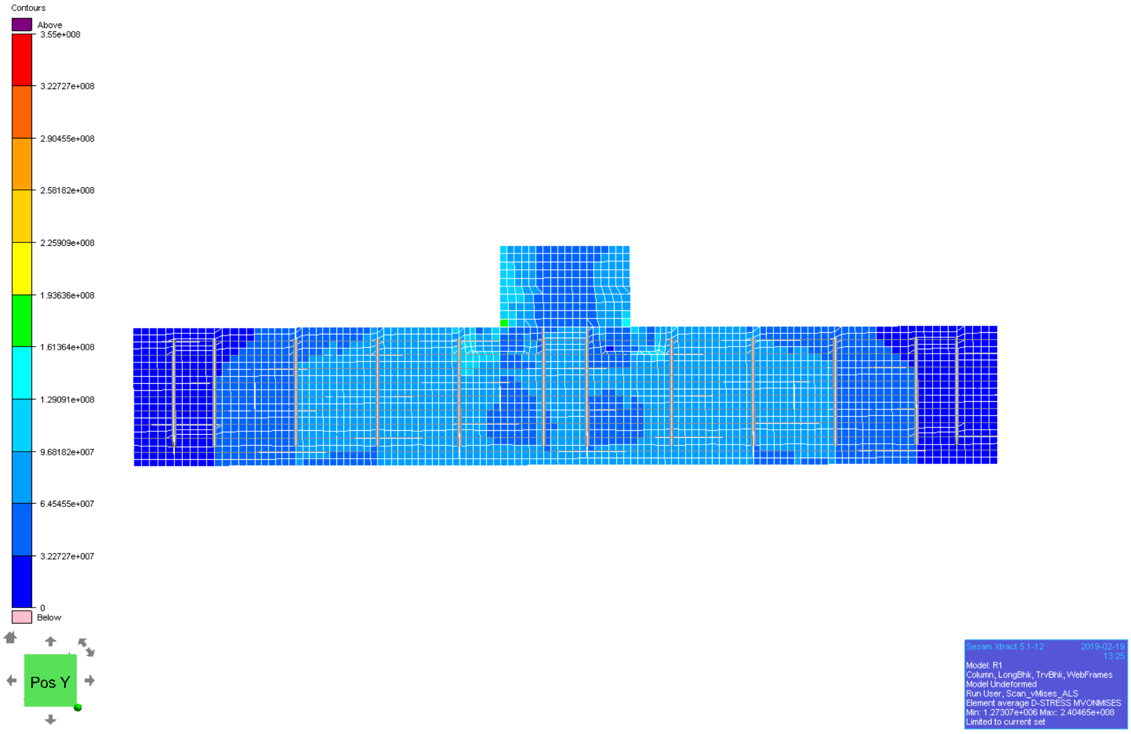
Figure 4-34 von Mises stresses for load case "ULS2" [N/m^2] centreline bulkhead



```
Sesam Xtract 5.1-12          2019-02-19
                                  13:25
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run User, Scan_vMises_ALS
Element average D-STRESS MVONMISES
Min: 1.27307e+006 Max: 2.40465e+008
Limited to current set
```

Figure 4-35 Scan of von Mises stresses for the ALS load combinations [N/m^2] centreline bulkhead

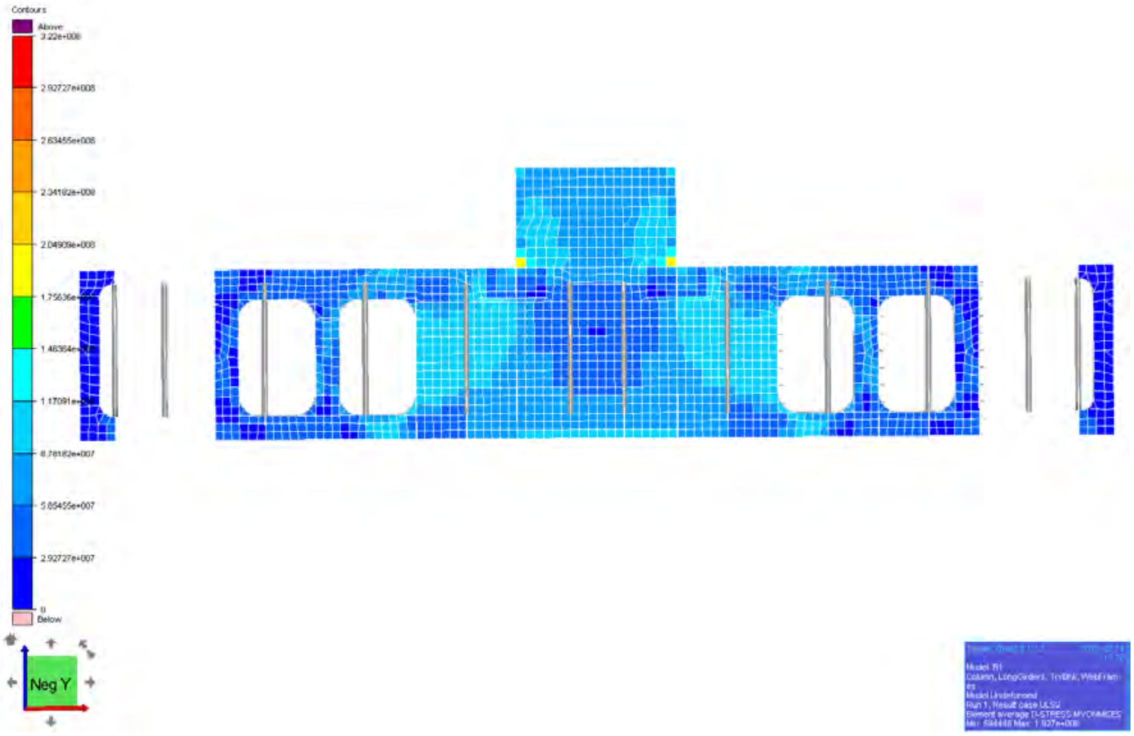


Figure 4-36 von Mises stresses for load case "ULS2" [N/m²] bulkhead 4.0 m of centreline

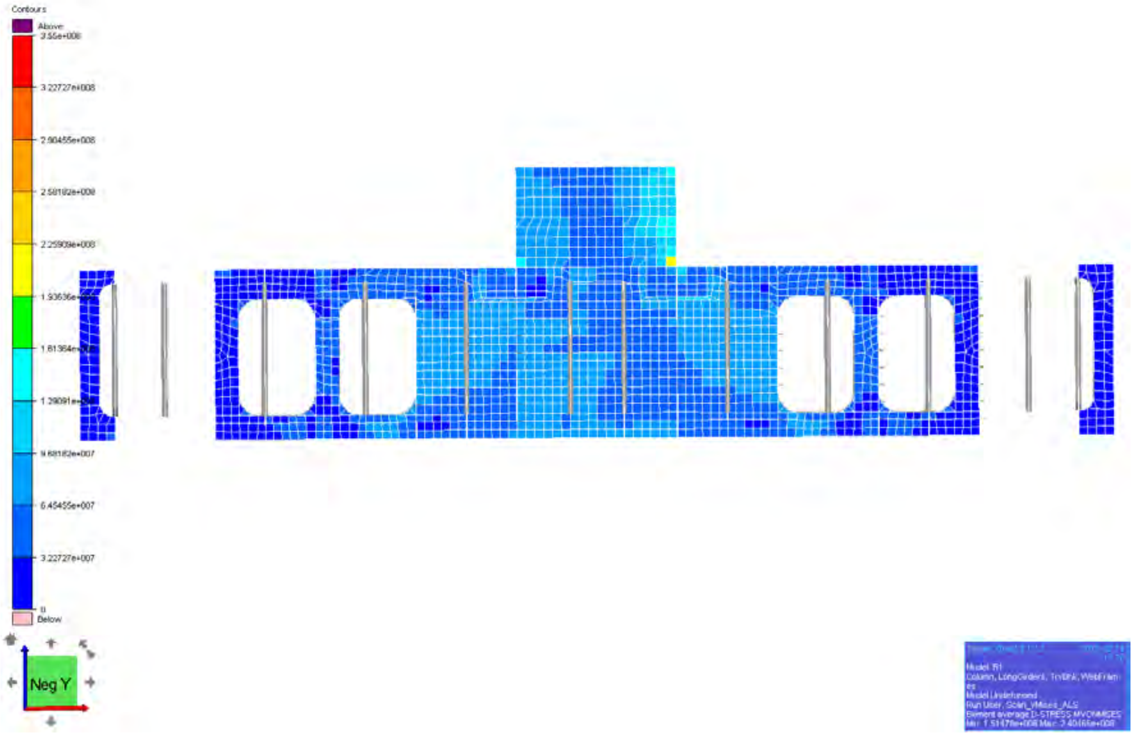


Figure 4-37 Scan of von Mises stresses for the ALS load combinations [N/m²] bulkhead 4.0 m of centreline

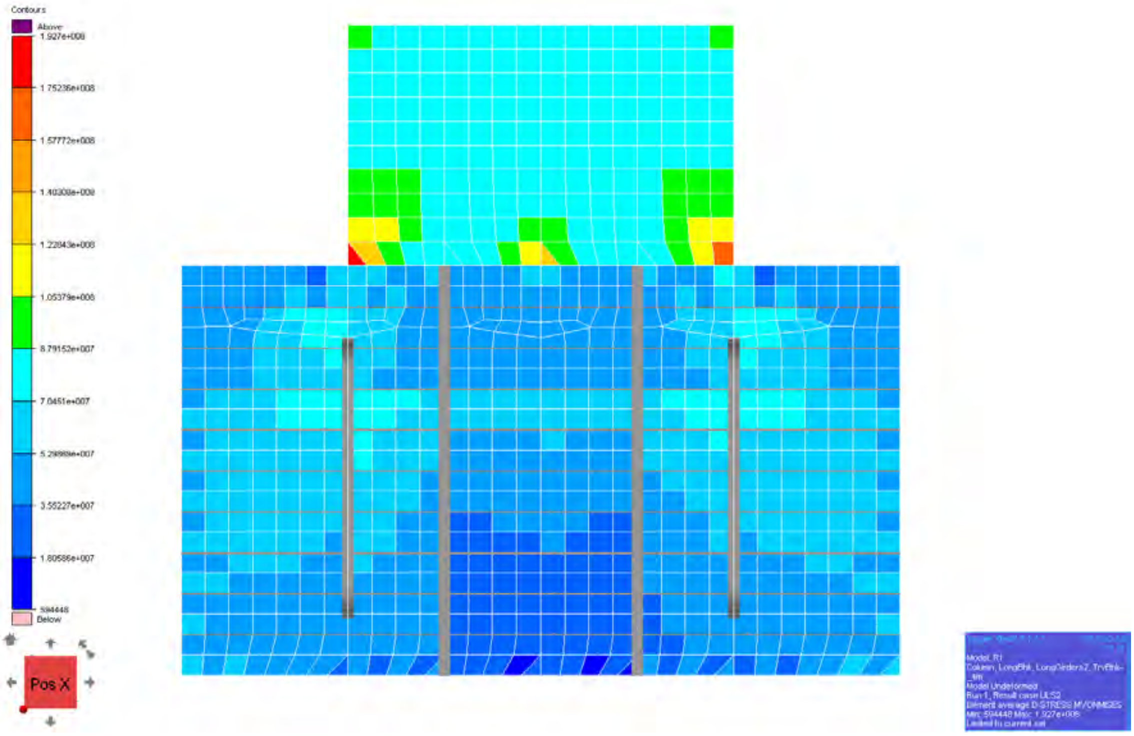


Figure 4-38 von Mises stresses for load case "ULS2" [N/m^2] for transverse bulkhead supporting column

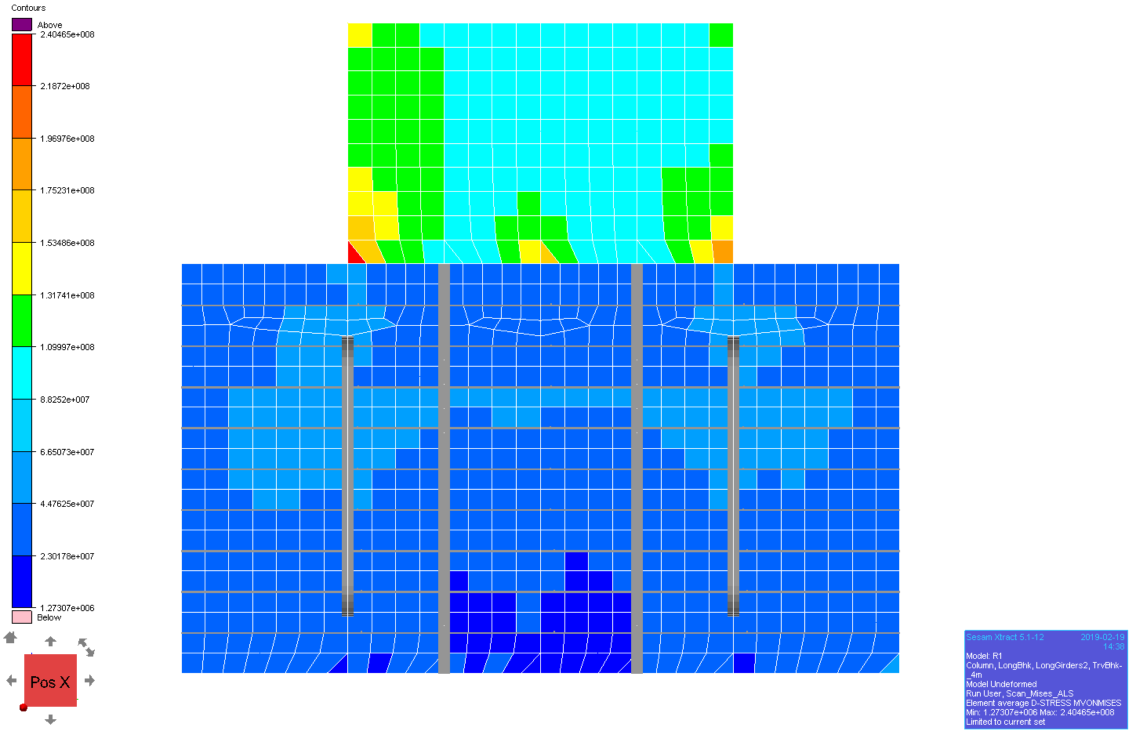


Figure 4-39 von Mises stresses for ALS load combinations [N/m^2] for transverse bulkhead supporting column

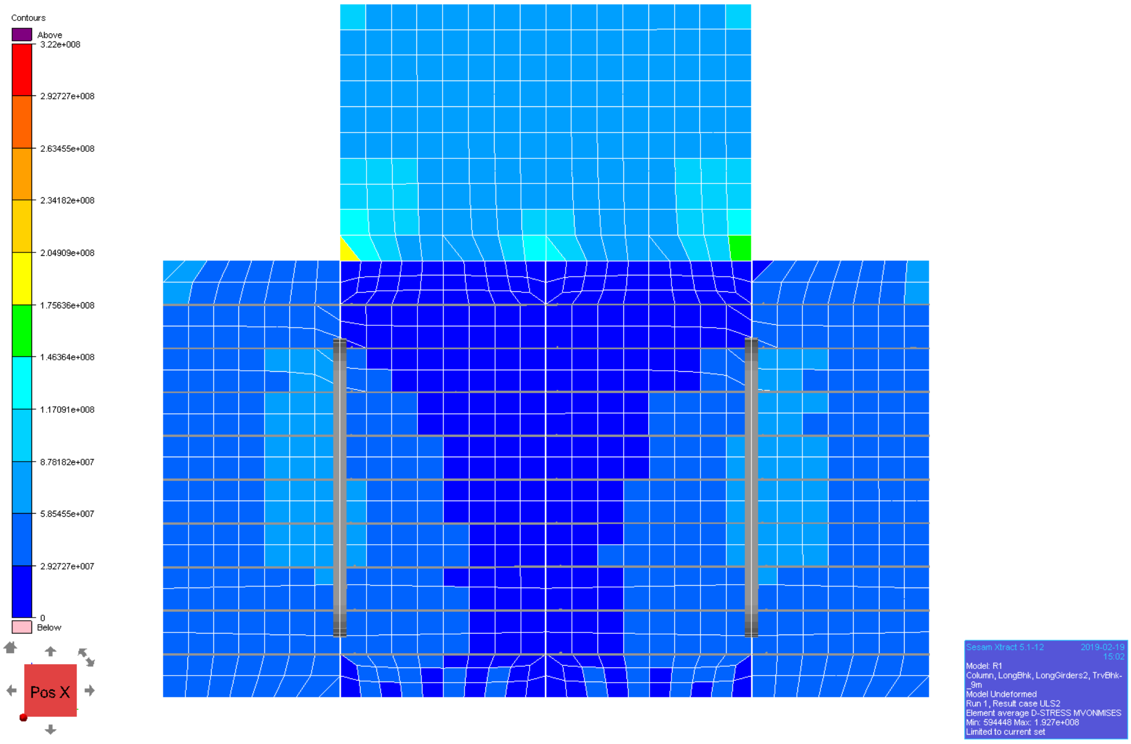


Figure 4-40 von Mises stresses for load case "ULS2" [N/m^2] for a typical transverse bulkhead

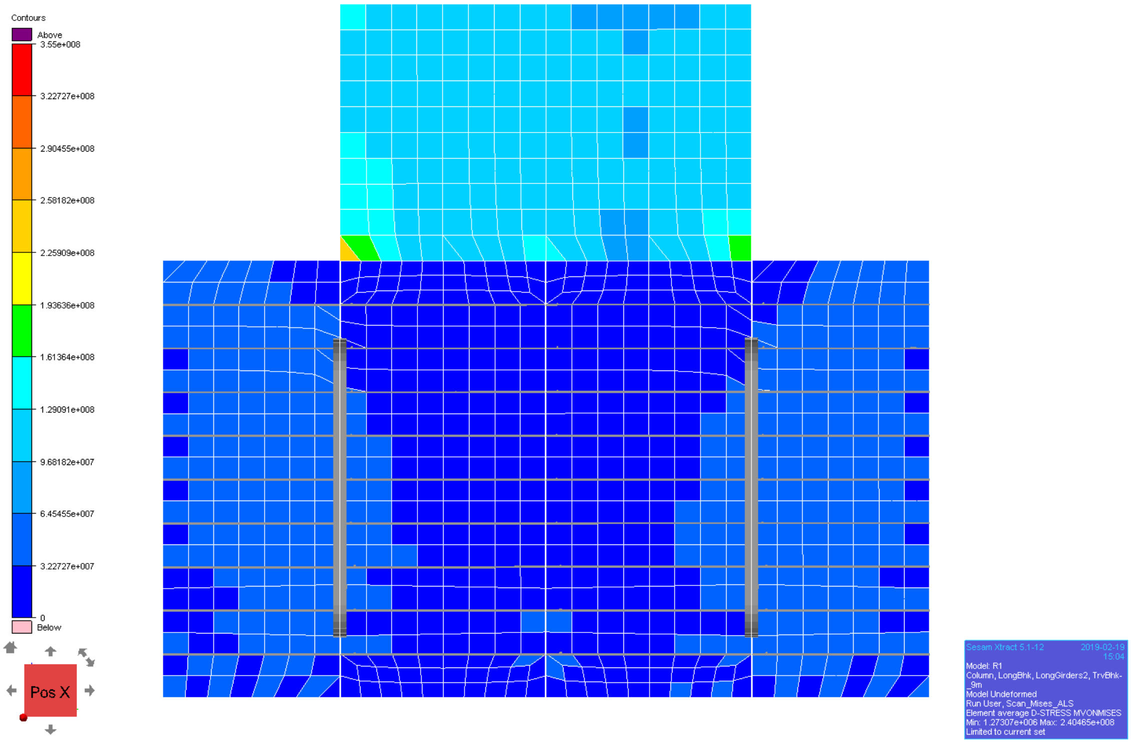


Figure 4-41 von Mises stresses for ALS load combinations [N/m^2] for a typical transverse bulkhead

4.5.2 Buckling and minimum scantling assessment

The buckling assessment is performed according to DNVGL-RP-C203 and the minimum scantling check is performed according to DNVGL-OS-C101 by use of STIPLA software.

Identification of the structural items checked herein is shown in Figure 4-42, Figure 4-46, Figure 4-50, Figure 4-54, Figure 4-61, Figure 4-68 and Figure 4-75 for the “pontoon base case”.

The stress components in local x- and y- direction are taken from the result scans of the ULS and ALS load combinations respectively and shown herein.

The buckling and minimum scantling results are shown in Table 4-1, and the proposed structural scantling for the “pontoon base case” fulfil the rule requirements.

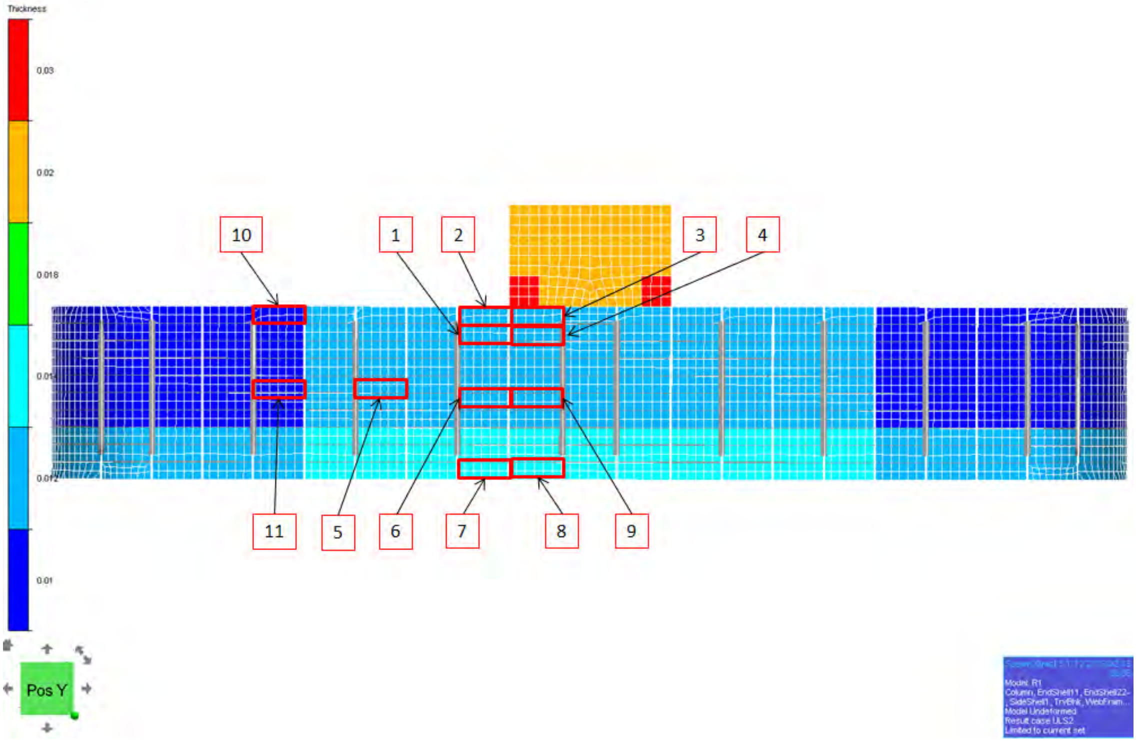
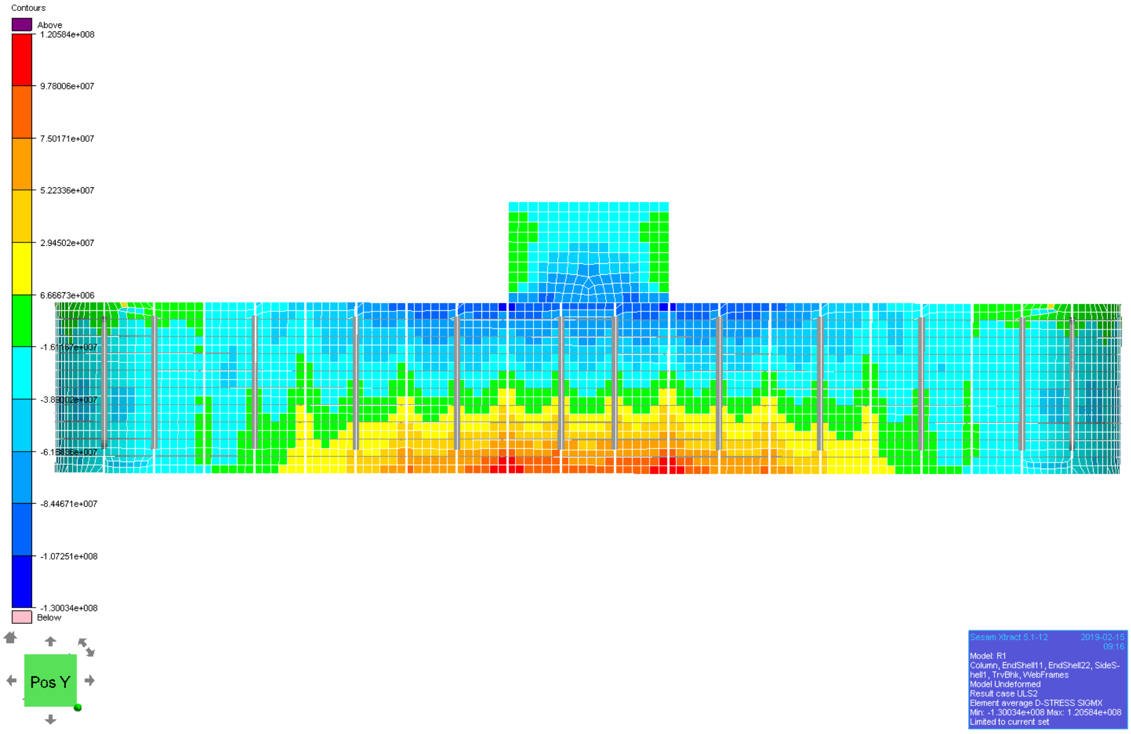
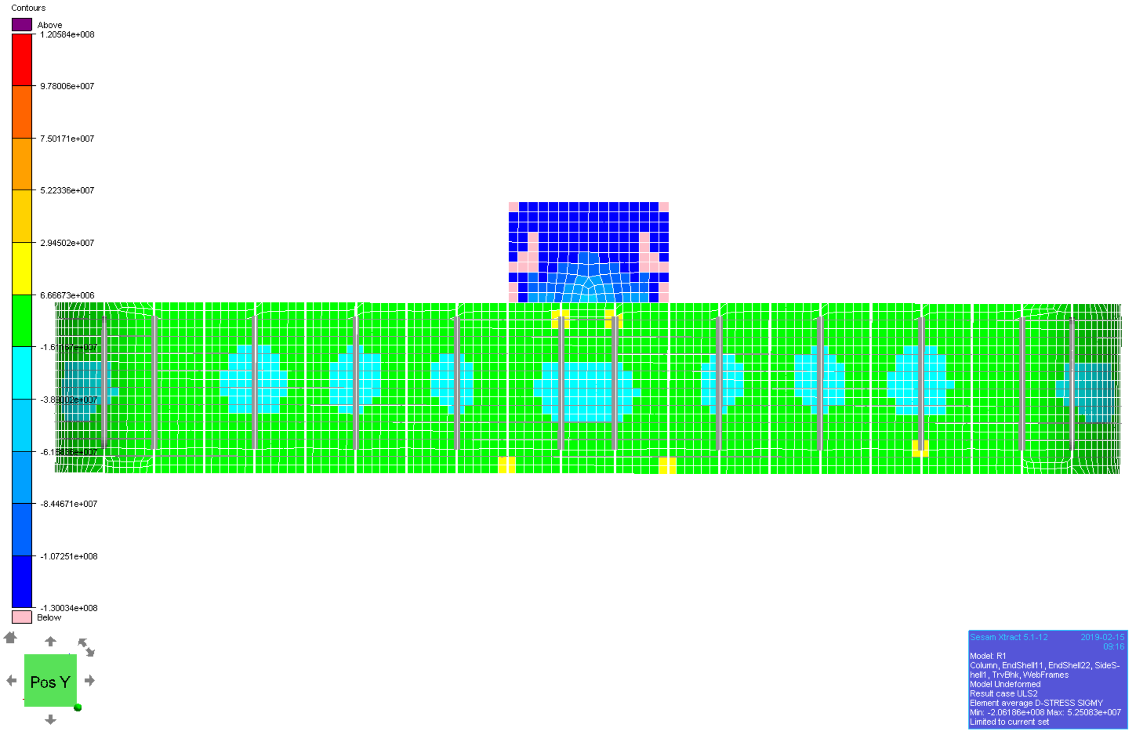


Figure 4-42 Identification of areas considered for buckling & scantling check for outer side shell



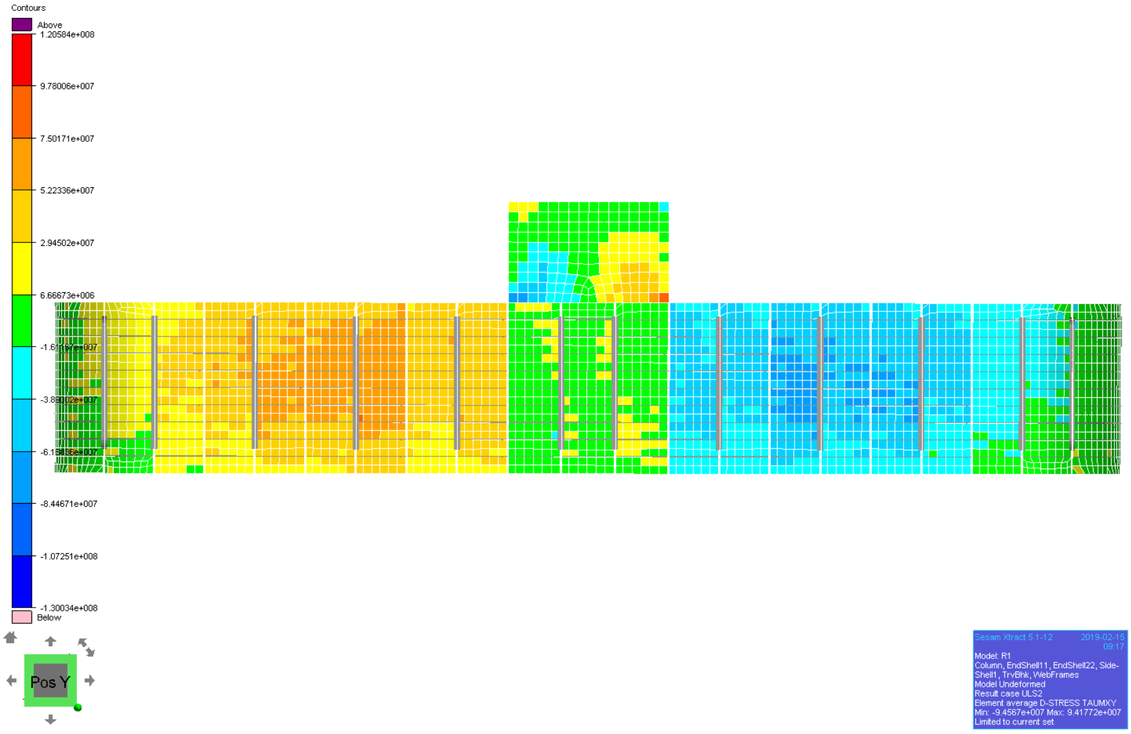
Sesam Xtract 5.1-12 2019-02-15
09:16
Model: R1
Column, EndShell11, EndShell22, SideShell1, TrvBhk, WebFrames
Model Undeformed
Result case ULS2
Element average D-STRESS SIGMX
Min: -1.30034e+008 Max: 1.20584e+008
Limited to current set

Figure 4-43 SIGMX stresses for load case "ULS2" [N/m^2]



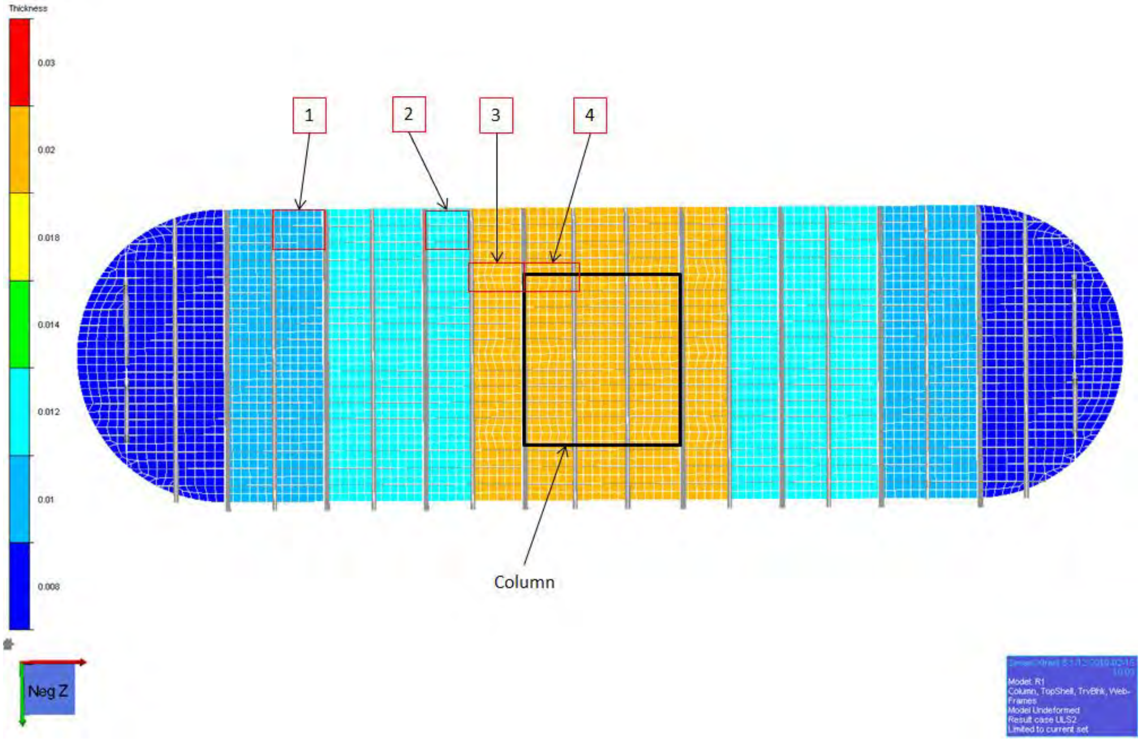
Sesam Xtract 5.1-12 2019-02-15
09:16
Model: R1
Column, EndShell11, EndShell22, SideShell1, TrvBhk, WebFrames
Model Undeformed
Result case ULS2
Element average D-STRESS SIGMY
Min: -2.06186e+008 Max: 5.25083e+007
Limited to current set

Figure 4-44 SIGMY stresses for load case "ULS2" [N/m^2]



Sesam Xtract 5.1-12 2019-02-15 09:17
Model: R1
Column, EndShell11, EndShell22, Side-Shell1, TrvBhk, WebFrames
Model Undeformed
Result case ULS2
Element average D-STRESS TAUMXY
Min: -9.4567e+007 Max: 9.41772e+007
Limited to current set

Figure 4-45 TAUMXY stresses for load case "ULS2" [N/m^2]



Sesam Xtract 5.1-12 2019-02-15 10:09
Model: R1
Column, TopShell, TrvBhk, Web-Frames
Model Undeformed
Result case ULS2
Limited to current set

Figure 4-46 Identification of areas considered for buckling & scantling check for outer top shell

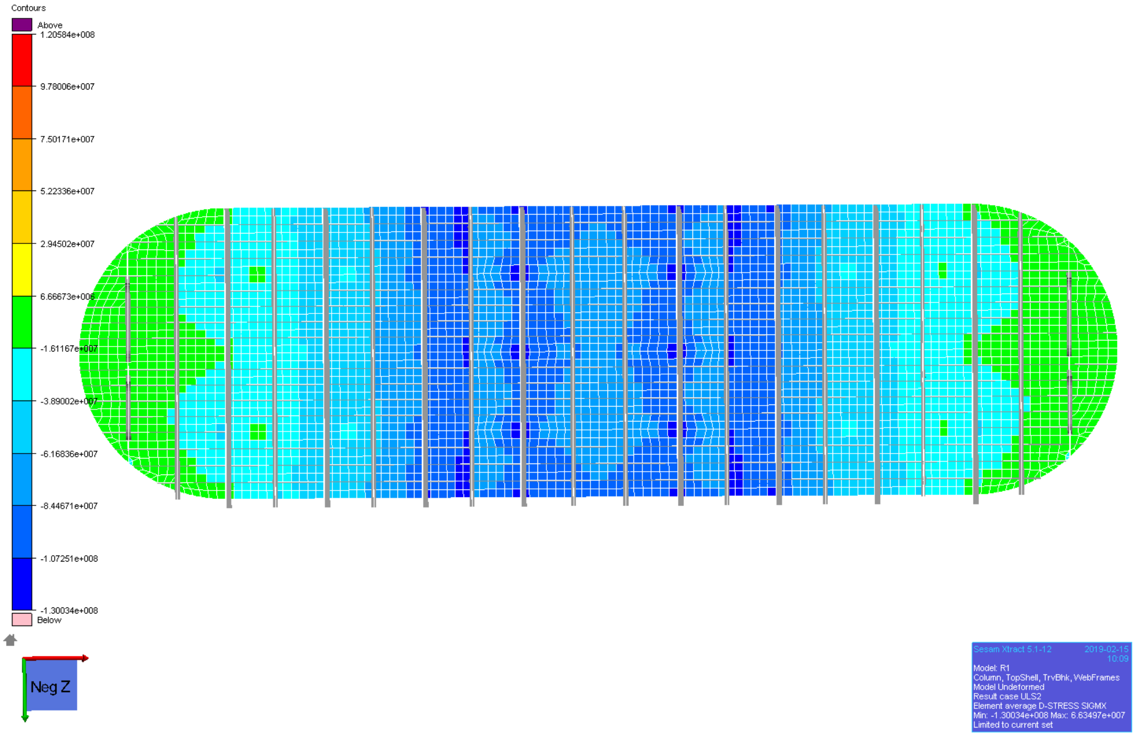


Figure 4-47 SIGMX stresses for load case "ULS2" [N/m^2] for outer top shell

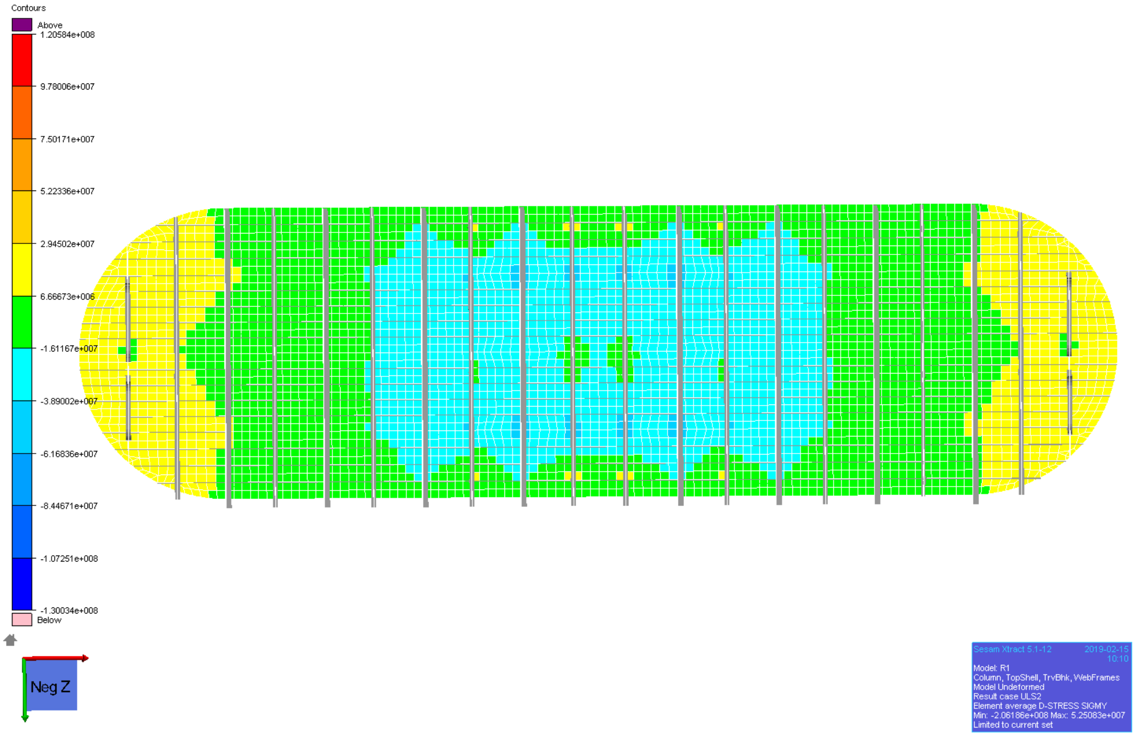


Figure 4-48 SIGMY stresses for load case "ULS2" [N/m^2] for outer top shell

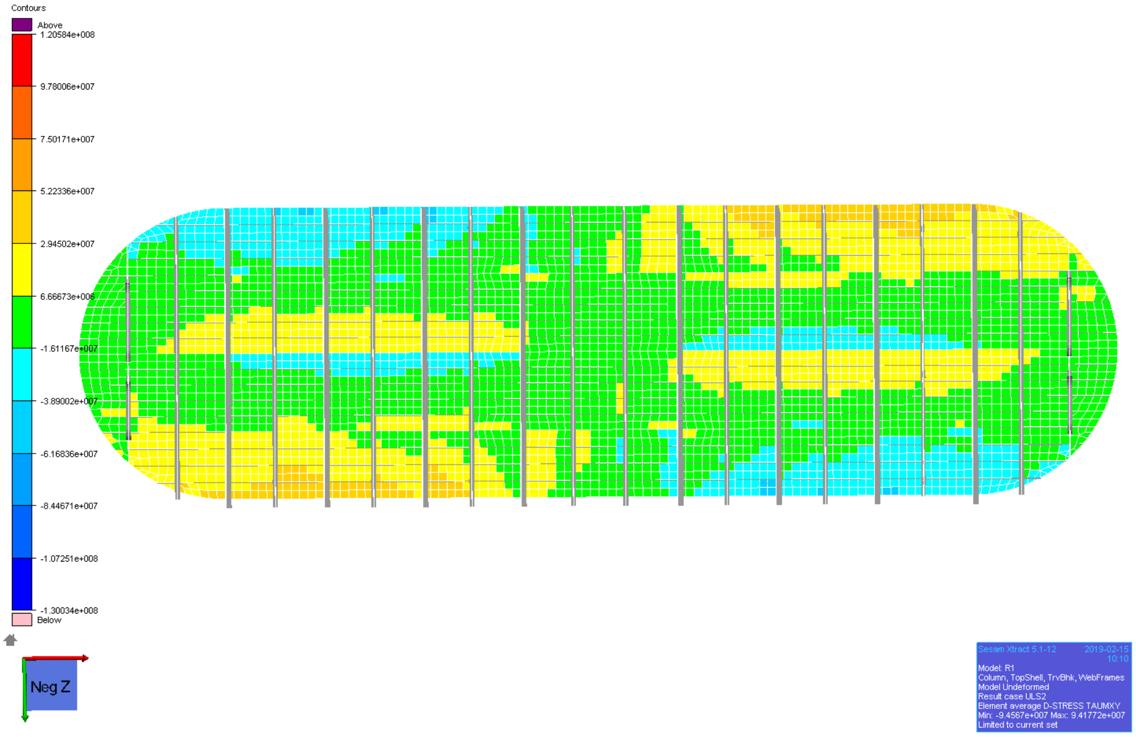


Figure 4-49 TAUMXY stresses for load case “ULS2” [N/m^2] for outer top shell

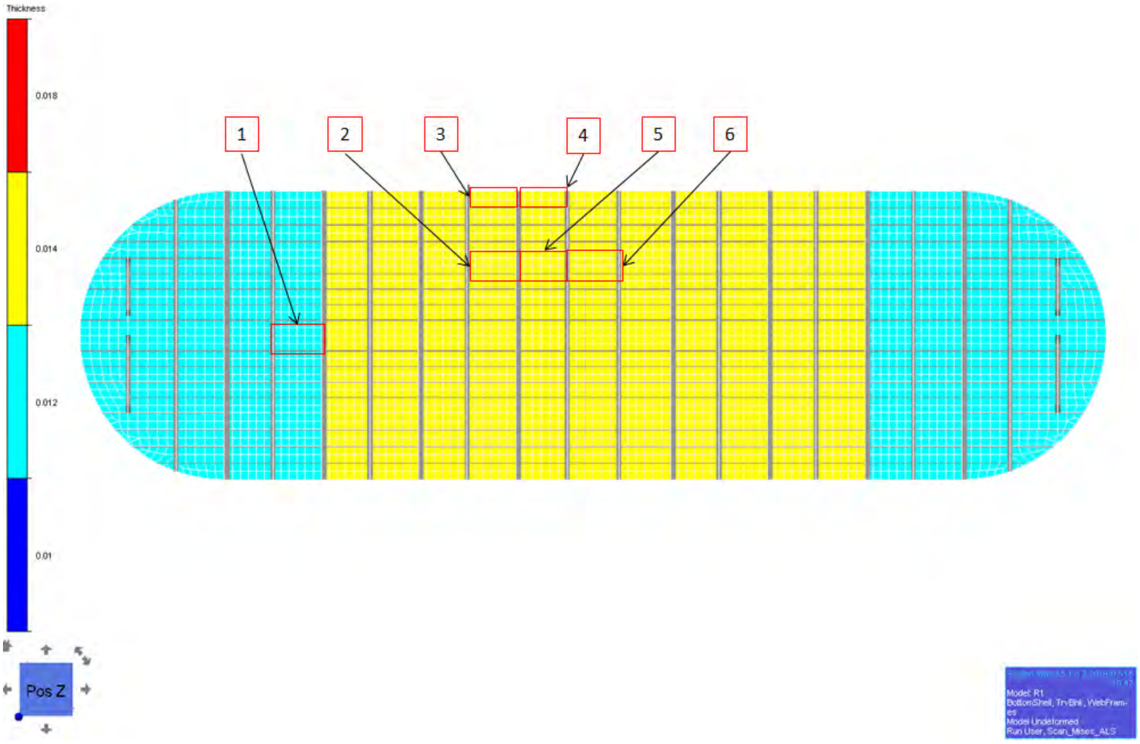
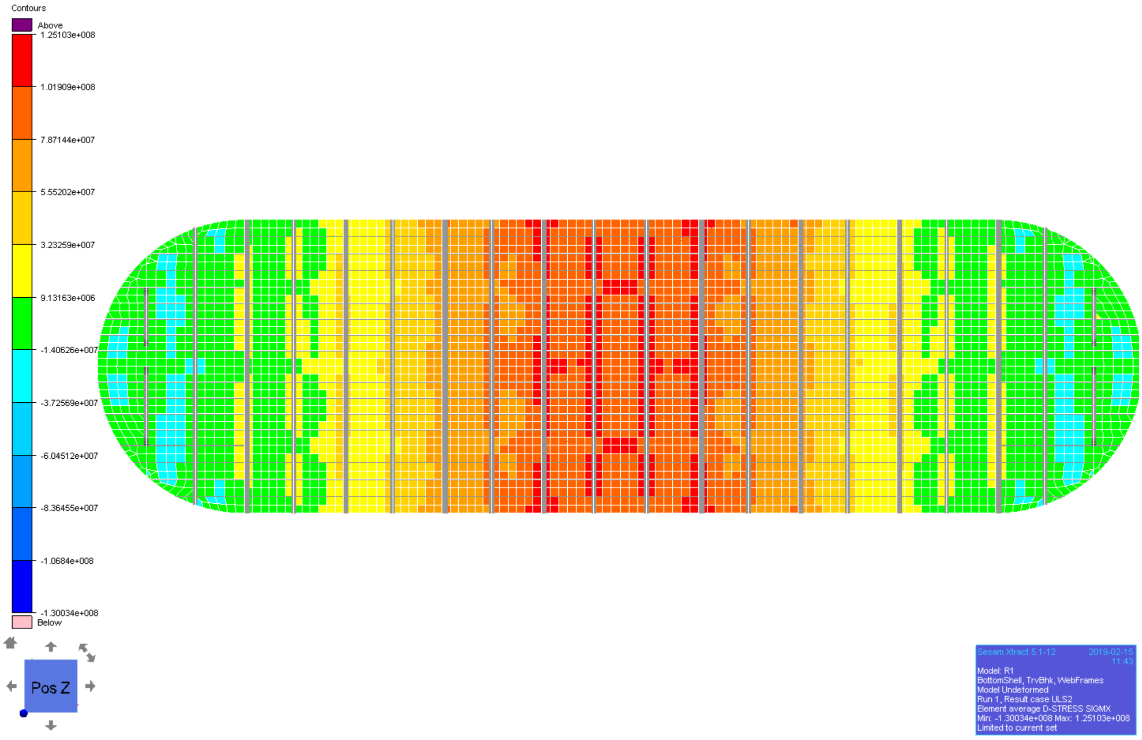


Figure 4-50 Identification of areas considered for buckling & scantling check for outer bottom shell



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Sesam Xtract 5.1-12          2019-02-15
                                  11:43
Model: R1
BottomShell, TrvBhk, WebFrames
Model Undeformed
Run 1, Result case ULS2
Element average D-STRESS SIGMX
Min: -1.30034e+008 Max: 1.25103e+008
Limited to current set
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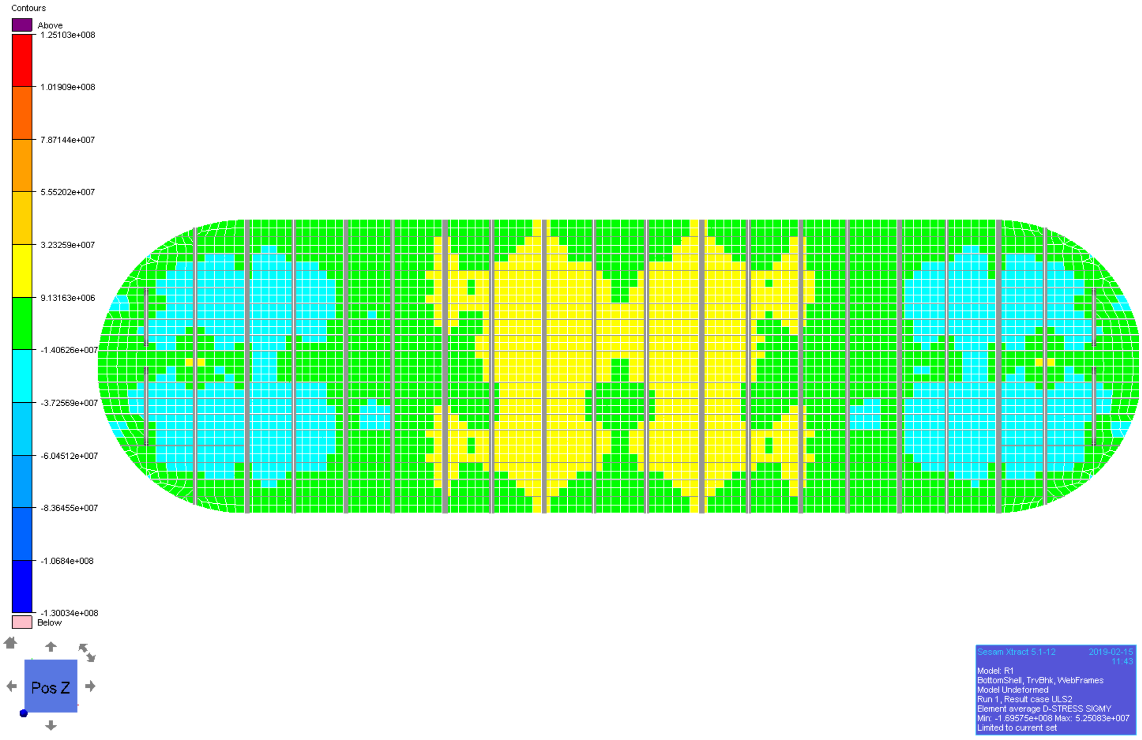
Figure 4-51 SIGMX stresses for load case "ULS2" [N/m^2] for outer bottom shell



```
Sesam Xtract 5.1-12          2019-02-15
                                  11:43
Model: R1
BottomShell, TrvBhk, WebFrames
Model Undeformed
Run 1, Result case ULS2
Element average D-STRESS SIGMY
Min: -1.69575e+008 Max: 5.25083e+007
Limited to current set
```

Figure 4-52 SIGMY stresses for load case "ULS2" [N/m^2] for outer bottom shell

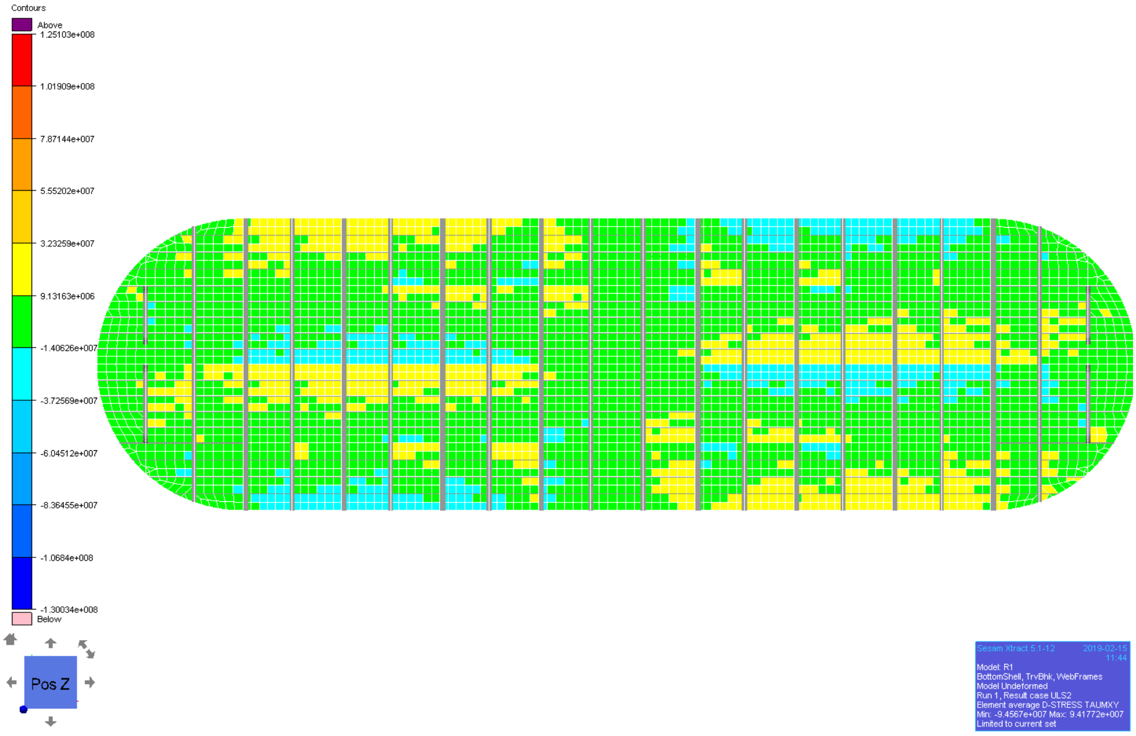


Figure 4-53 TAUMXY stresses for load case "ULS2" [N/m^2] for outer bottom shell

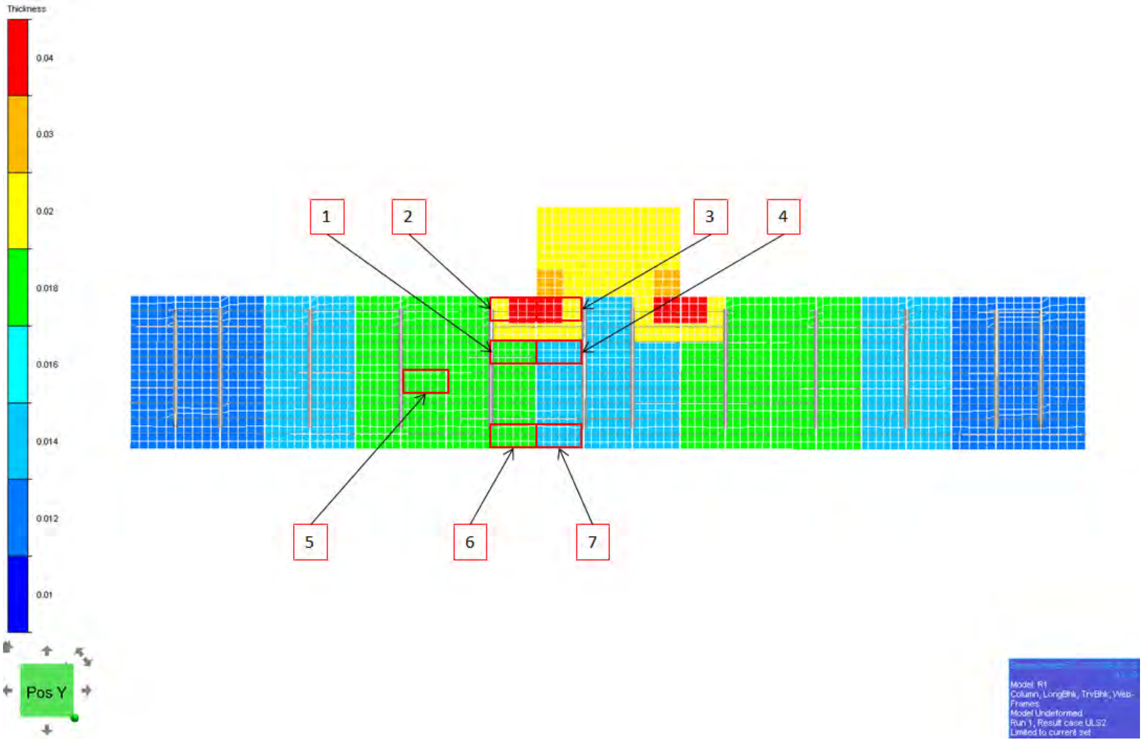


Figure 4-54 Identification of areas considered for buckling & scantling check for centreline bulkhead

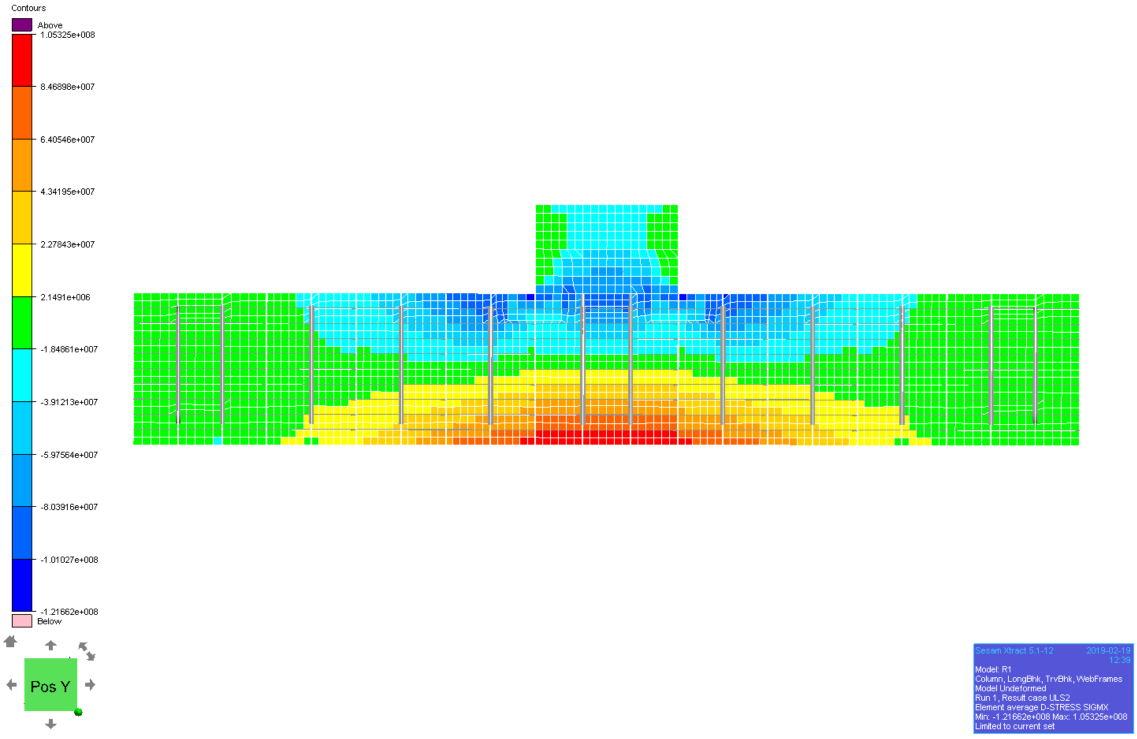


Figure 4-55 SIGMX stresses for load case "ULS2" [N/m^2] for centreline bulkhead

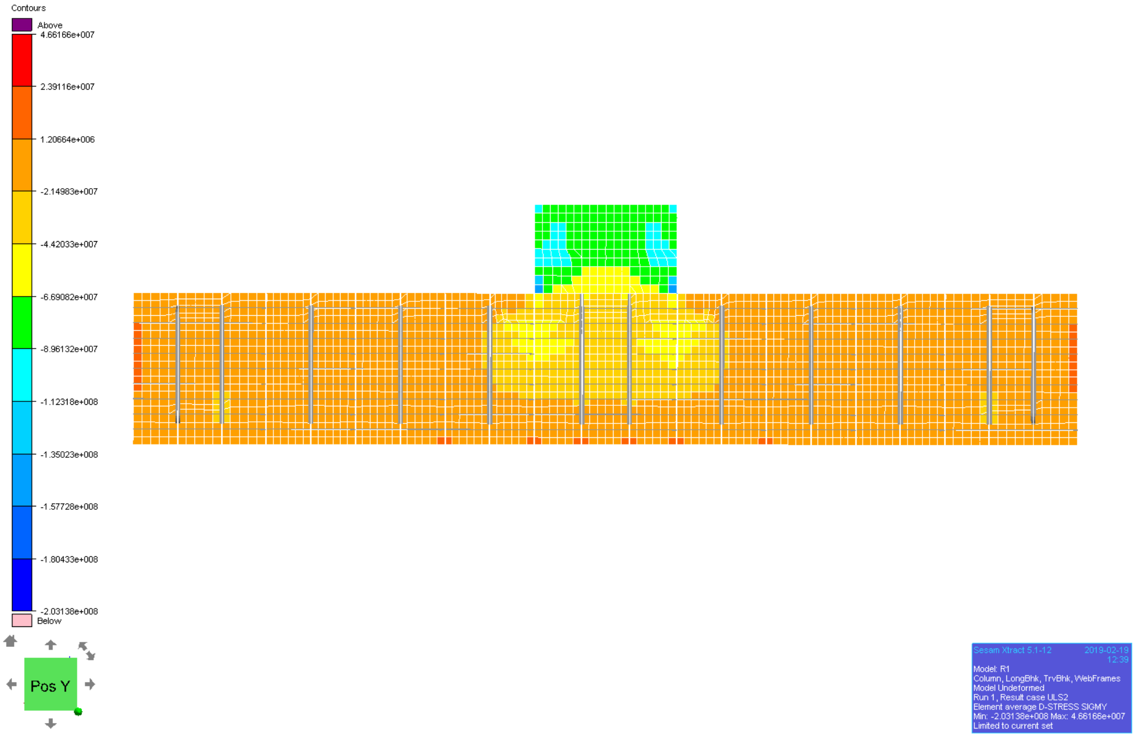
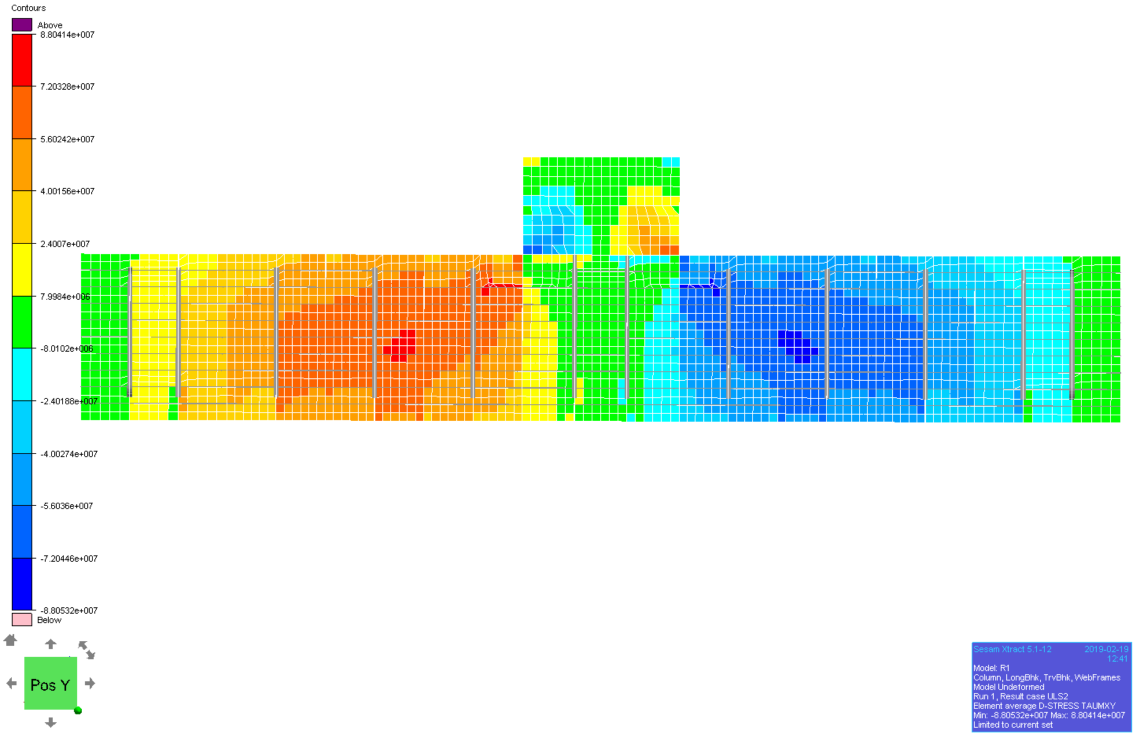


Figure 4-56 SIGMY stresses for load case "ULS2" [N/m^2] for centreline bulkhead



```
Sesam Xtract 5.1-12          2019-02-19
                                  12:41
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run 1, Result case ULS2
Element average D-STRESS TAUMXY
Min: -8.80532e+007 Max: 8.80414e+007
Limited to current set
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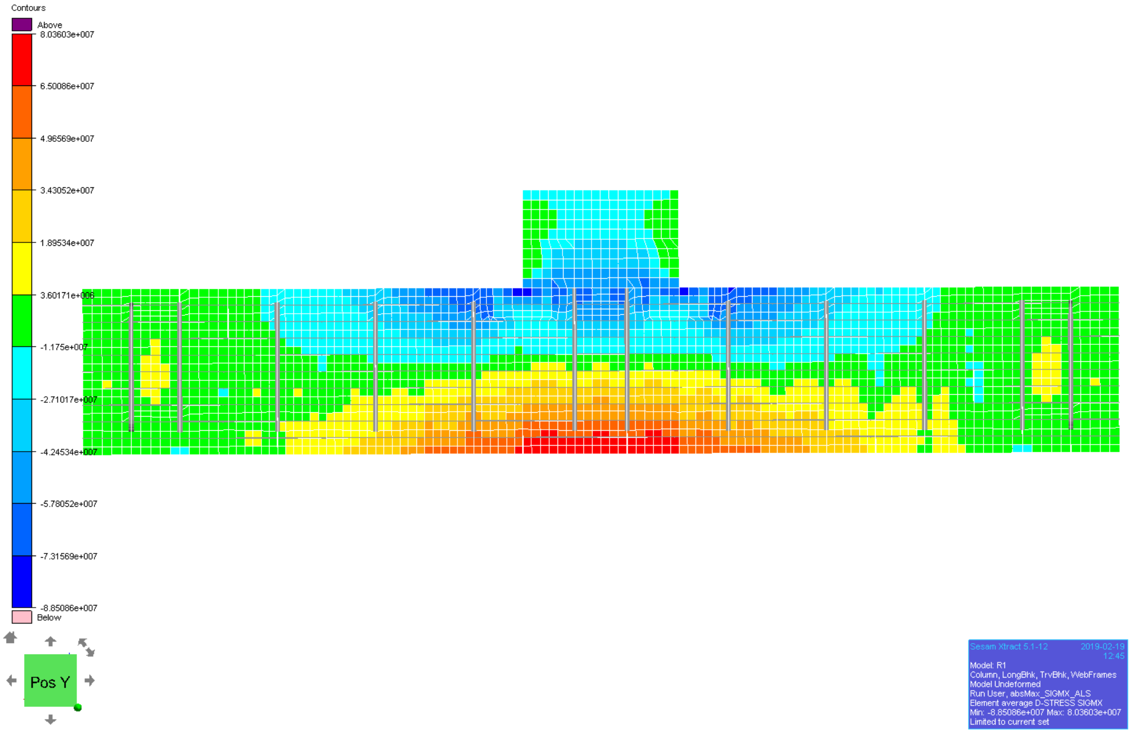
Figure 4-57 TAUMXY stresses for load case “ULS2” [N/m^2] for centreline bulkhead



```
Sesam Xtract 5.1-12          2019-02-19
                                  12:45
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run User, absMax_SIGMX_ALS
Element average D-STRESS SIGMX
Min: -8.85086e+007 Max: 8.03603e+007
Limited to current set
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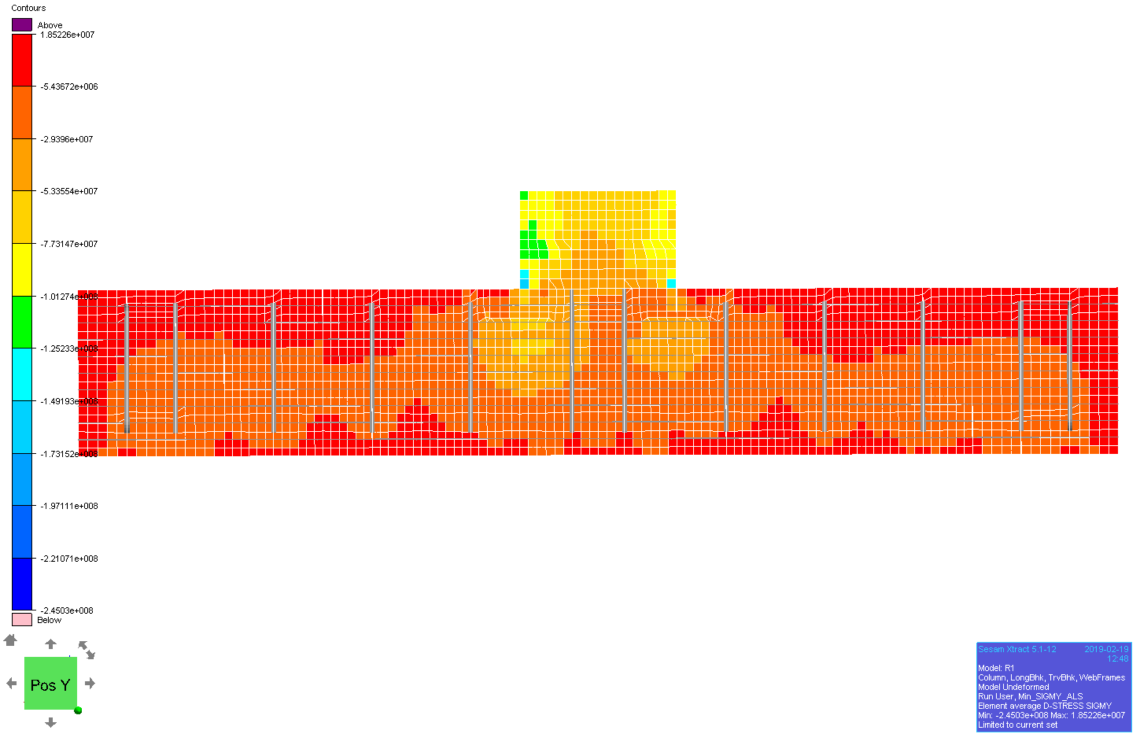
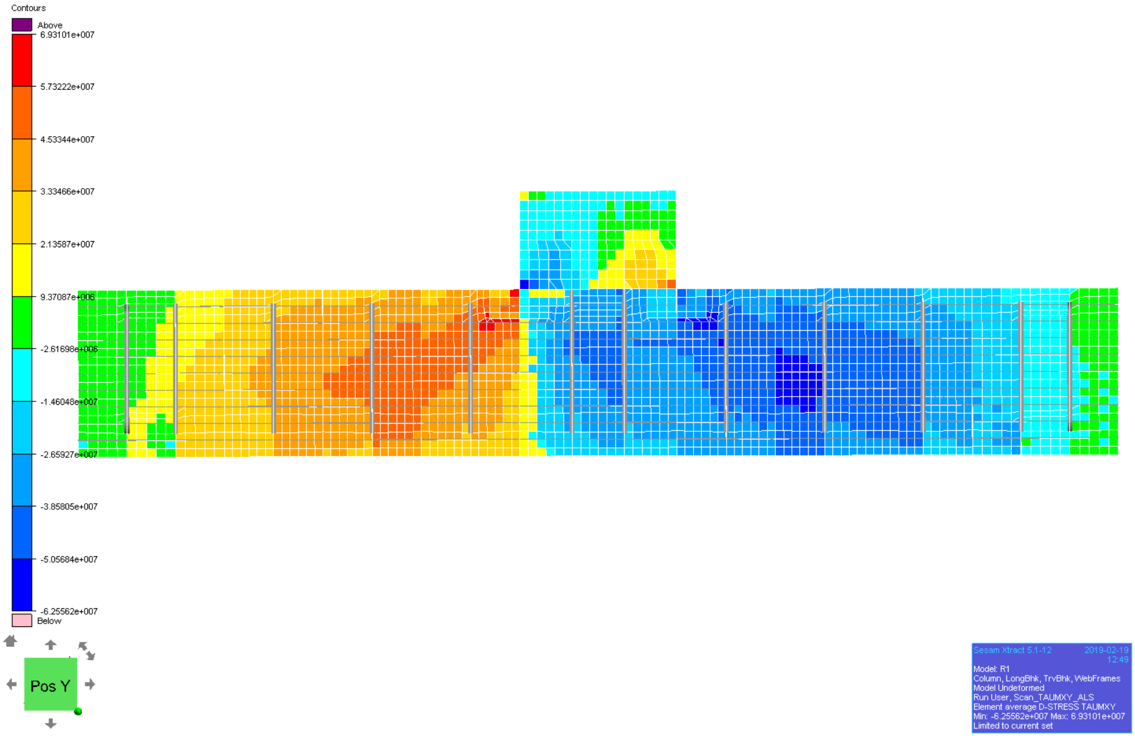
Figure 4-58 SIGMX stresses for ALS load combinations [N/m^2] for centreline bulkhead



```
Sesam Xtract 5.1-12          2019-02-19
                                  12:48
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run User, Min_SIGMY_ALS
Element average D-STRESS SIGMY
Min: -2.4503e+008 Max: 1.85226e+007
Limited to current set
```

Figure 4-59 SIGMY stresses for ALS load combinations [N/m^2] for centreline bulkhead



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Sesam Xtract 5.1-12          2019-02-19
                                  12:49
Model: R1
Column, LongBhk, TrvBhk, WebFrames
Model Undeformed
Run User, Scan_TAUMXY_ALS
Element average D-STRESS TAUMXY
Min: -6.25562e+007 Max: 6.93101e+007
Limited to current set
```

Figure 4-60 TAUMXY stresses for ALS load combinations [N/m^2] for centreline bulkhead

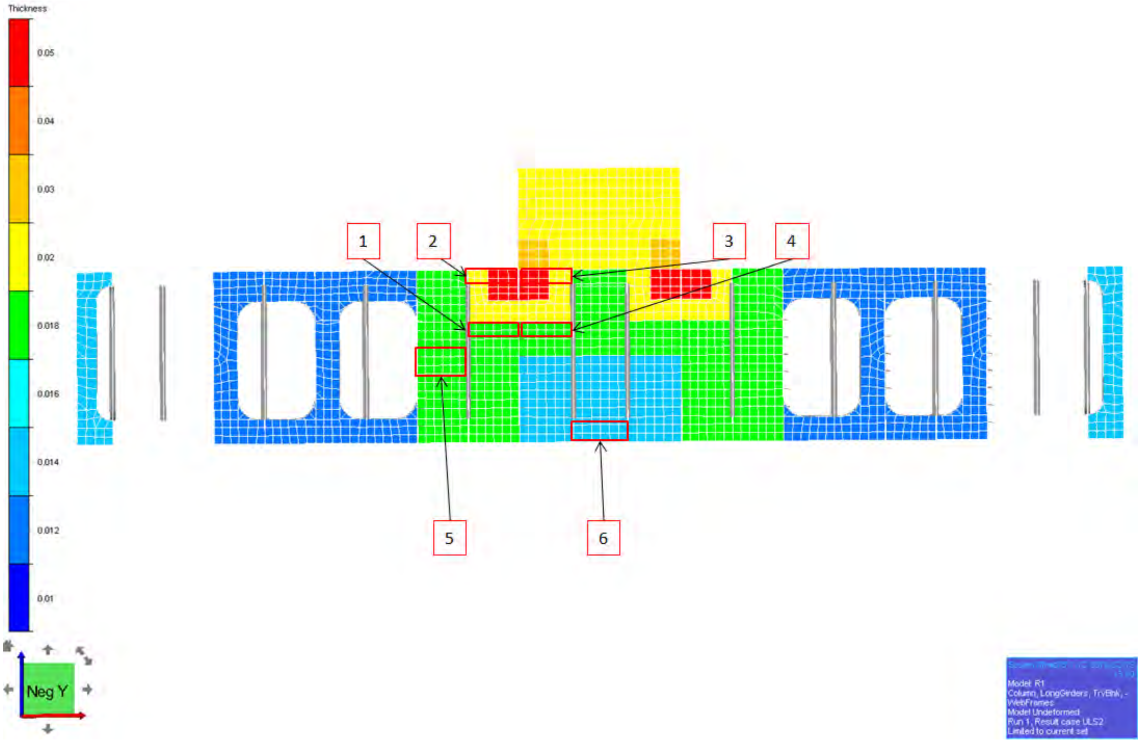


Figure 4-61 Identification of areas considered for buckling & scantling check for bulkhead 4.0 m of centreline

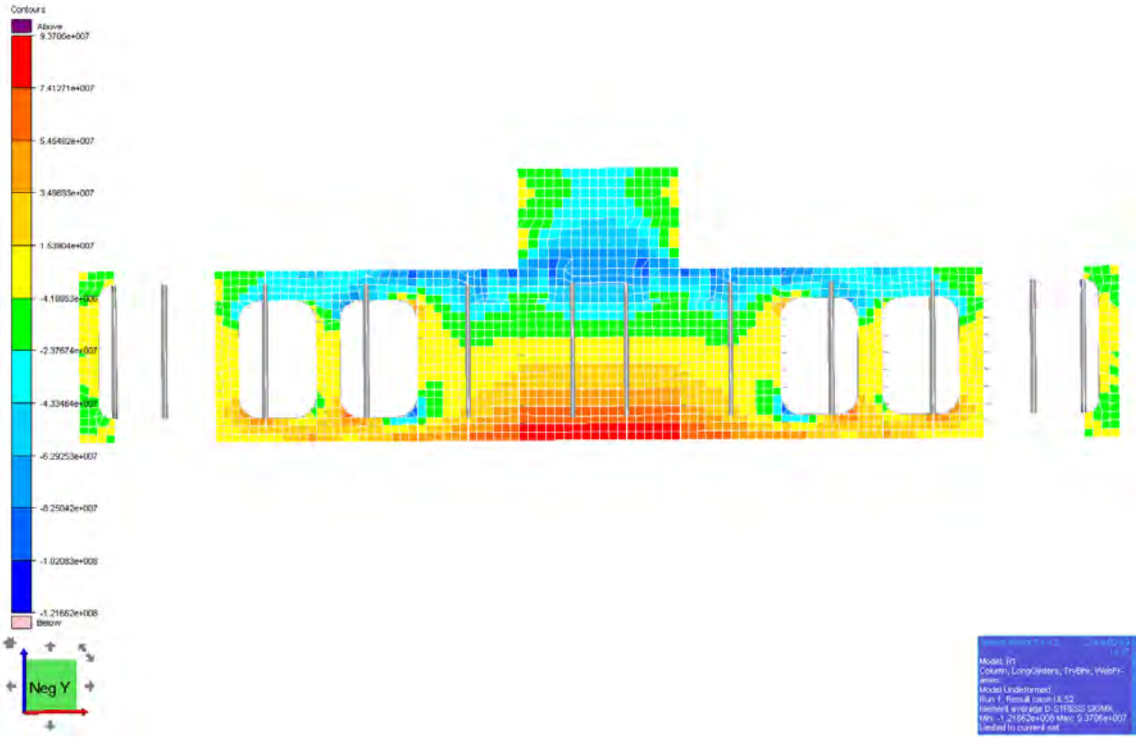


Figure 4-62 SIGMX stresses for load case "ULS2" [N/m^2] for bulkhead 4.0 m of centreline

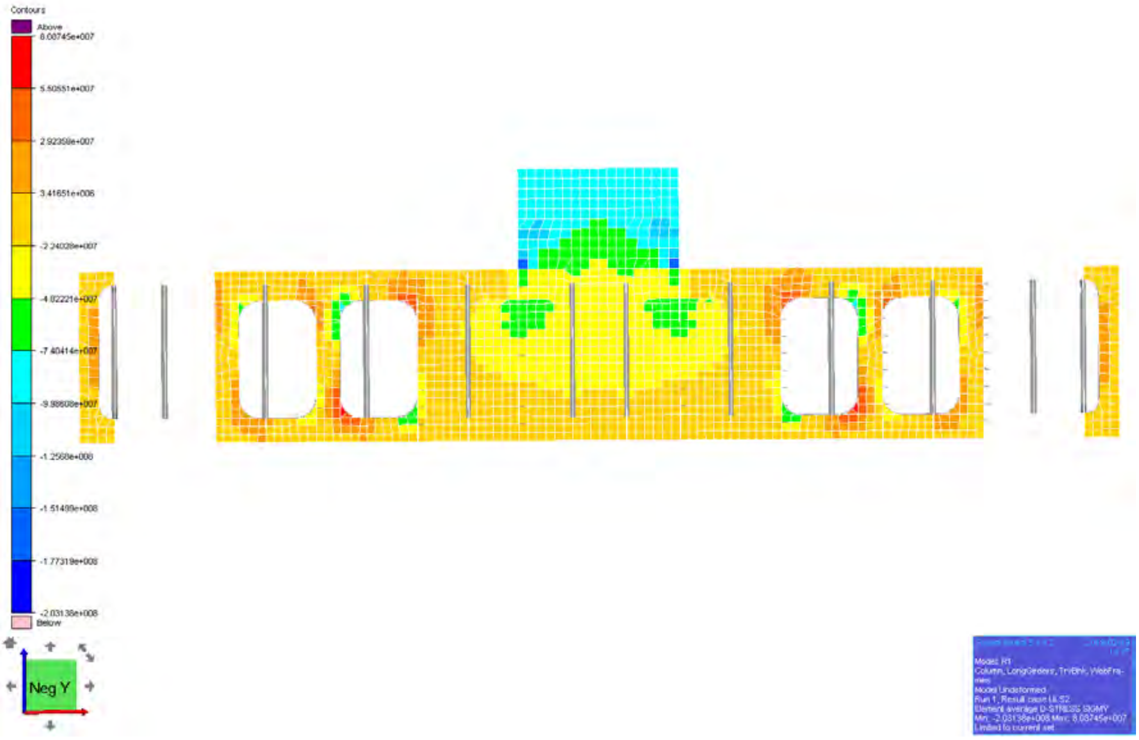


Figure 4-63 SIGMY stresses for load case "ULS2" [N/m^2] for bulkhead 4.0 m of centreline

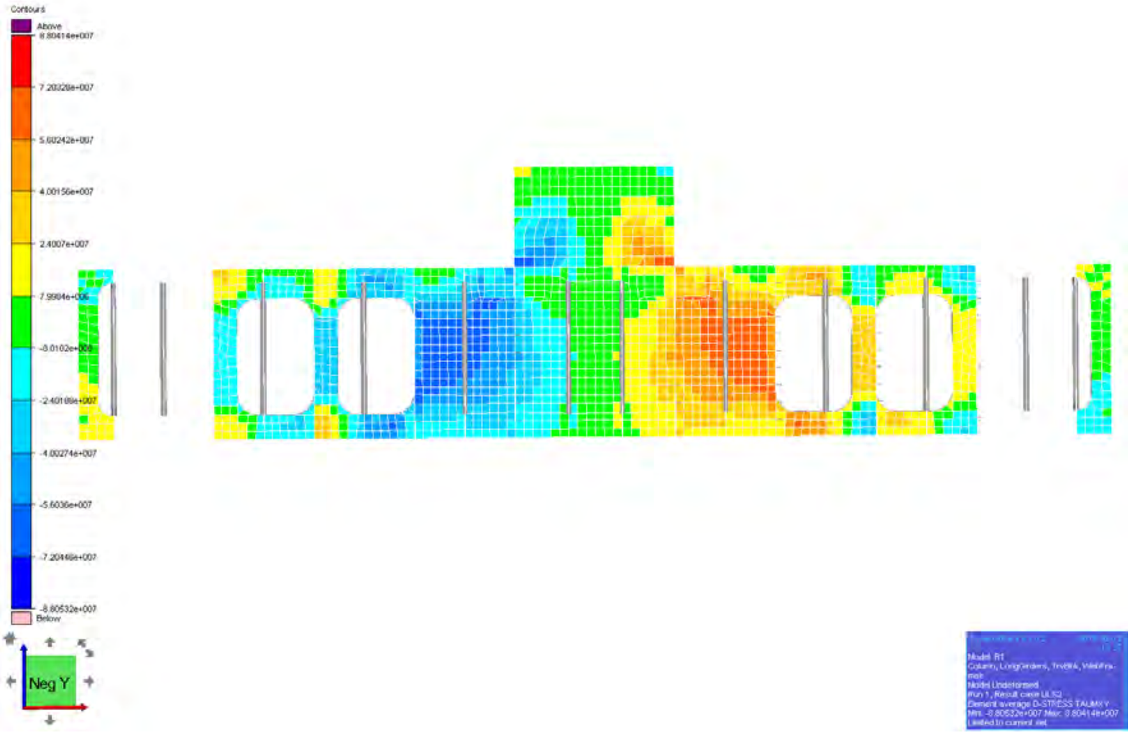


Figure 4-64 TAUMXY stresses for load case "ULS2" [N/m^2] for bulkhead 4.0 m of centreline

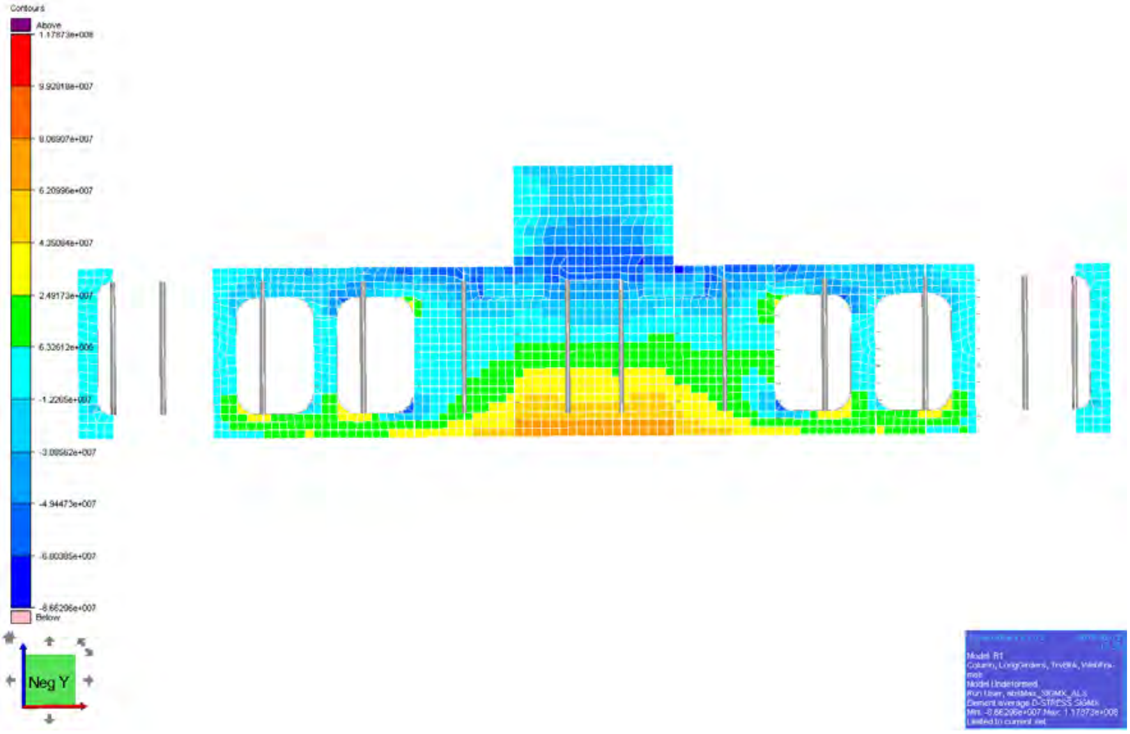


Figure 4-65 SIGMX stresses for ALS load combinations [N/m²] for bulkhead 4.0 m of centreline

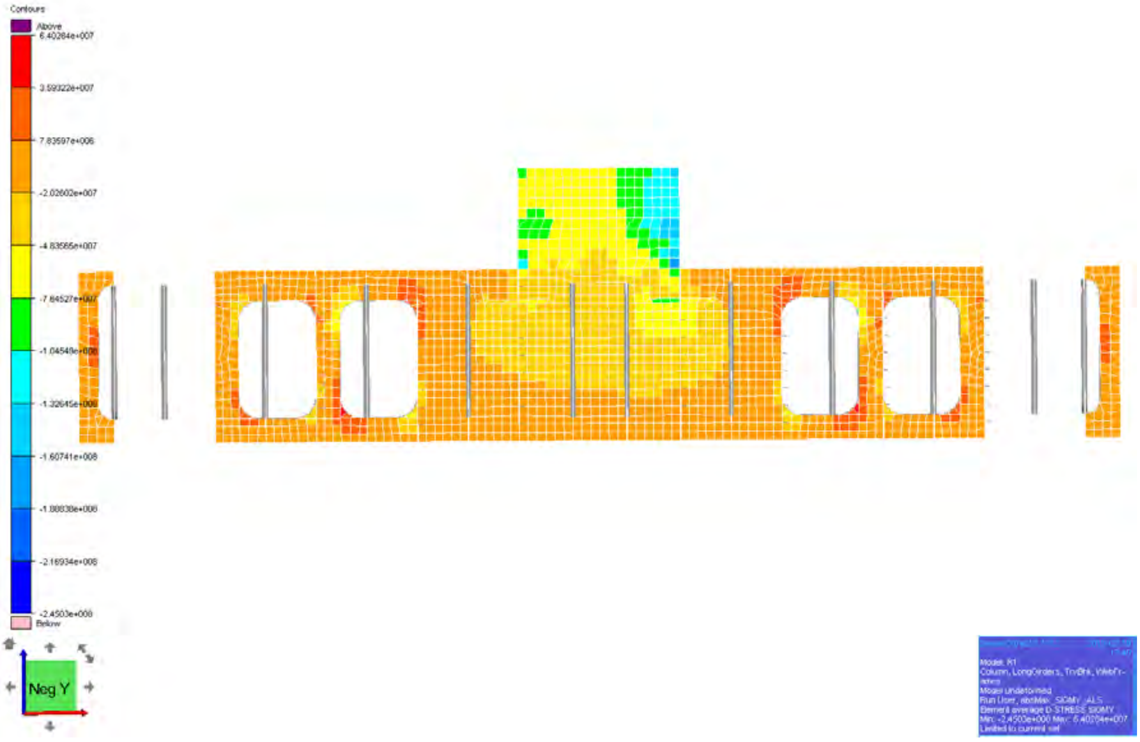


Figure 4-66 SIGMY stresses for ALS load combinations [N/m²] for bulkhead 4.0 m of centreline

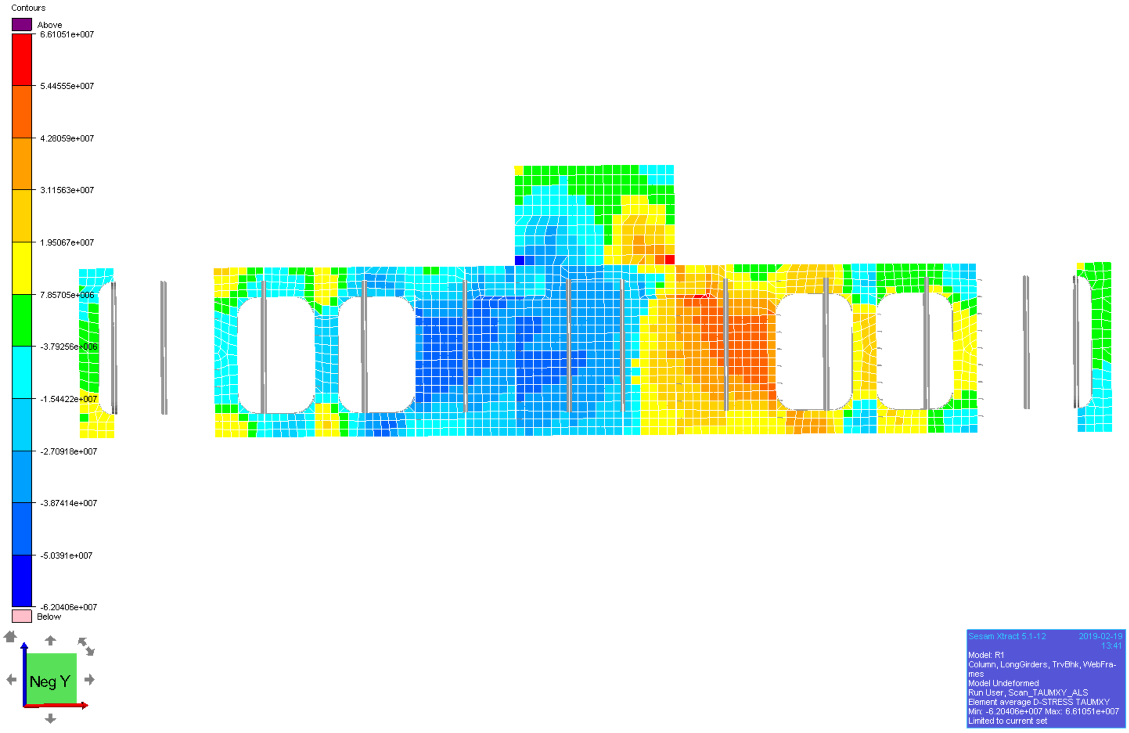


Figure 4-67 TAUMXY stresses for ALS load combinations [N/m²] for bulkhead 4.0 m of centreline

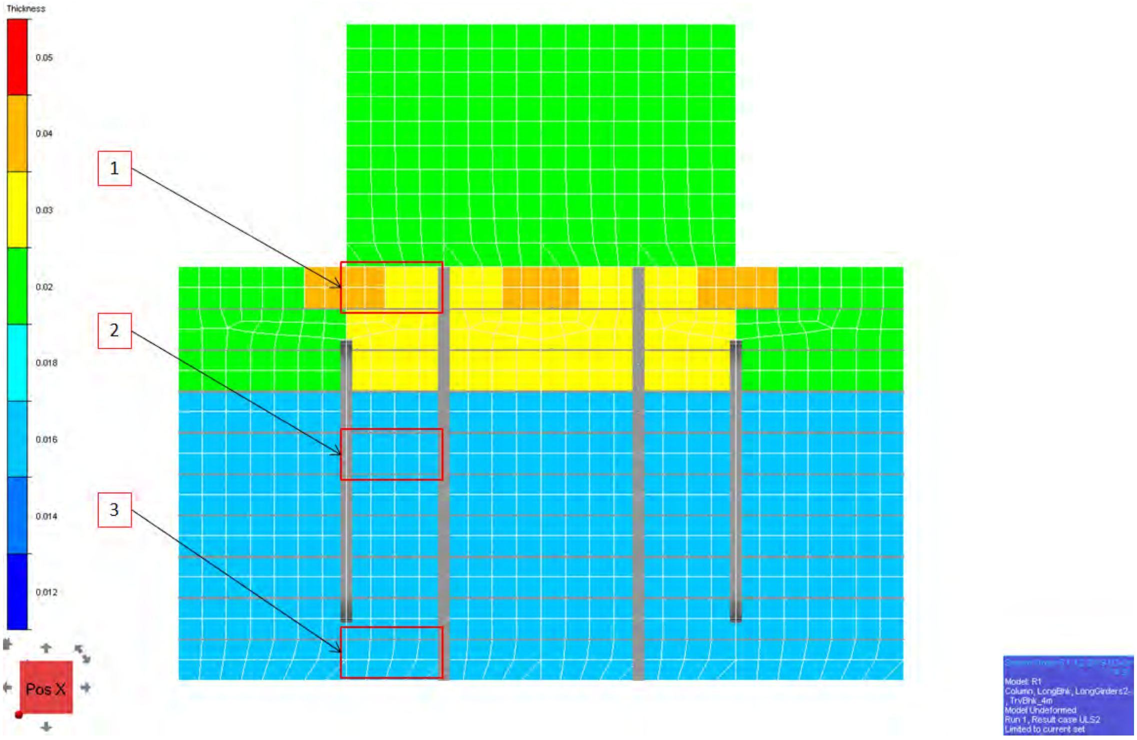


Figure 4-68 Identification of areas considered for buckling & scantling check for transverse bulkhead supporting column

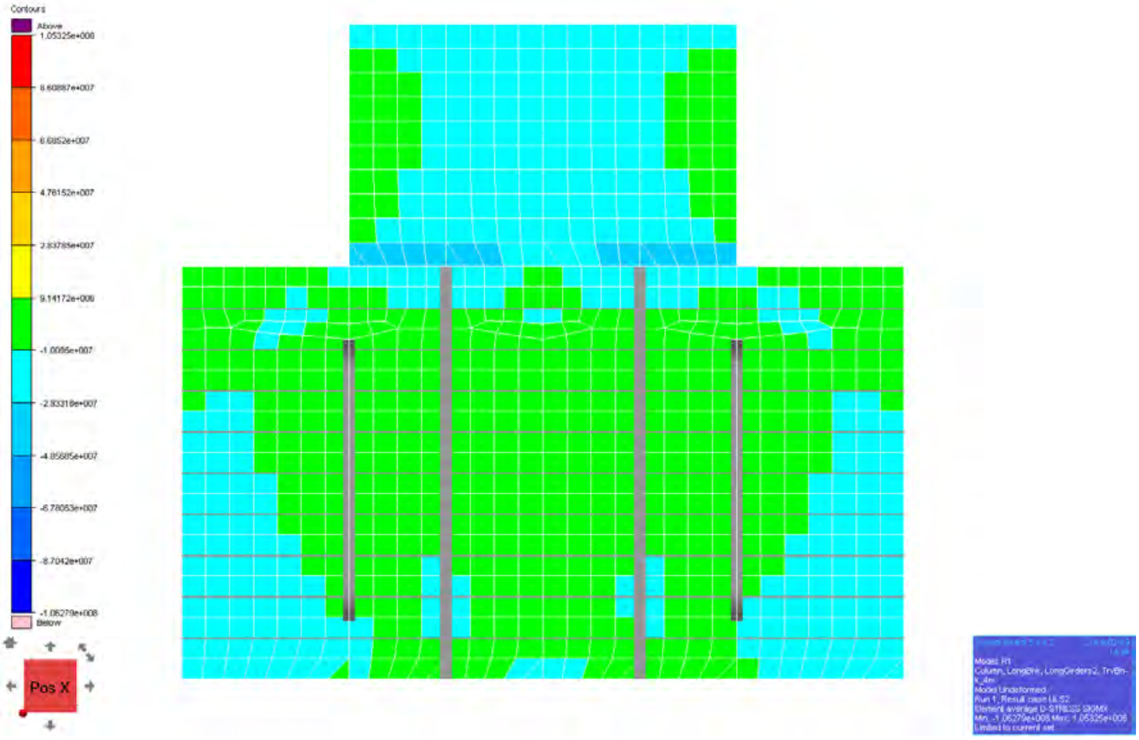


Figure 4-69 SIGMX stresses for load case "ULS2" [N/m^2] for transverse bulkhead supporting column

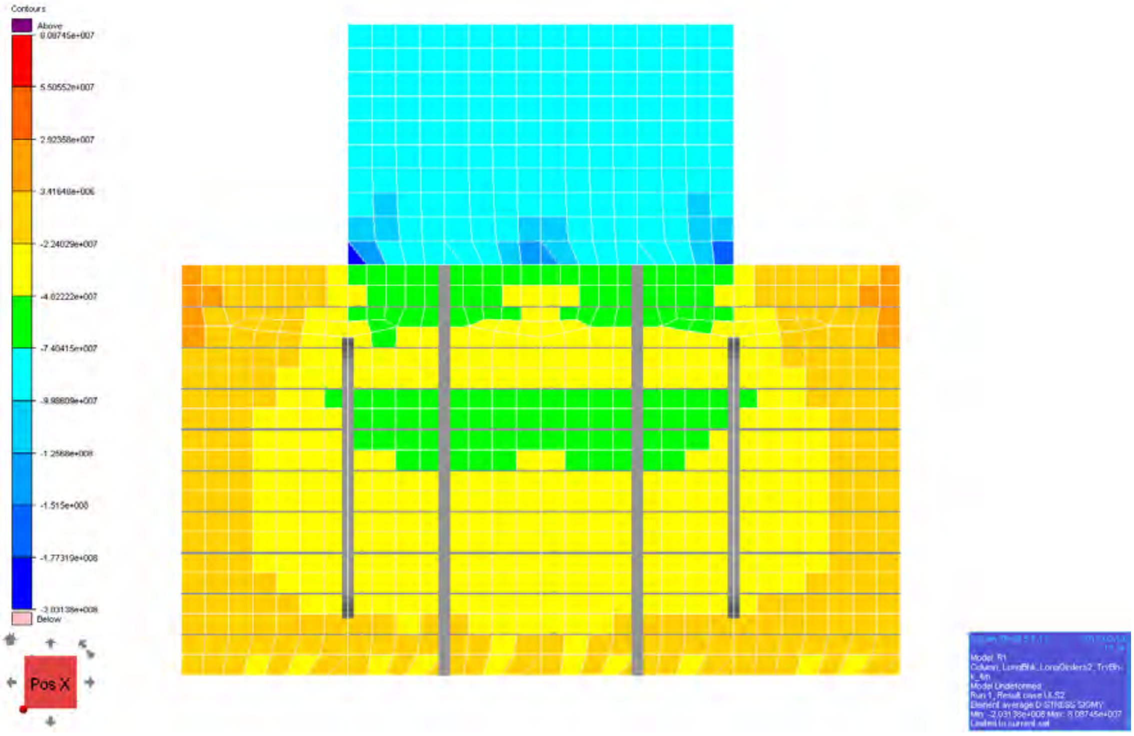


Figure 4-70 SIGMY stresses for load case "ULS2" [N/m^2] for transverse bulkhead supporting column

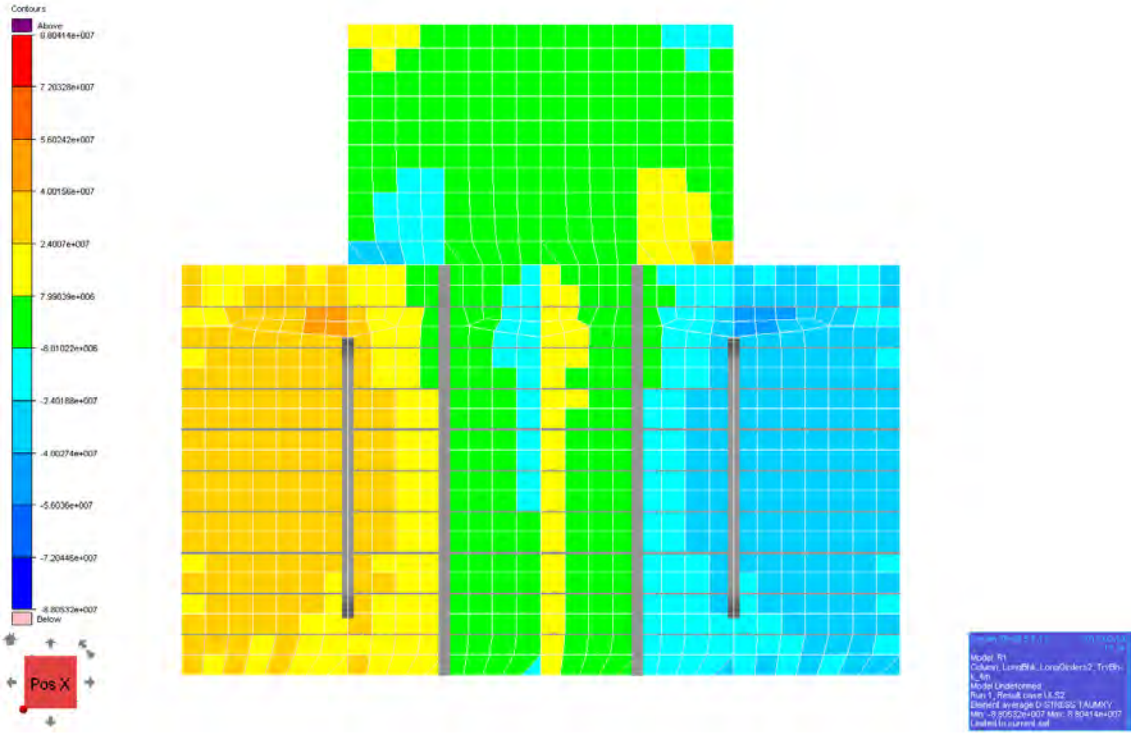


Figure 4-71 TAUMXY stresses for load case "ULS2" [N/m^2] for transverse bulkhead supporting column

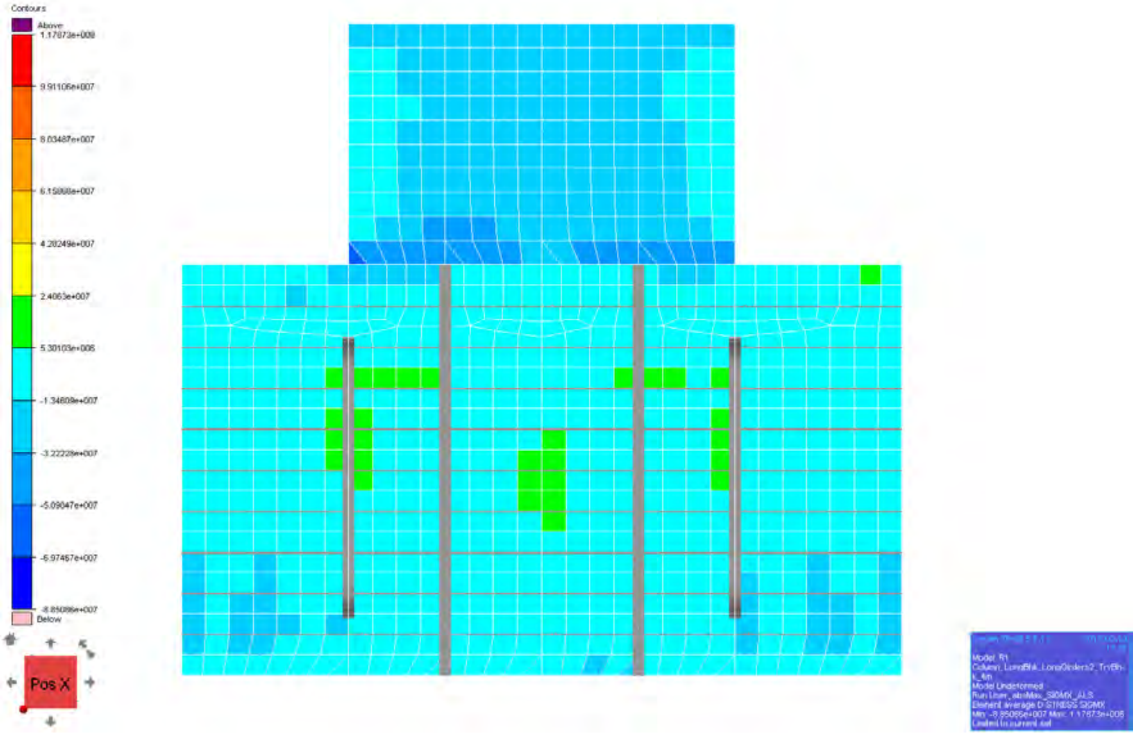


Figure 4-72 Scan of min SIGMX stresses for ALS load combinations [N/m^2] for transverse bulkhead supporting column

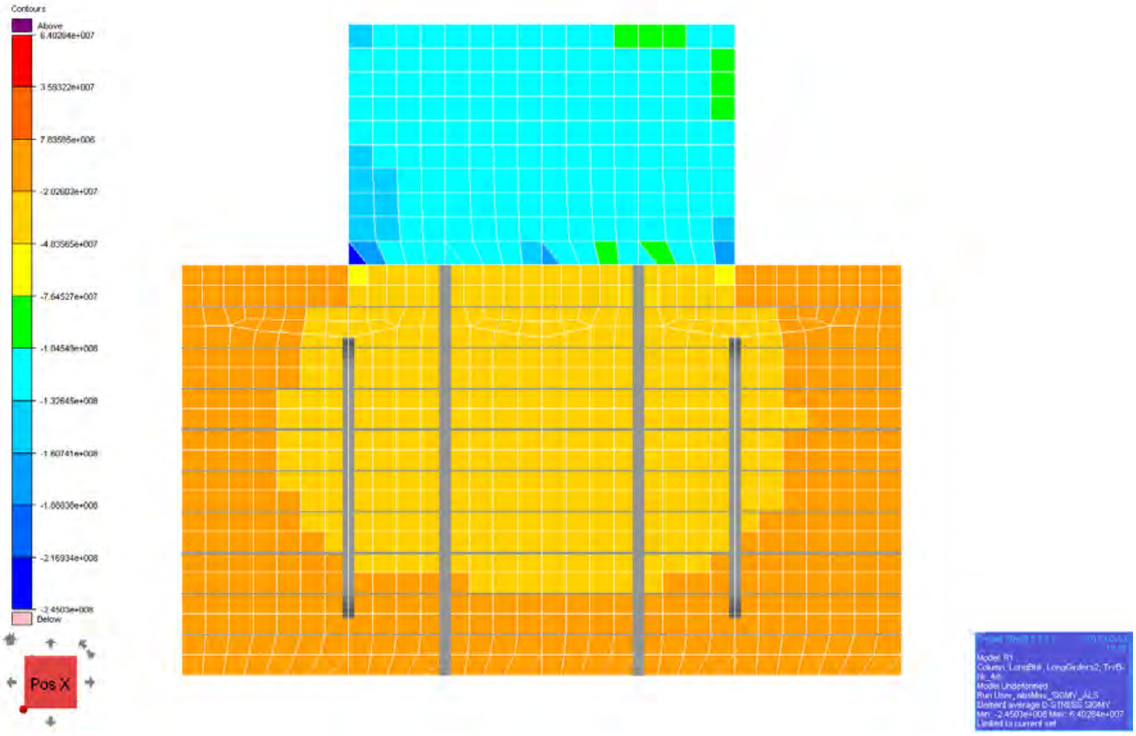


Figure 4-73 Scan of min SIGMY stresses for ALS load combinations [N/m^2] for transverse bulkhead supporting column

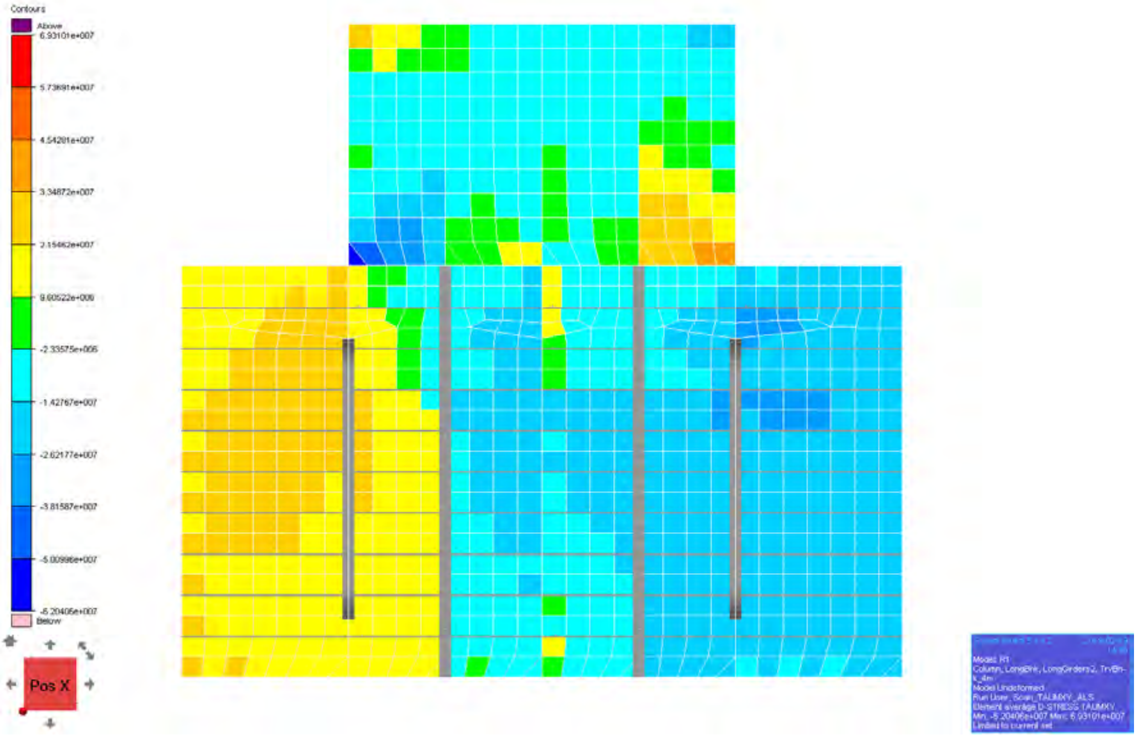


Figure 4-74 Scan of TAUMXY stresses for ALS load combinations [N/m^2] for transverse bulkhead supporting column

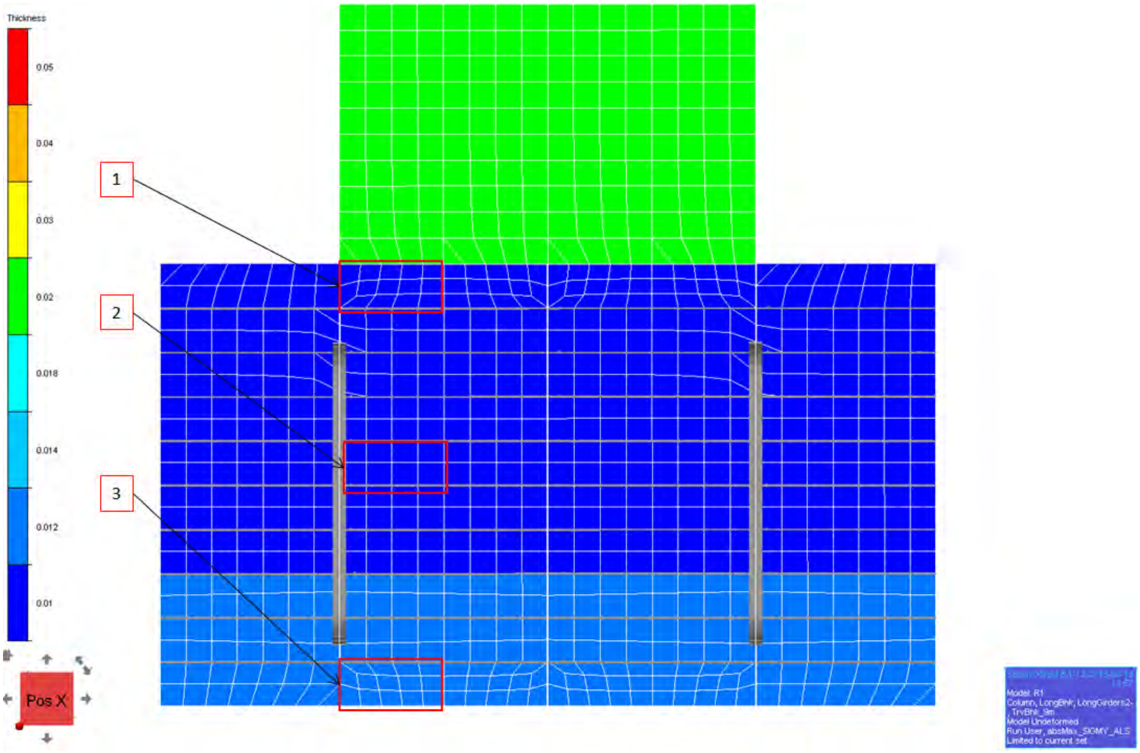


Figure 4-75 Identification of areas considered for buckling & scantling check for a typical transverse bulkhead

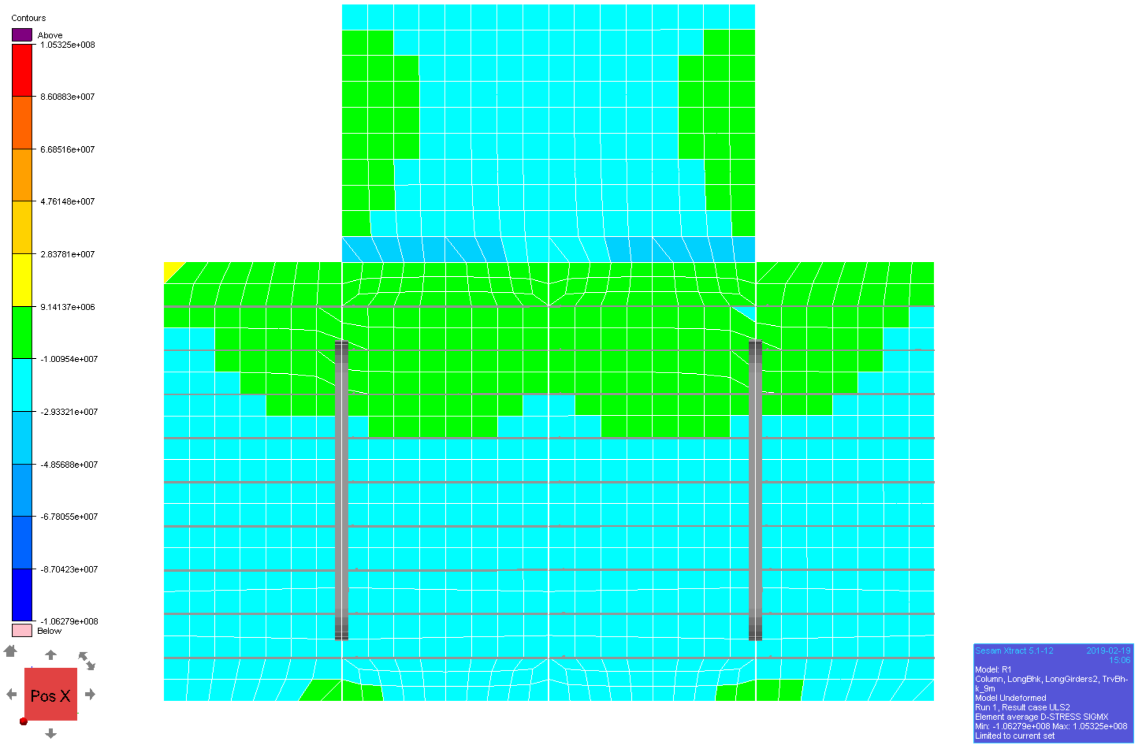


Figure 4-76 SIGMX stresses for load case "ULS2" [N/m^2] for a typical transverse bulkhead

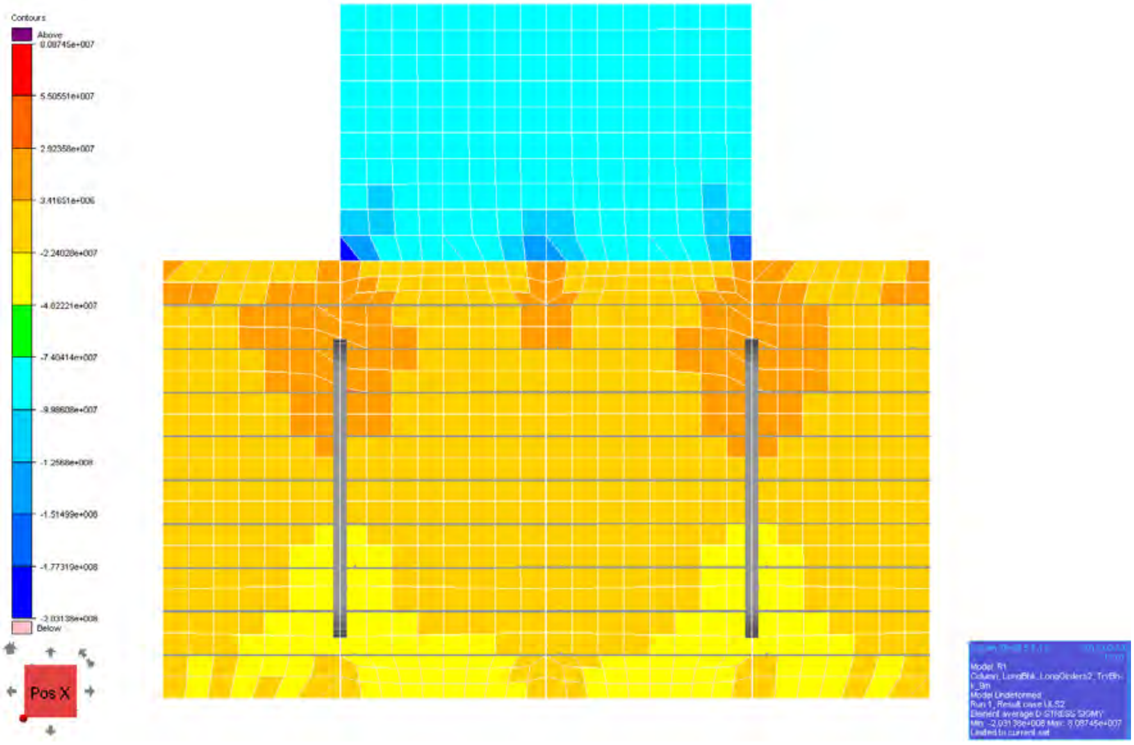


Figure 4-77 SIGMY stresses for load case "ULS2" [N/m^2] for a typical transverse bulkhead

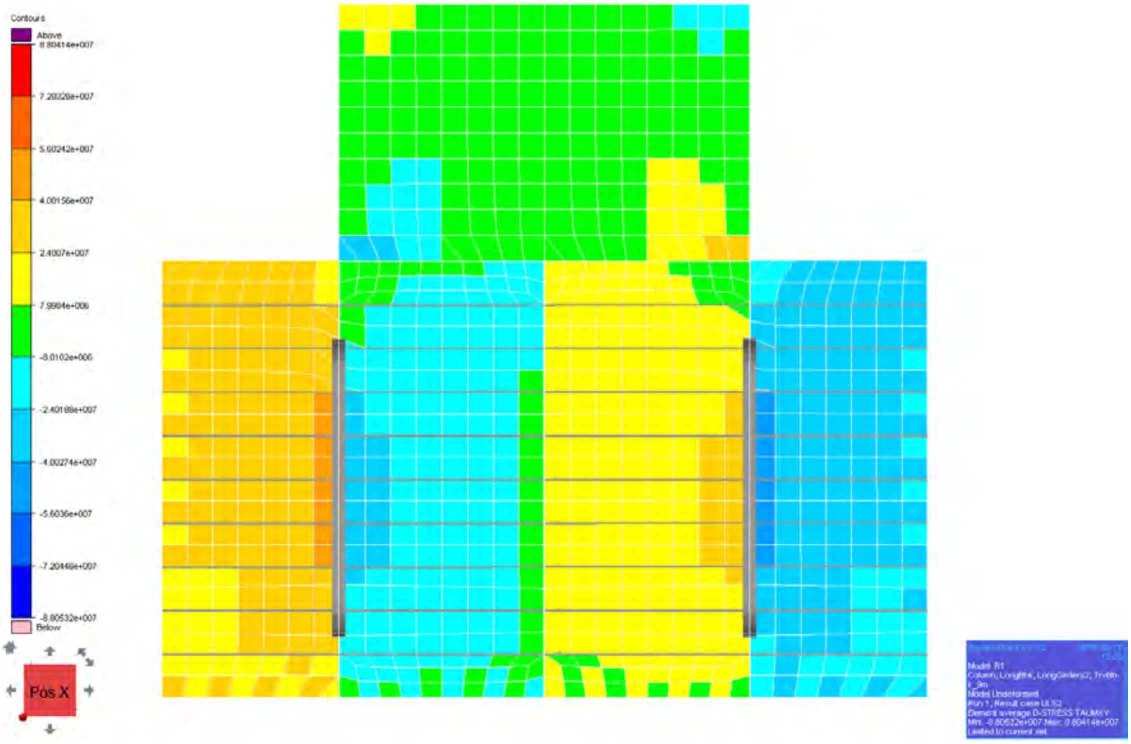


Figure 4-78 TAUMXY stresses for load case "ULS2" [N/m^2] for a typical transverse bulkhead

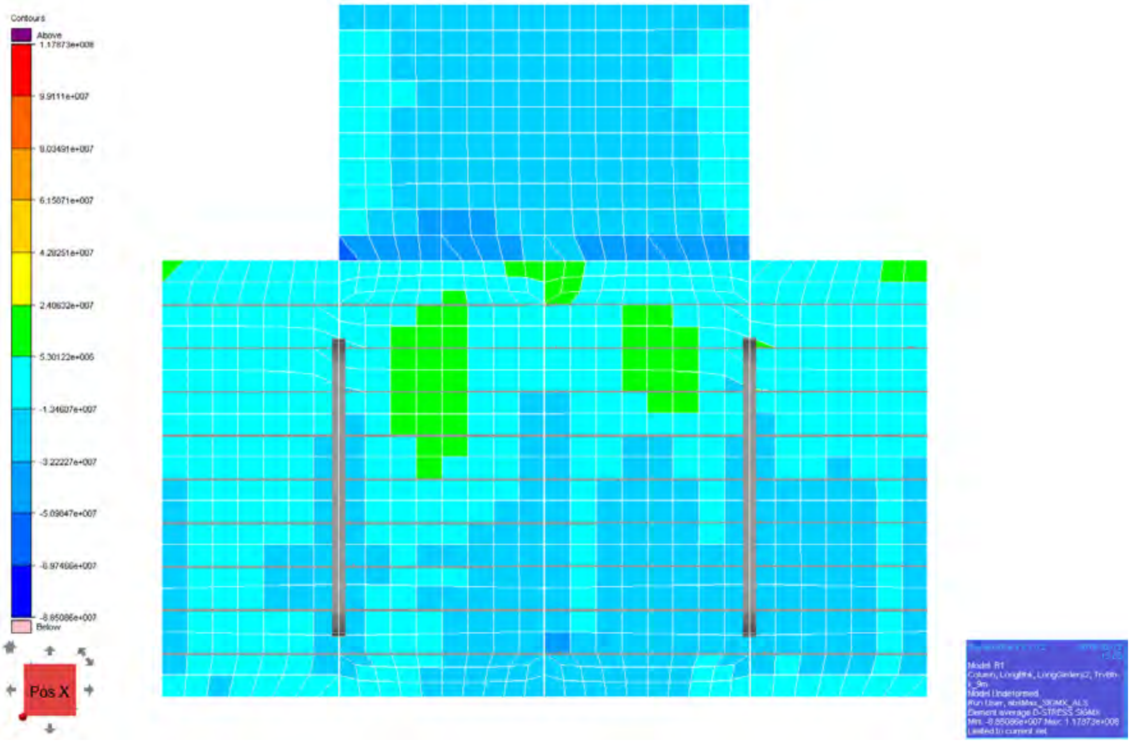


Figure 4-79 *SIGMX stresses for ALS load combinations [N/m^2] for a typical transverse bulkhead*

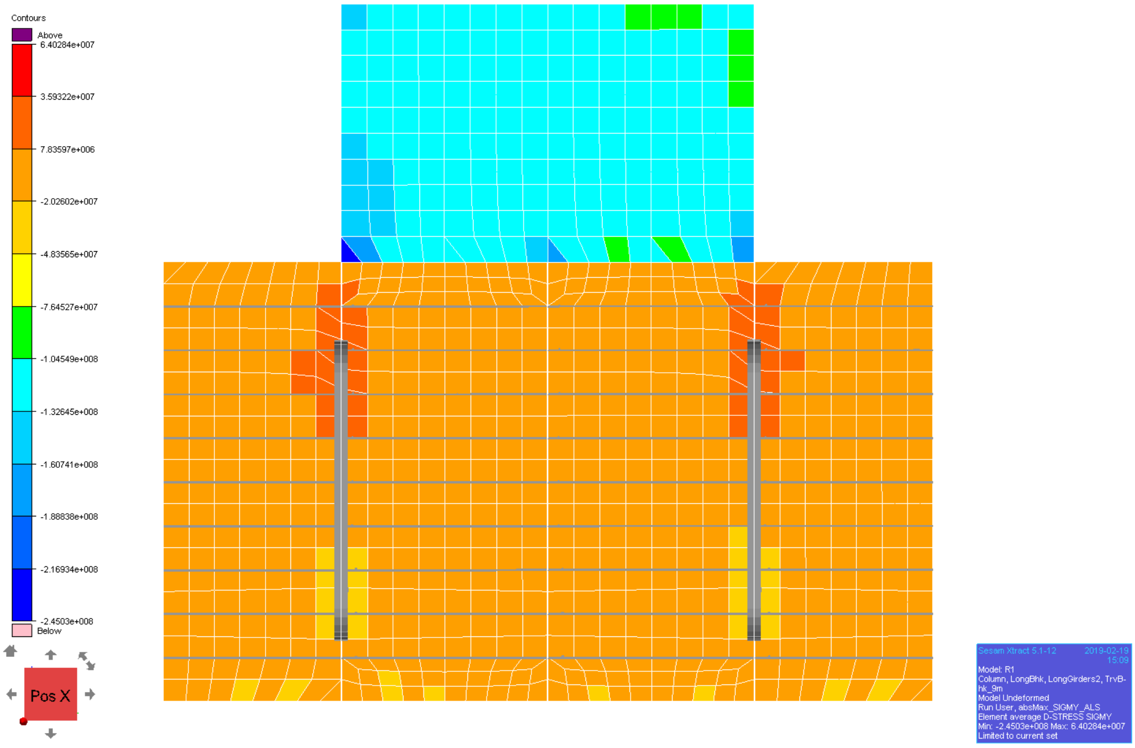


Figure 4-80 SIGMY stresses for ALS load combinations [N/m^2] for a typical transverse bulkhead

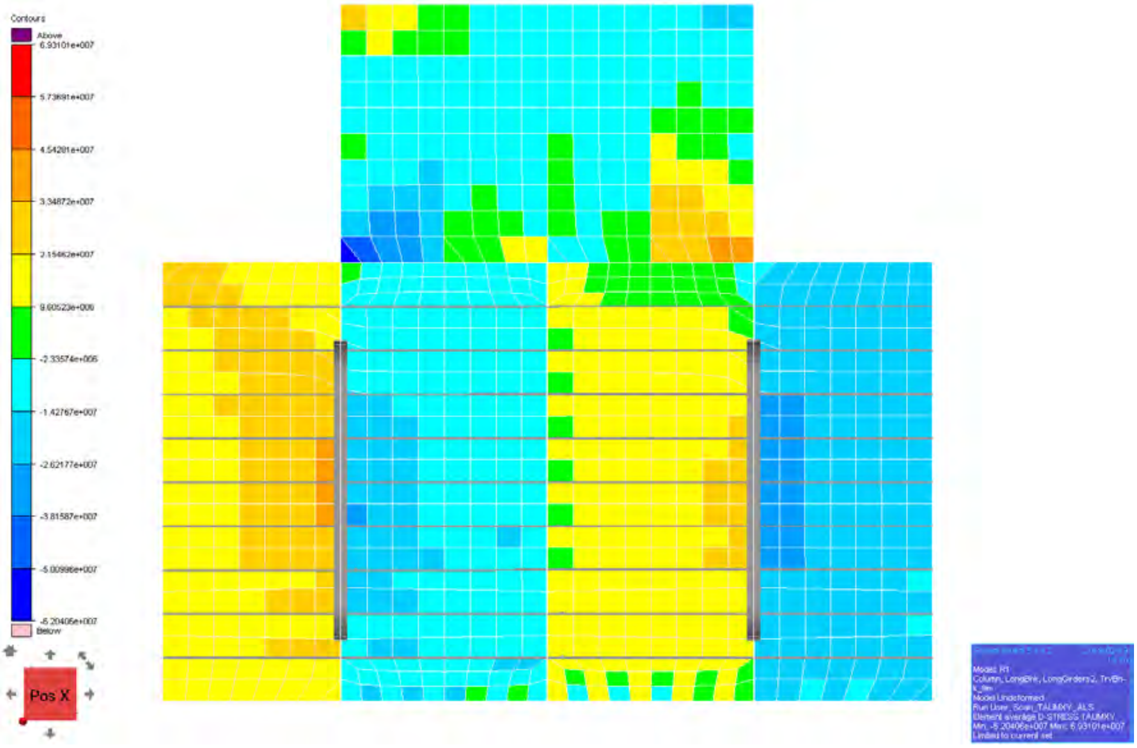
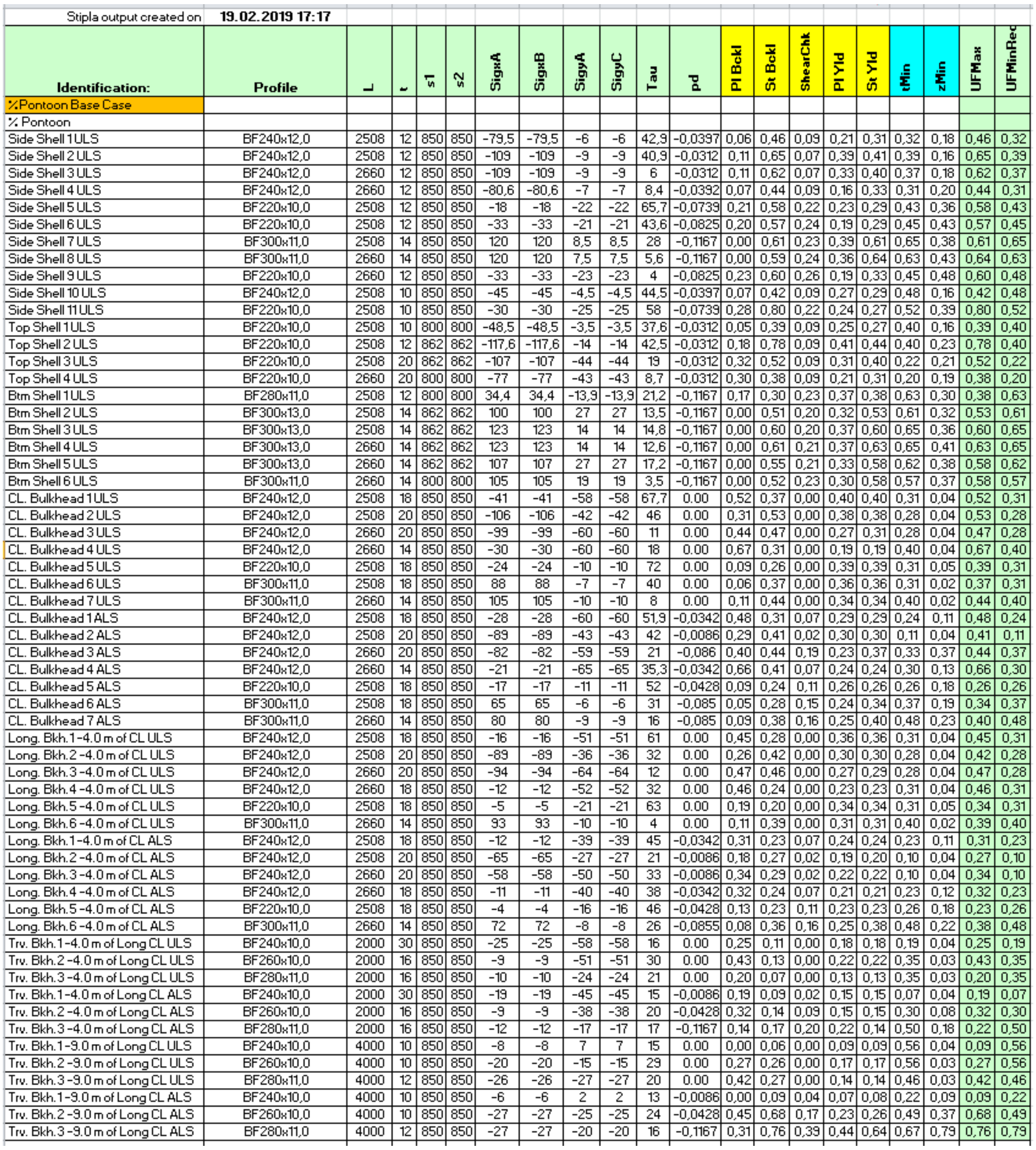


Figure 4-81 TAUMXY stresses for ALS load combinations [N/m^2] for a typical transverse bulkhead

Table 4-1 Buckling and scantling results for ULS and ALS load combinations



Stipla output created on	19.02.2019 17:17																			
Identification:	**Profile**	**L**	**t**	**s1**	**s2**	**SigxA**	**SigxB**	**SigyA**	**SigyC**	**Tau**	**pd**	**Pl Bckl**	**St Bckl**	**ShearChk**	**Pl Yld**	**St Yld**	**tMin**	**zMin**	**UFMax**	**UFMinRec**
%Pontoon Base Case																				
% Pontoon																				
Side Shell 1 ULS	BF240x12,0	2508	12	850	850	-79,5	-79,5	-6	-6	42,9	-0,0397	0,06	0,46	0,09	0,21	0,31	0,32	0,18	0,46	0,32
Side Shell 2 ULS	BF240x12,0	2508	12	850	850	-109	-109	-9	-9	40,9	-0,0312	0,11	0,65	0,07	0,39	0,41	0,39	0,16	0,65	0,39
Side Shell 3 ULS	BF240x12,0	2660	12	850	850	-109	-109	-9	-9	6	-0,0312	0,11	0,62	0,07	0,33	0,40	0,37	0,18	0,62	0,37
Side Shell 4 ULS	BF240x12,0	2660	12	850	850	-80,6	-80,6	-7	-7	8,4	-0,0392	0,07	0,44	0,09	0,16	0,33	0,31	0,20	0,44	0,31
Side Shell 5 ULS	BF220x10,0	2508	12	850	850	-18	-18	-22	-22	65,7	-0,0739	0,21	0,58	0,22	0,23	0,29	0,43	0,36	0,58	0,43
Side Shell 6 ULS	BF220x10,0	2508	12	850	850	-33	-33	-21	-21	43,6	-0,0825	0,20	0,57	0,24	0,19	0,29	0,45	0,43	0,57	0,45
Side Shell 7 ULS	BF300x11,0	2508	14	850	850	120	120	8,5	8,5	28	-0,1167	0,00	0,61	0,23	0,39	0,61	0,65	0,38	0,61	0,65
Side Shell 8 ULS	BF300x11,0	2660	14	850	850	120	120	7,5	7,5	5,6	-0,1167	0,00	0,59	0,24	0,36	0,64	0,63	0,43	0,64	0,63
Side Shell 9 ULS	BF220x10,0	2660	12	850	850	-33	-33	-23	-23	4	-0,0825	0,23	0,60	0,26	0,19	0,33	0,45	0,48	0,60	0,48
Side Shell 10 ULS	BF240x12,0	2508	10	850	850	-45	-45	-4,5	-4,5	44,5	-0,0397	0,07	0,42	0,09	0,27	0,29	0,48	0,16	0,42	0,48
Side Shell 11 ULS	BF220x10,0	2508	10	850	850	-30	-30	-25	-25	58	-0,0739	0,28	0,80	0,22	0,24	0,27	0,52	0,39	0,80	0,52
Top Shell 1 ULS	BF220x10,0	2508	10	800	800	-48,5	-48,5	-3,5	-3,5	37,6	-0,0312	0,05	0,39	0,09	0,25	0,27	0,40	0,16	0,39	0,40
Top Shell 2 ULS	BF220x10,0	2508	12	862	862	-117,6	-117,6	-14	-14	42,5	-0,0312	0,18	0,78	0,09	0,41	0,44	0,40	0,23	0,78	0,40
Top Shell 3 ULS	BF220x10,0	2508	20	862	862	-107	-107	-44	-44	19	-0,0312	0,32	0,52	0,09	0,31	0,40	0,22	0,21	0,52	0,22
Top Shell 4 ULS	BF220x10,0	2660	20	800	800	-77	-77	-43	-43	8,7	-0,0312	0,30	0,38	0,09	0,21	0,31	0,20	0,19	0,38	0,20
Btm Shell 1 ULS	BF280x11,0	2508	12	800	800	34,4	34,4	-13,9	-13,9	21,2	-0,1167	0,17	0,30	0,23	0,37	0,38	0,63	0,30	0,38	0,63
Btm Shell 2 ULS	BF300x13,0	2508	14	862	862	100	100	27	27	13,5	-0,1167	0,00	0,51	0,20	0,32	0,53	0,61	0,32	0,53	0,61
Btm Shell 3 ULS	BF300x13,0	2508	14	862	862	123	123	14	14	14,8	-0,1167	0,00	0,60	0,20	0,37	0,60	0,65	0,36	0,60	0,65
Btm Shell 4 ULS	BF300x13,0	2660	14	862	862	123	123	14	14	12,6	-0,1167	0,00	0,61	0,21	0,37	0,63	0,65	0,41	0,63	0,65
Btm Shell 5 ULS	BF300x13,0	2660	14	862	862	107	107	27	27	17,2	-0,1167	0,00	0,55	0,21	0,33	0,58	0,62	0,38	0,58	0,62
Btm Shell 6 ULS	BF300x11,0	2660	14	800	800	105	105	19	19	3,5	-0,1167	0,00	0,52	0,23	0,30	0,58	0,57	0,37	0,58	0,57
CL. Bulkhead 1 ULS	BF240x12,0	2508	18	850	850	-41	-41	-58	-58	67,7	0.00	0,52	0,37	0,00	0,40	0,40	0,31	0,04	0,52	0,31
CL. Bulkhead 2 ULS	BF240x12,0	2508	20	850	850	-106	-106	-42	-42	46	0.00	0,31	0,53	0,00	0,38	0,38	0,28	0,04	0,53	0,28
CL. Bulkhead 3 ULS	BF240x12,0	2660	20	850	850	-99	-99	-60	-60	11	0.00	0,44	0,47	0,00	0,27	0,31	0,28	0,04	0,47	0,28
CL. Bulkhead 4 ULS	BF240x12,0	2660	14	850	850	-30	-30	-60	-60	18	0.00	0,67	0,31	0,00	0,19	0,19	0,40	0,04	0,67	0,40
CL. Bulkhead 5 ULS	BF220x10,0	2508	18	850	850	-24	-24	-10	-10	72	0.00	0,09	0,26	0,00	0,39	0,39	0,31	0,05	0,39	0,31
CL. Bulkhead 6 ULS	BF300x11,0	2508	18	850	850	88	88	-7	-7	40	0.00	0,06	0,37	0,00	0,36	0,36	0,31	0,02	0,37	0,31
CL. Bulkhead 7 ULS	BF300x11,0	2660	14	850	850	105	105	-10	-10	8	0.00	0,11	0,44	0,00	0,34	0,34	0,40	0,02	0,44	0,40
CL. Bulkhead 1 ALS	BF240x12,0	2508	18	850	850	-28	-28	-60	-60	51,9	-0,0342	0,48	0,31	0,07	0,29	0,29	0,24	0,11	0,48	0,24
CL. Bulkhead 2 ALS	BF240x12,0	2508	20	850	850	-89	-89	-43	-43	42	-0,0086	0,29	0,41	0,02	0,30	0,30	0,11	0,04	0,41	0,11
CL. Bulkhead 3 ALS	BF240x12,0	2660	20	850	850	-82	-82	-59	-59	21	-0,086	0,40	0,44	0,19	0,23	0,37	0,33	0,37	0,44	0,37
CL. Bulkhead 4 ALS	BF240x12,0	2660	14	850	850	-21	-21	-65	-65	35,3	-0,0342	0,66	0,41	0,07	0,24	0,24	0,30	0,13	0,66	0,30
CL. Bulkhead 5 ALS	BF220x10,0	2508	18	850	850	-17	-17	-11	-11	52	-0,0428	0,09	0,24	0,11	0,26	0,26	0,26	0,18	0,26	0,26
CL. Bulkhead 6 ALS	BF300x11,0	2508	18	850	850	65	65	-6	-6	31	-0,085	0,05	0,28	0,15	0,24	0,34	0,37	0,19	0,34	0,37
CL. Bulkhead 7 ALS	BF300x11,0	2660	14	850	850	80	80	-9	-9	16	-0,085	0,09	0,38	0,16	0,25	0,40	0,48	0,23	0,40	0,48
Long. Bkh.1 -4.0 m of CL ULS	BF240x12,0	2508	18	850	850	-16	-16	-51	-51	61	0.00	0,45	0,28	0,00	0,36	0,36	0,31	0,04	0,45	0,31
Long. Bkh.2 -4.0 m of CL ULS	BF240x12,0	2508	20	850	850	-89	-89	-36	-36	32	0.00	0,26	0,42	0,00	0,30	0,30	0,28	0,04	0,42	0,28
Long. Bkh.3 -4.0 m of CL ULS	BF240x12,0	2660	20	850	850	-94	-94	-64	-64	12	0.00	0,47	0,46	0,00	0,27	0,29	0,28	0,04	0,47	0,28
Long. Bkh.4 -4.0 m of CL ULS	BF240x12,0	2660	18	850	850	-12	-12	-52	-52	32	0.00	0,46	0,24	0,00	0,23	0,23	0,31	0,04	0,46	0,31
Long. Bkh.5 -4.0 m of CL ULS	BF220x10,0	2508	18	850	850	-5	-5	-21	-21	63	0.00	0,19	0,20	0,00	0,34	0,34	0,31	0,05	0,34	0,31
Long. Bkh.6 -4.0 m of CL ULS	BF300x11,0	2660	14	850	850	93	93	-10	-10	4	0.00	0,11	0,39	0,00	0,31	0,31	0,40	0,02	0,39	0,40
Long. Bkh.1 -4.0 m of CL ALS	BF240x12,0	2508	18	850	850	-12	-12	-39	-39	45	-0,0342	0,31	0,23	0,07	0,24	0,24	0,23	0,11	0,31	0,23
Long. Bkh.2 -4.0 m of CL ALS	BF240x12,0	2508	20	850	850	-65	-65	-27	-27	21	-0,0086	0,18	0,27	0,02	0,19	0,20	0,10	0,04	0,27	0,10
Long. Bkh.3 -4.0 m of CL ALS	BF240x12,0	2660	20	850	850	-58	-58	-50	-50	33	-0,0086	0,34	0,29	0,02	0,22	0,22	0,10	0,04	0,34	0,10
Long. Bkh.4 -4.0 m of CL ALS	BF240x12,0	2660	18	850	850	-11	-11	-40	-40	38	-0,0342	0,32	0,24	0,07	0,21	0,21	0,23	0,12	0,32	0,23
Long. Bkh.5 -4.0 m of CL ALS	BF220x10,0	2508	18	850	850	-4	-4	-16	-16	46	-0,0428	0,13	0,23	0,11	0,23	0,23	0,26	0,18	0,23	0,26
Long. Bkh.6 -4.0 m of CL ALS	BF300x11,0	2660	14	850	850	72	72	-8	-8	26	-0,0855	0,08	0,36	0,16	0,25	0,38	0,48	0,22	0,38	0,48
Trv. Bkh.1 -4.0 m of Long CL ULS	BF240x10,0	2000	30	850	850	-25	-25	-58	-58	16	0.00	0,25	0,11	0,00	0,18	0,18	0,19	0,04	0,25	0,19
Trv. Bkh.2 -4.0 m of Long CL ULS	BF260x10,0	2000	16	850	850	-9	-9	-51	-51	30	0.00	0,43	0,13	0,00	0,22	0,22	0,35	0,03	0,43	0,35
Trv. Bkh.3 -4.0 m of Long CL ULS	BF280x11,0	2000	16	850	850	-10	-10	-24	-24	21	0.00	0,20	0,07	0,00	0,13	0,13	0,35	0,03	0,20	0,35
Trv. Bkh.1 -4.0 m of Long CL ALS	BF240x10,0	2000	30	850	850	-19	-19	-45	-45	15	-0,0086	0,19	0,09	0,02	0,15	0,15	0,07	0,04	0,19	0,07
Trv. Bkh.2 -4.0 m of Long CL ALS	BF260x10,0	2000	16	850	850	-9	-9	-38	-38	20	-0,0428	0,32	0,14	0,09	0,15	0,15	0,30	0,08	0,32	0,30
Trv. Bkh.3 -4.0 m of Long CL ALS	BF280x11,0	2000	16	850	850	-12	-12	-17	-17	17	-0,1167	0,14	0,17	0,20	0,22	0,14	0,50	0,18	0,22	0,50
Trv. Bkh.1 -9.0 m of Long CL ULS	BF240x10,0	4000	10	850	850	-8	-8	7	7	15	0.00	0,00	0,06	0,00	0,09	0,09	0,56	0,04	0,09	0,56
Trv. Bkh.2 -9.0 m of Long CL ULS	BF260x10,0	4000	10	850	850	-20	-20	-15	-15	29	0.00	0,27	0,26	0,00	0,17	0,17	0,56	0,03	0,27	0,56
Trv. Bkh.3 -9.0 m of Long CL ULS	BF280x11,0	4000	12	850	850	-26	-26	-27	-27	20	0.00	0,42	0,27	0,00	0,14	0,14	0,46	0,03	0,42	0,46
Trv. Bkh.1 -9.0 m of Long CL ALS	BF240x10,0	4000	10	850	850	-6	-6	2	2	13	-0,0086	0,00	0,09	0,04	0,07	0,08	0,22	0,09	0,09	0,22
Trv. Bkh.2 -9.0 m of Long CL ALS	BF260x10,0	4000	10	850	850	-27	-27	-25	-25	24	-0,0428	0,45	0,68	0,17	0,23	0,26	0,49	0,37	0,68	0,49
Trv. Bkh.3 -9.0 m of Long CL ALS	BF280x11,0	4000	12	850	850	-27	-27	-20	-20	16	-0,1167	0,31	0,76	0,39	0,44	0,64	0,67	0,79	0,76	0,79

5 FE analysis – pontoon with mooring line supports

5.1 Description of FE model

A finite element model is made of the "base case" pontoon with support structure for eight mooring lines using DNVGL Software GeniE. A combination of 2nd order beam elements and plate elements has been used. The mesh size is set to 500 mm.

5.2 Applied loads

The considered ULS and ALS load cases for the "pontoon with mooring lines" are shown in Figure 5-1 and in section 4.2.

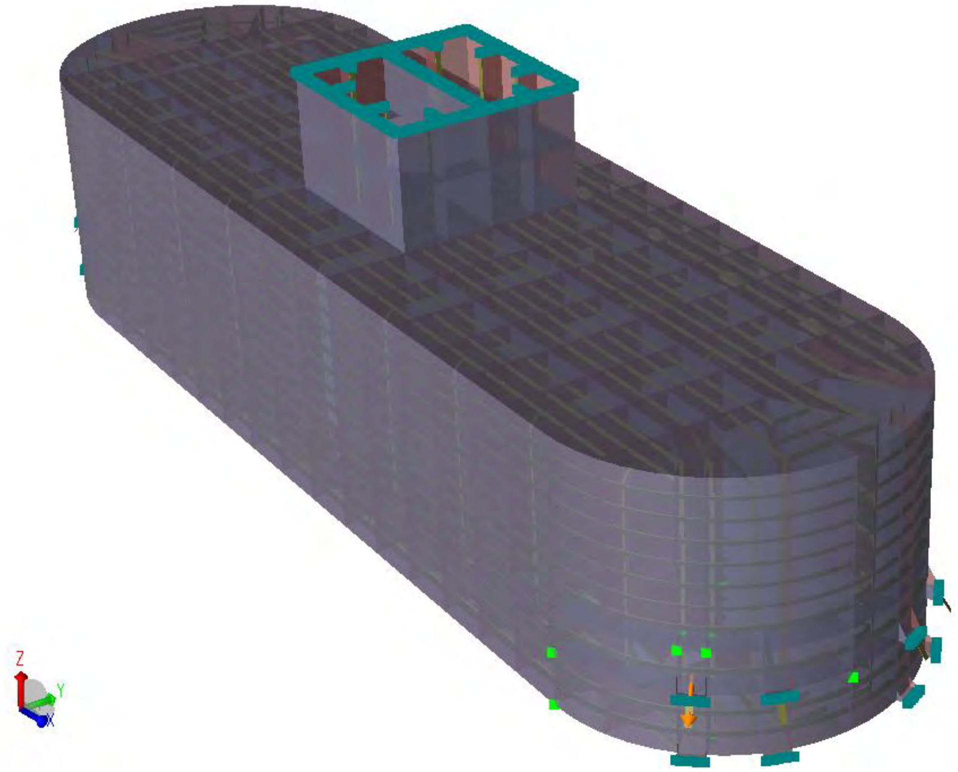


Figure 5-1 Load case "FL1ULS"

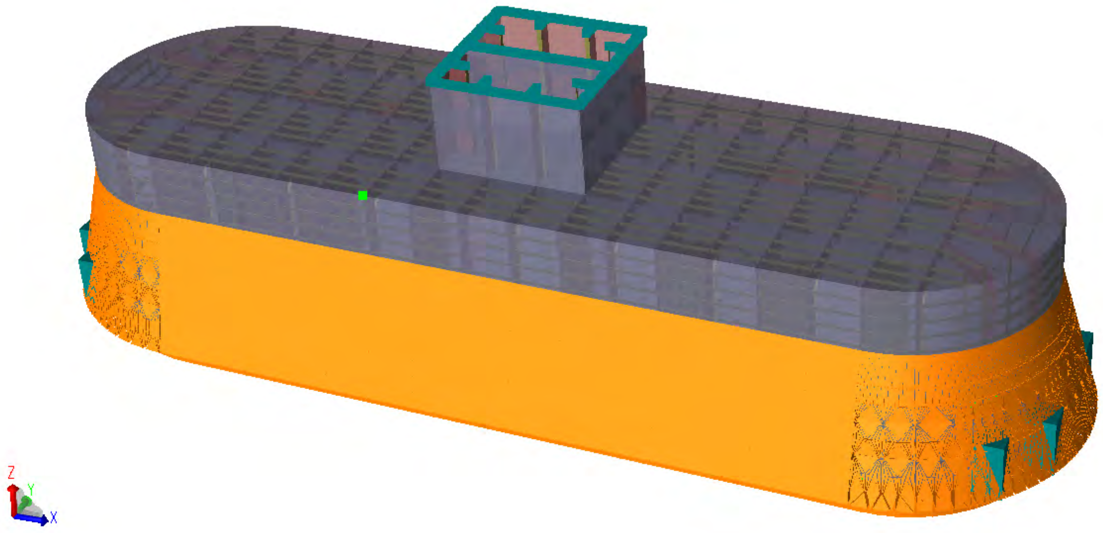


Figure 5-2 Load case "P_SWL"

5.3 Boundary conditions

The boundary conditions are applied to the lower part of the column and are shown in Figure 5-3. All degrees of freedom are fixed.

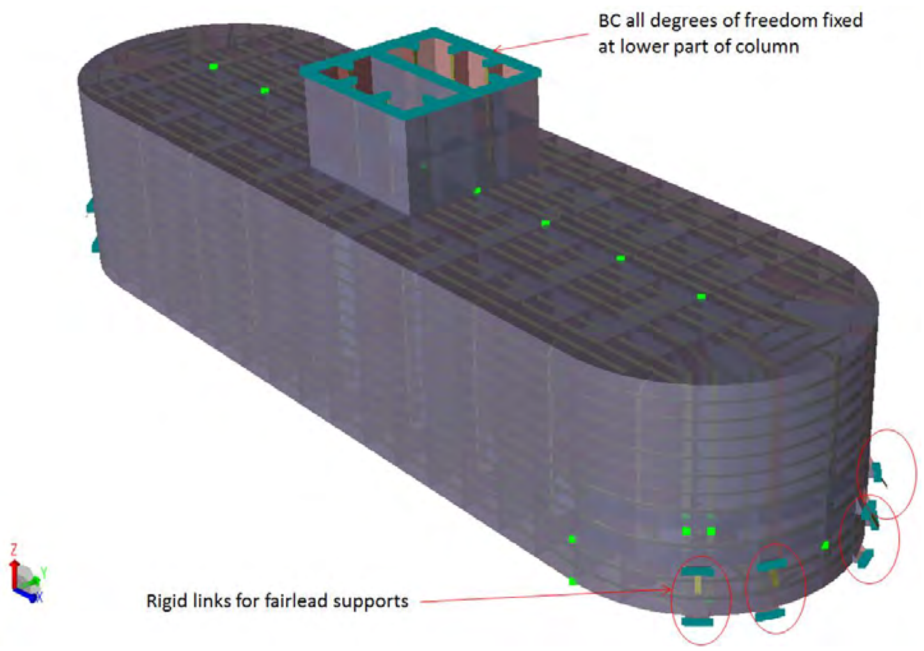


Figure 5-3 Boundary condition

5.4 Material dimensions

The material dimensions are for pontoon with mooring lines is shown herein.

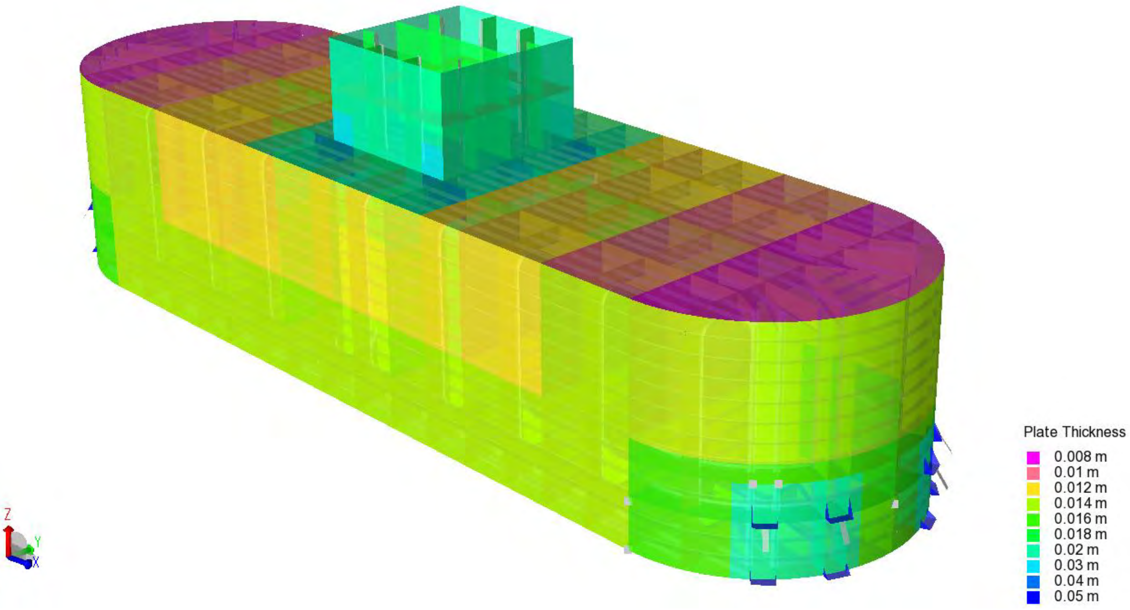


Figure 5-4 Material thicknesses [m]

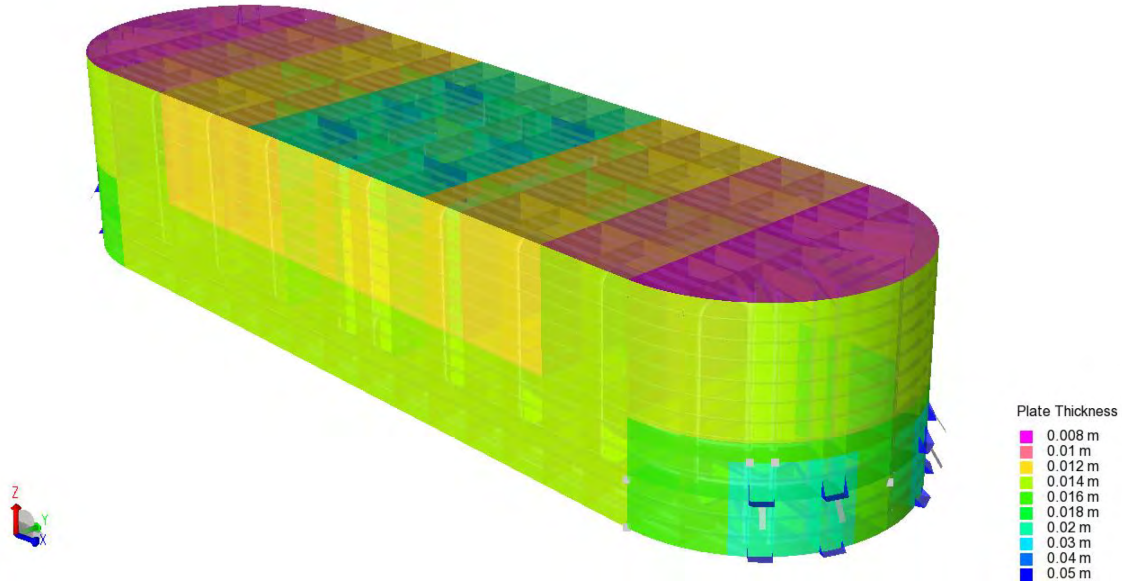


Figure 5-5 Material thicknesses [m]

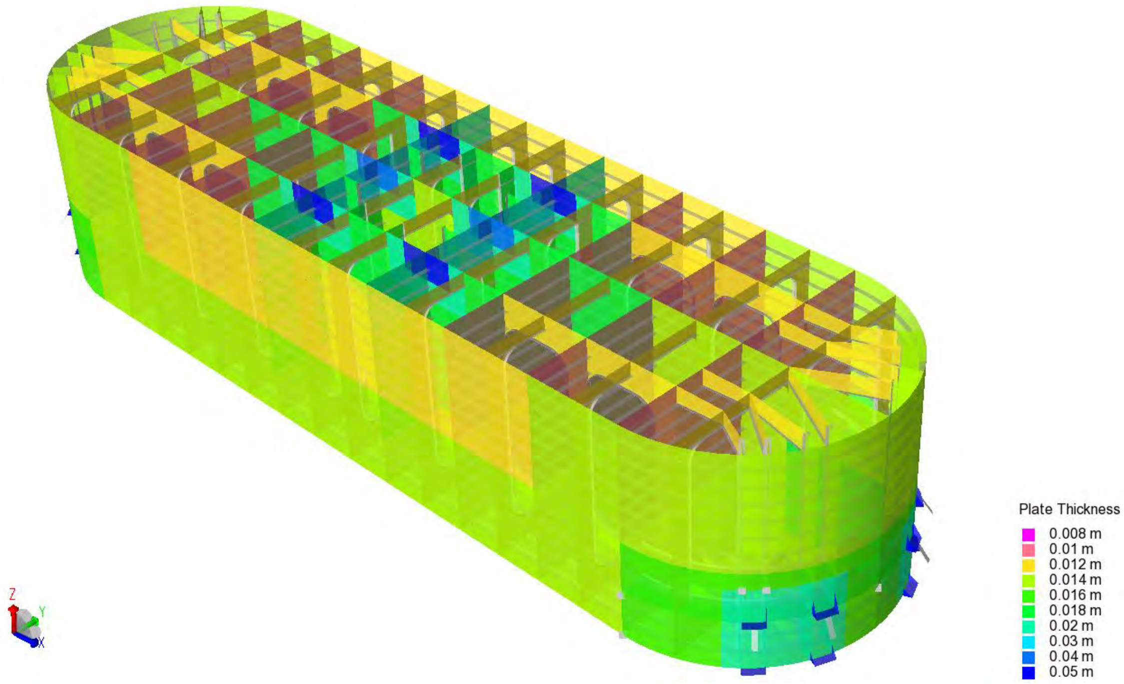


Figure 5-6 Material thicknesses [m]

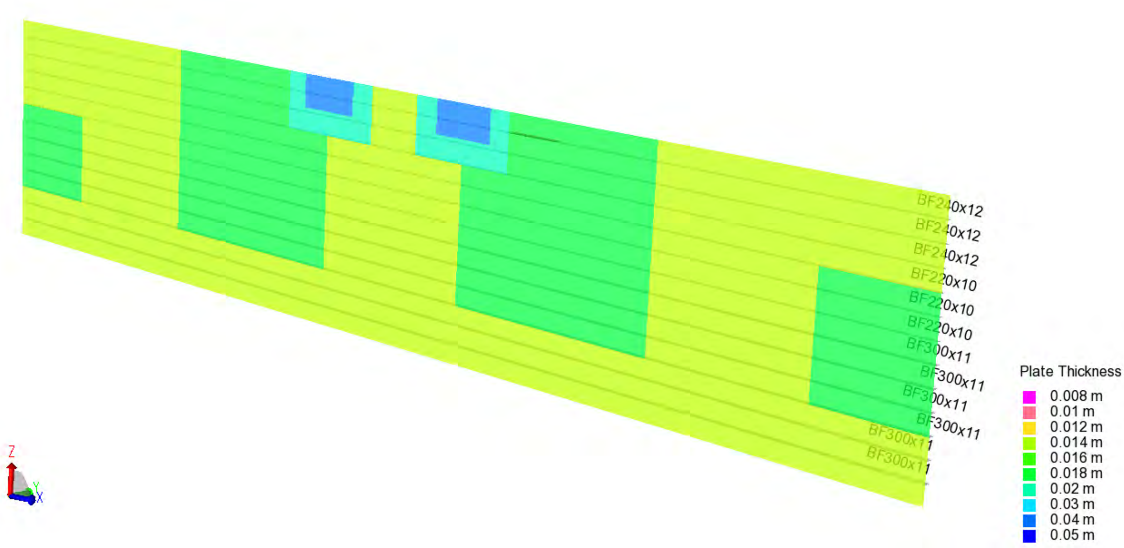


Figure 5-7 Material thicknesses [m] and section names, CL longitudinal bulkhead

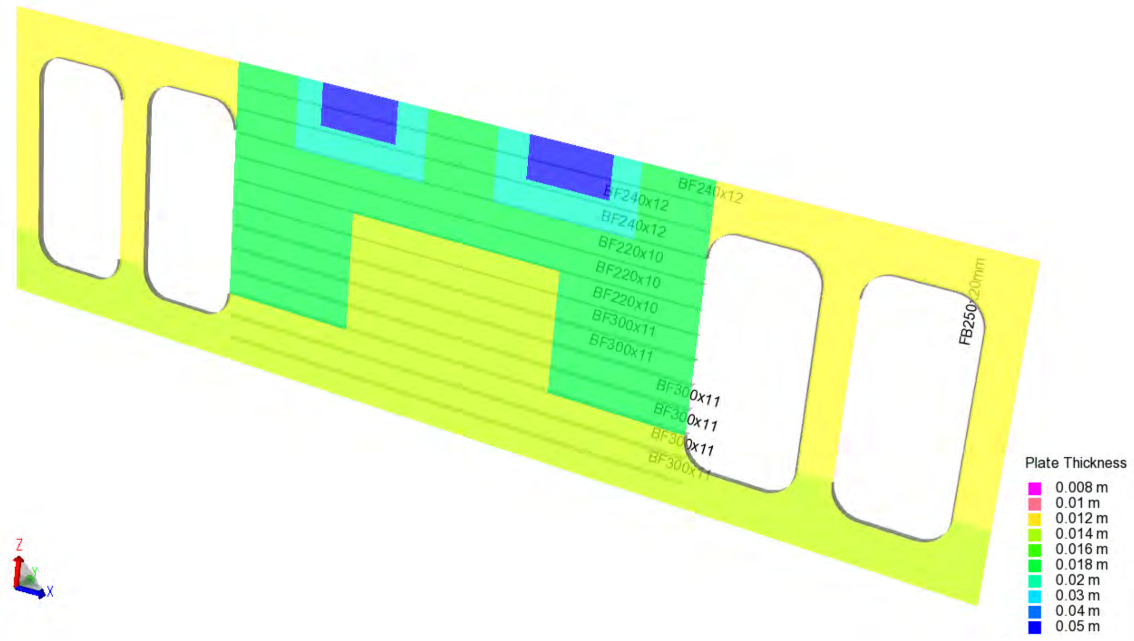


Figure 5-8 Material thicknesses [m] and section names, longitudinal bulkhead 4.0 m of CL

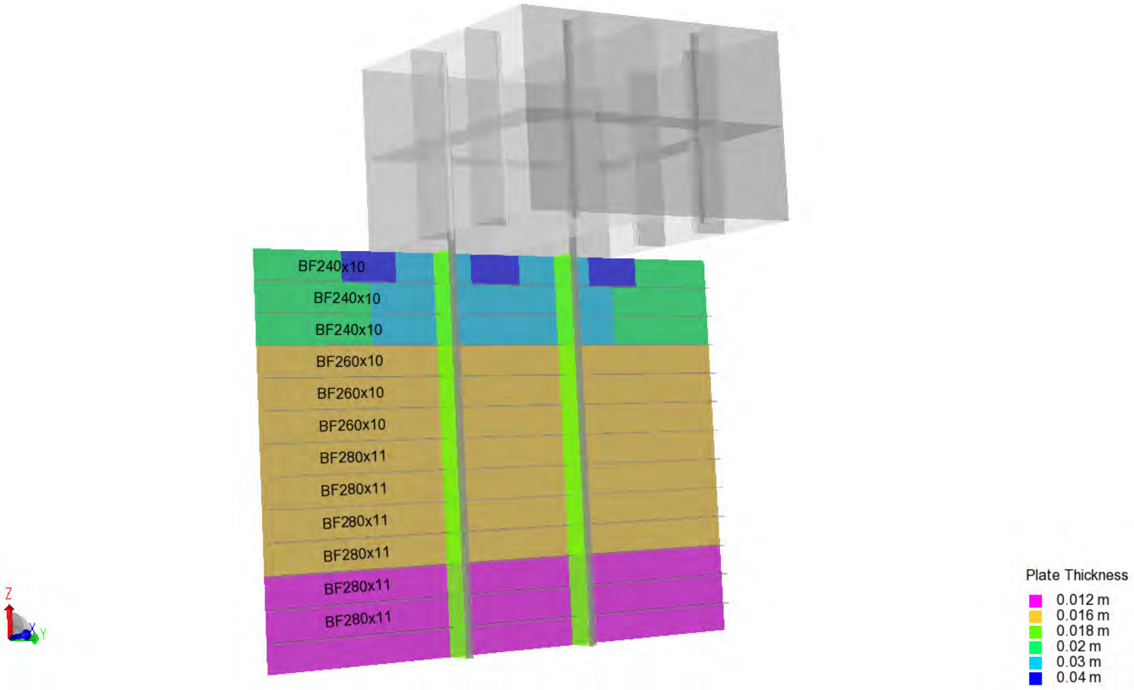


Figure 5-9 Material thicknesses [m] and section names, transverse bulkhead underneath the column

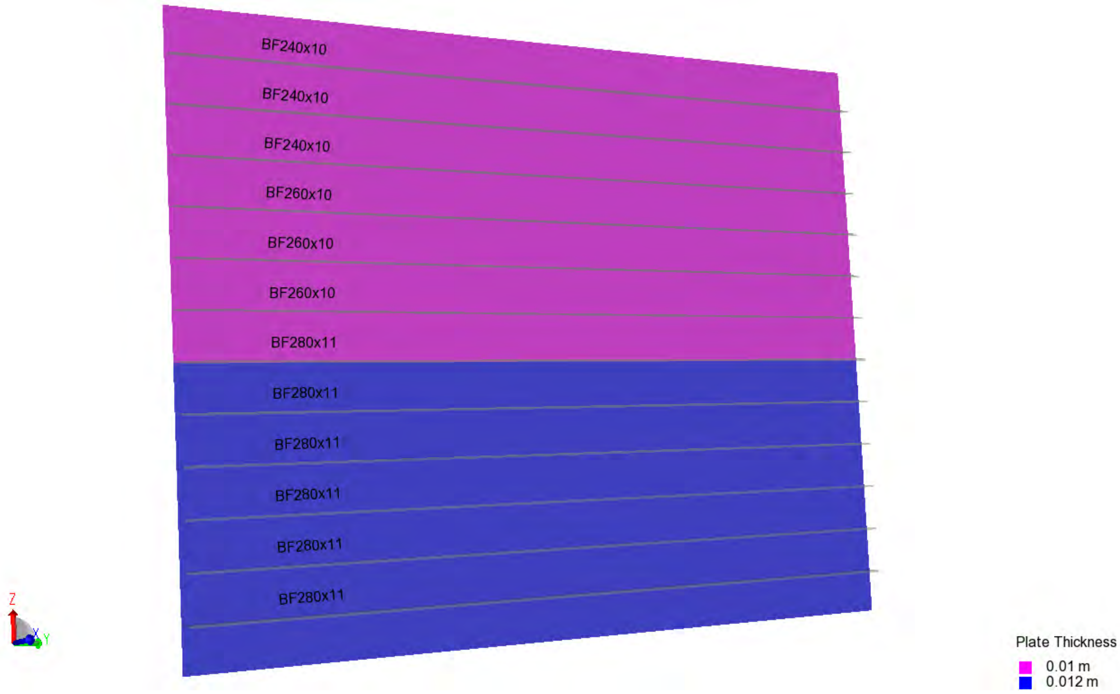


Figure 5-10 Material thicknesses [m] and section names, typical transverse bulkhead

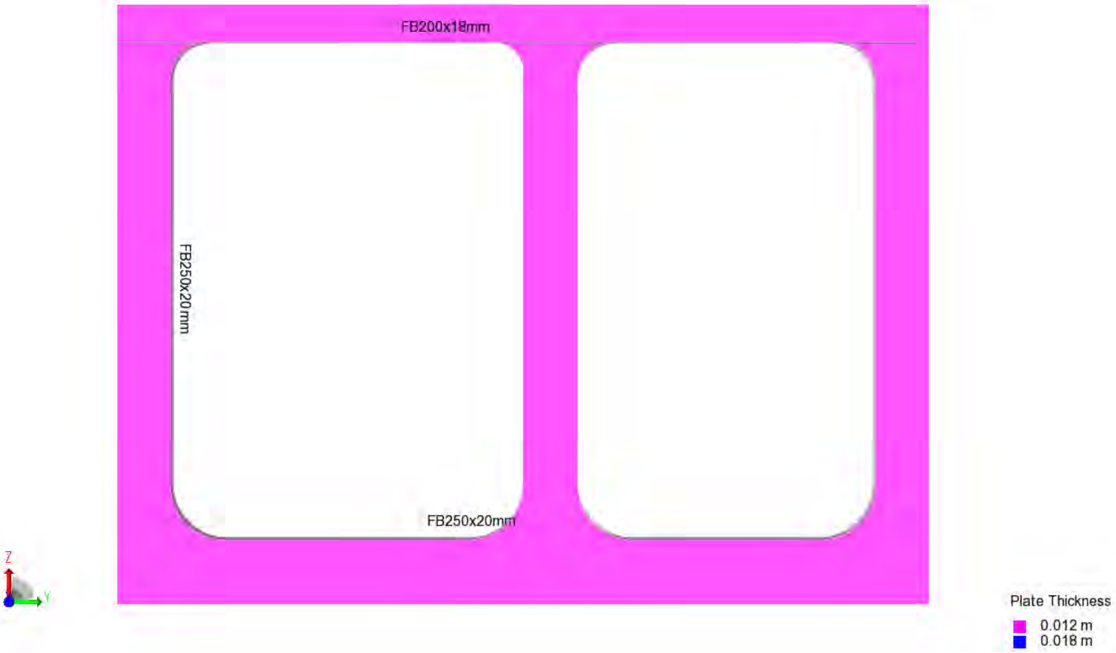


Figure 5-11 Material thicknesses [m] and section names, transverse web-frame type 1

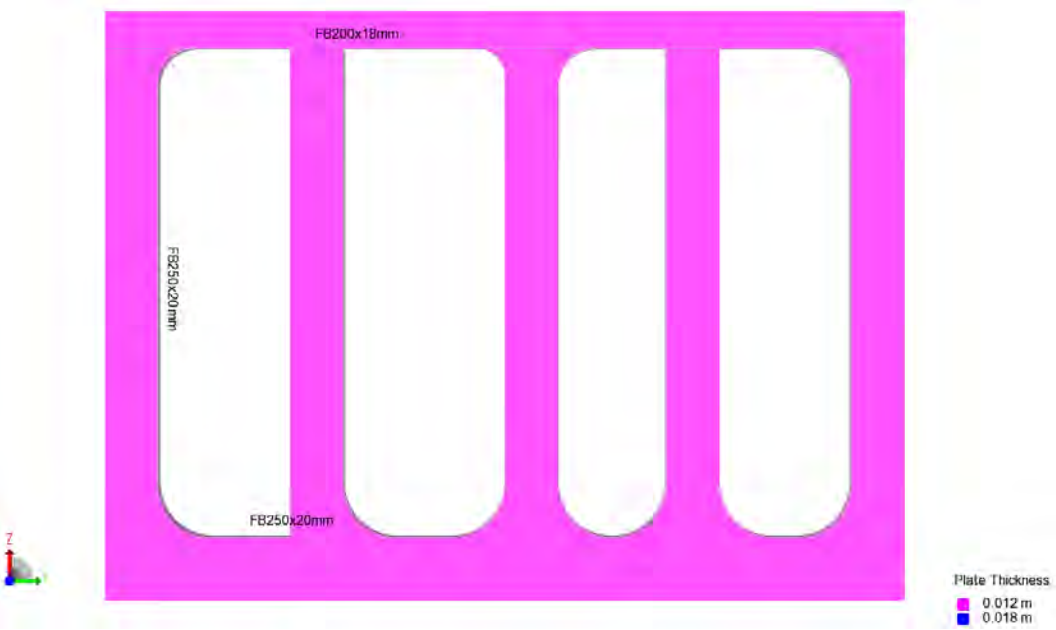


Figure 5-12 Material thicknesses [m] and section names, transverse web-frame type 2

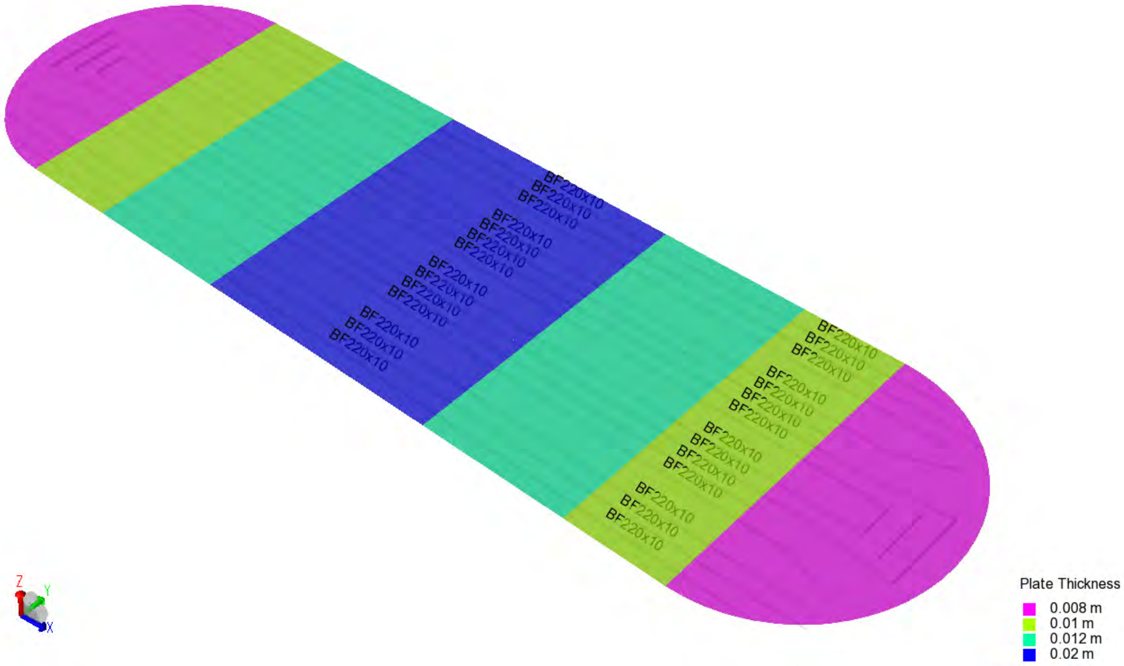


Figure 5-13 Material thicknesses [m] and section names, pontoon top plate

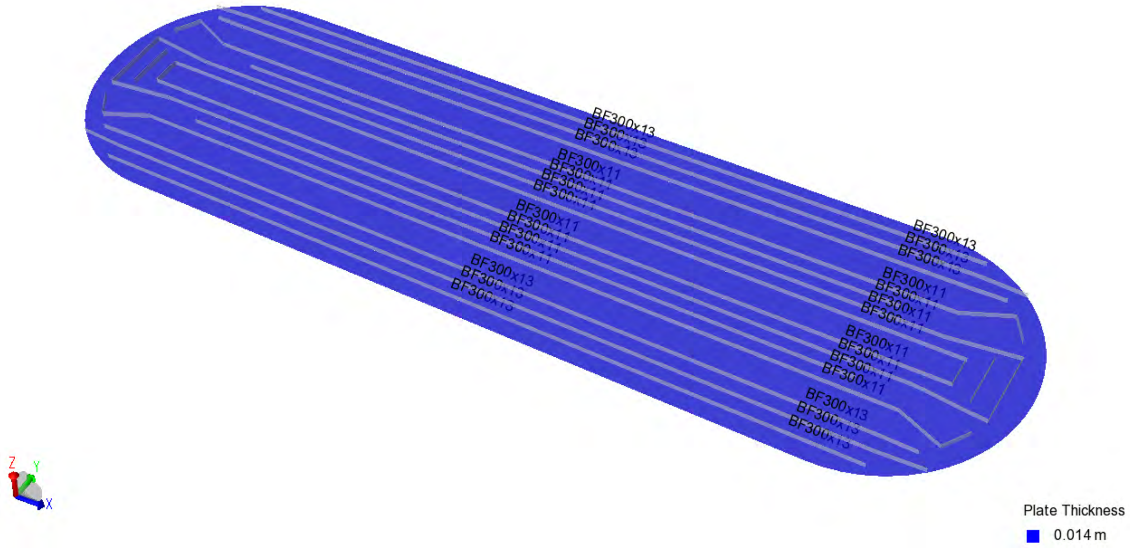


Figure 5-14 Material thicknesses [m] and section names, pontoon bottom plate

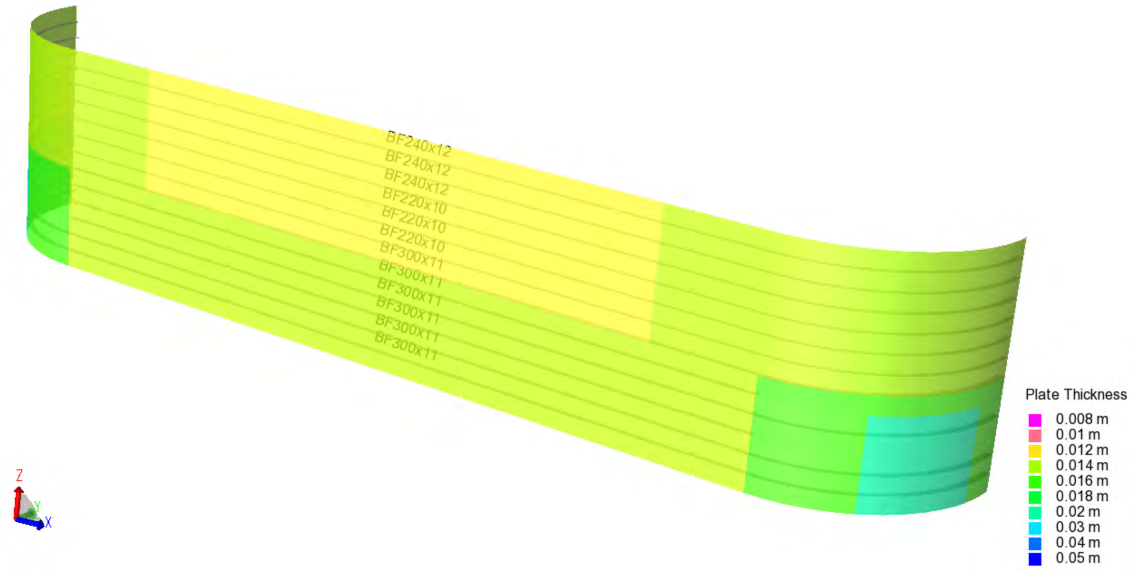


Figure 5-15 Material thicknesses [m] and section names, pontoon side shell

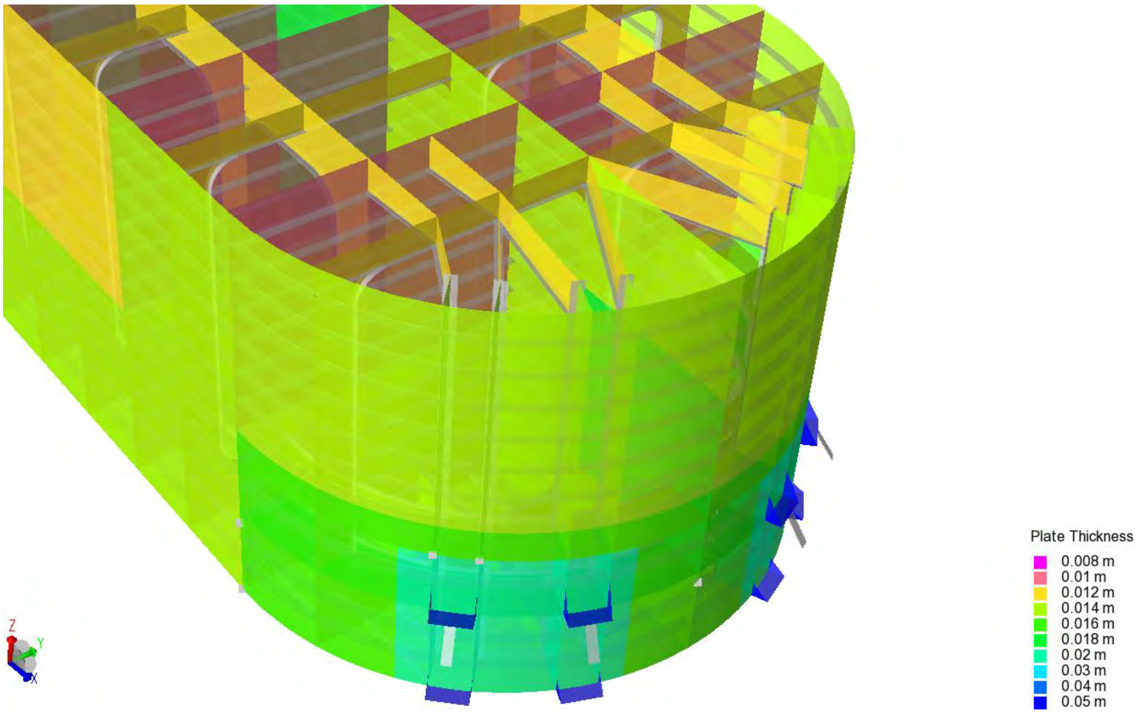


Figure 5-16 Material thicknesses [m] and section names, pontoon end with fairlead supporting structure

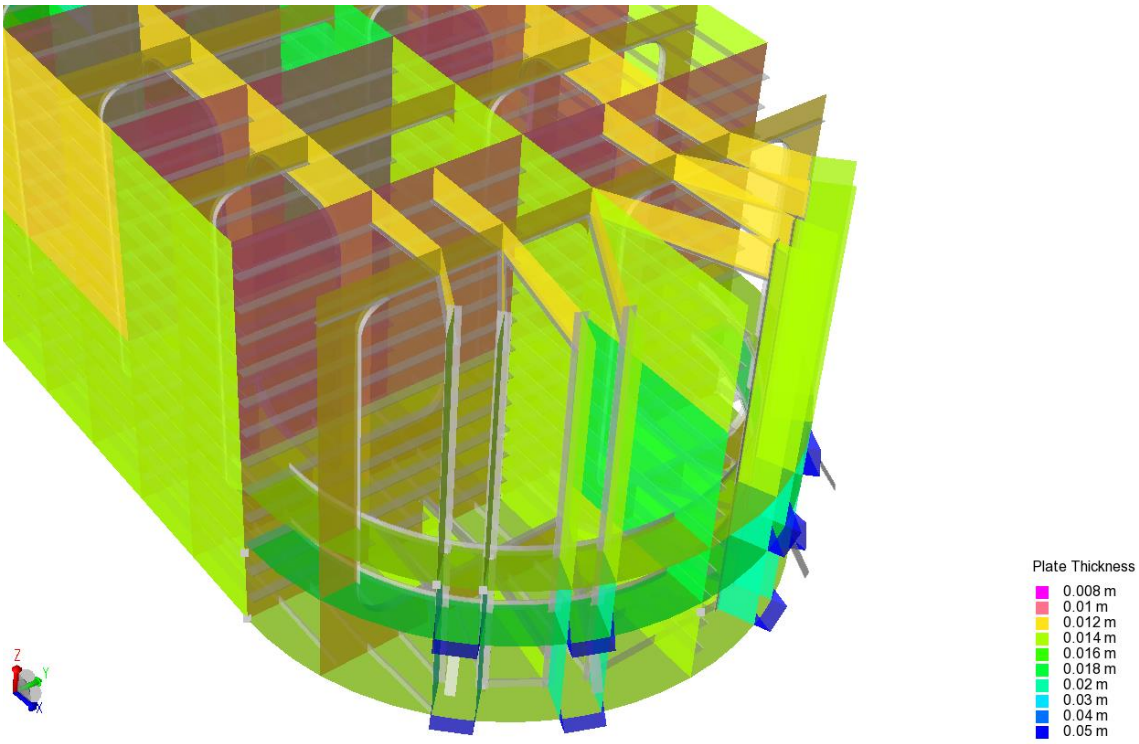


Figure 5-17 Material thicknesses [m] and section names, pontoon end with fairlead supporting structure

5.5 Results

Note that the steel quality has been changed from S355 to S420 after the analysis presented below was performed. Hence; the allowable stresses are somewhat higher compared to upper limit in the stress plots shown. In addition, the results presented in Table 5-1 and Table 5-2 will be conservative, the pontoons buckling capacity will be increased after increasing the yield strength.

Note that the thickness of the outer shell was changed after changed after the analyses were performed; the plate joint at elevation 5100mm was moved 600mm down. This was done to limit number of plate joints in the splash zone. The thickness change is assumed to have minimal effect on the results taken the stress levels presented in the following into account.

In addition the tank plan has been changed; the longitudinal bulkheads located 4000mm from centre line has been made watertight. The plate thickness of the bulkheads is similar as shown in Figure 5-8, i.e. 12mm/14mm. The centre line bulkhead is made non-watertight by introducing manholes. These changes are not assumed to have any negative effect on the structural strength of the pontoon. The pontoon will be more robust against collisions from striking vessels hitting the side of the pontoon with a small angle.

5.5.1 Yield assessment

The yield assessment is based on scan of maximum von Mises membrane stresses for the ULS and ALS conditions respectively. Allowable stress limits are set according to the relevant limit state as follows:

- ULS: $\sigma_{Allowable}$ = 355/1.1 MPa = 322 MPa for steel quality S355

- ULS: $\sigma_{Allowable}$ = 550/1.1 MPa = 500 MPa for steel quality SDSS

- ALS: $\sigma_{Allowable}$ = 355/1.0 MPa = 355 MPa for steel quality S355

- ALS: $\sigma_{Allowable}$ = 550/1.0 MPa = 550 MPa for steel quality SDSS

The yield assessment performed for the “pontoon supporting mooring lines” shows that the proposed structure scantling has sufficient strength. The results are shown in Figure 5-18 through Figure 5-37.

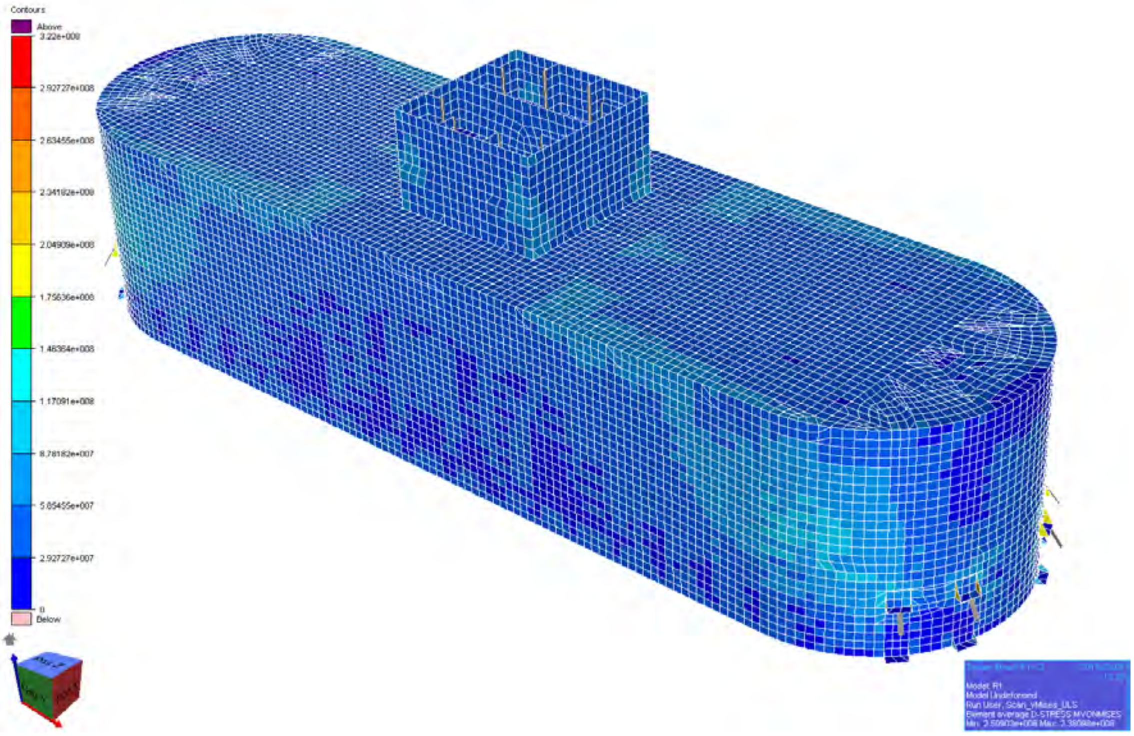


Figure 5-18 von Mises stresses for ULS load combinations [N/m^2]

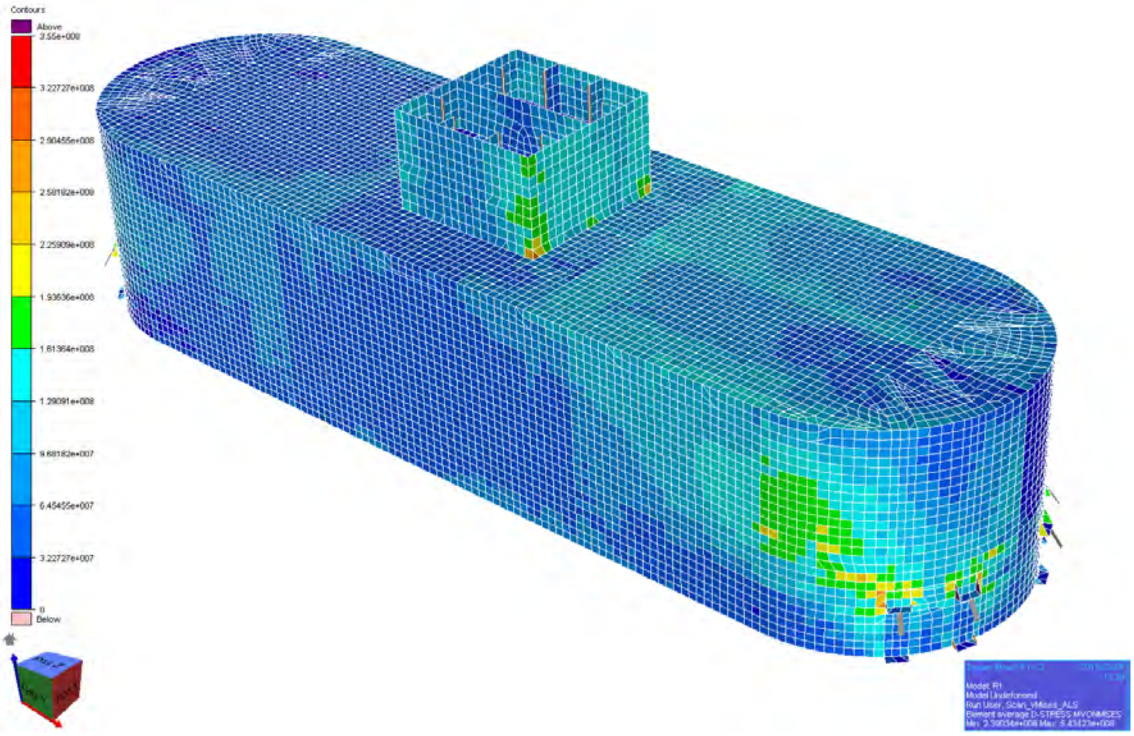


Figure 5-19 von Mises stresses for ALS load combinations [N/m^2]

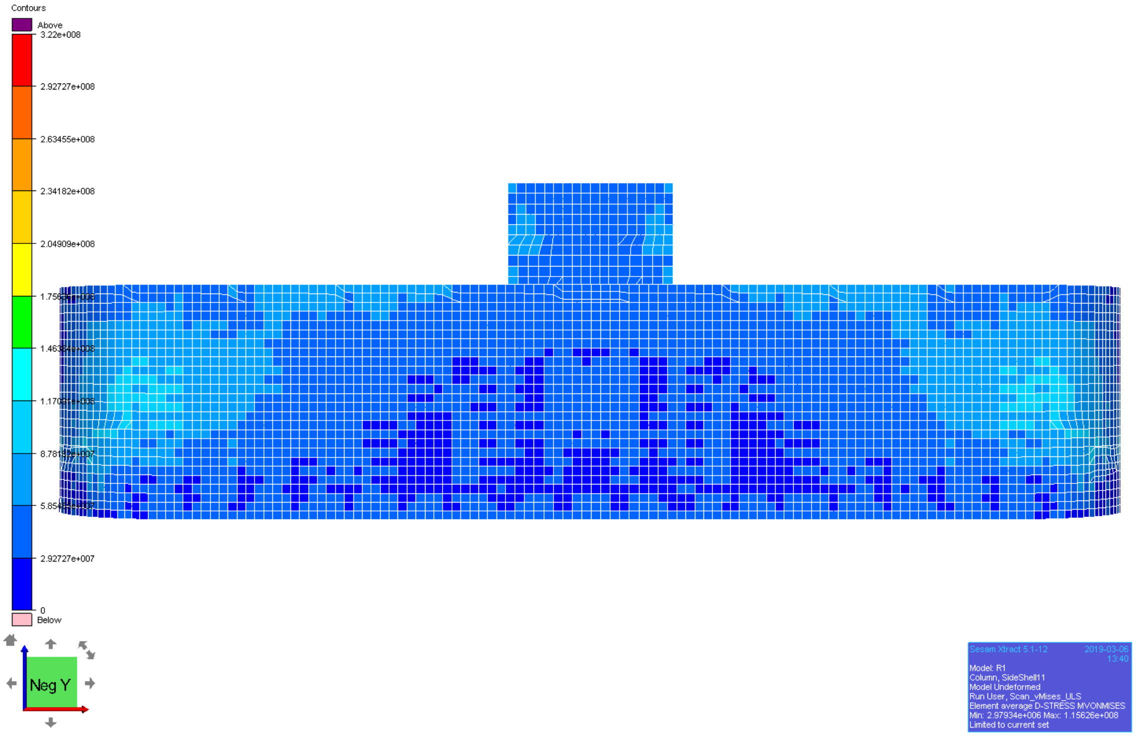


Figure 5-20 von Mises stresses for ULS load combinations [N/m^2] outer side shell

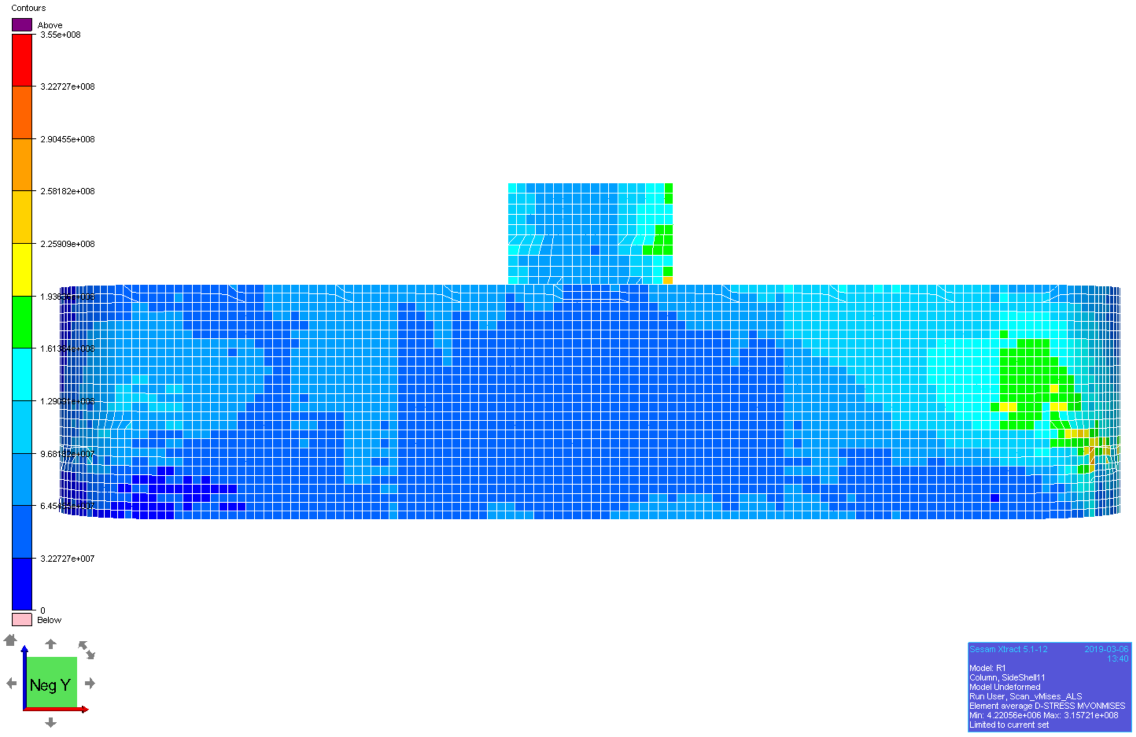


Figure 5-21 von Mises stresses for ALS load combinations [N/m^2] outer side shell

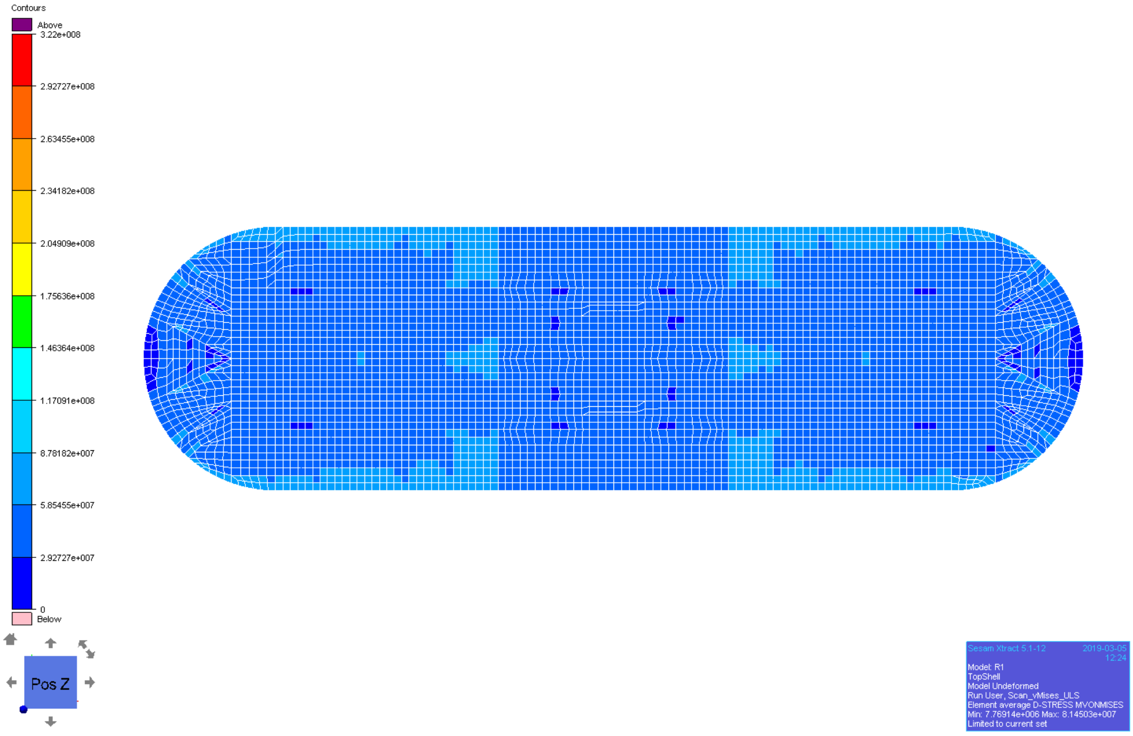


Figure 5-22 von Mises stresses for ULS load combinations [N/m^2] outer top shell

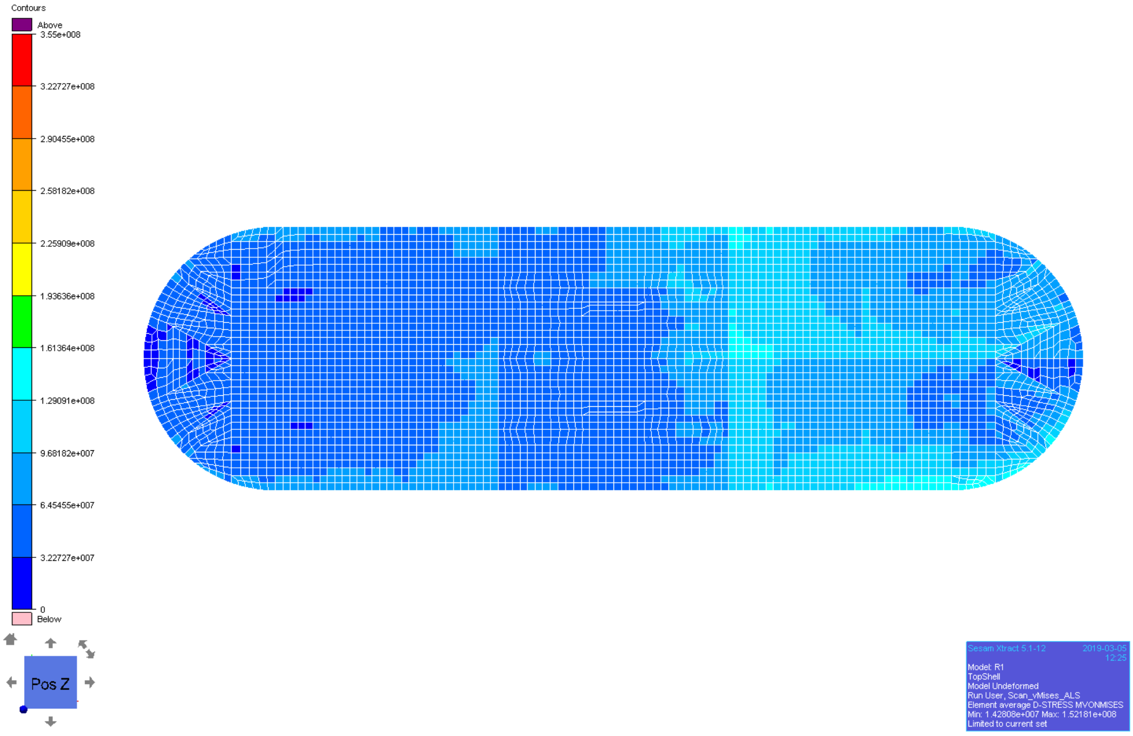


Figure 5-23 von Mises stresses for ALS load combinations [N/m^2] outer top shell

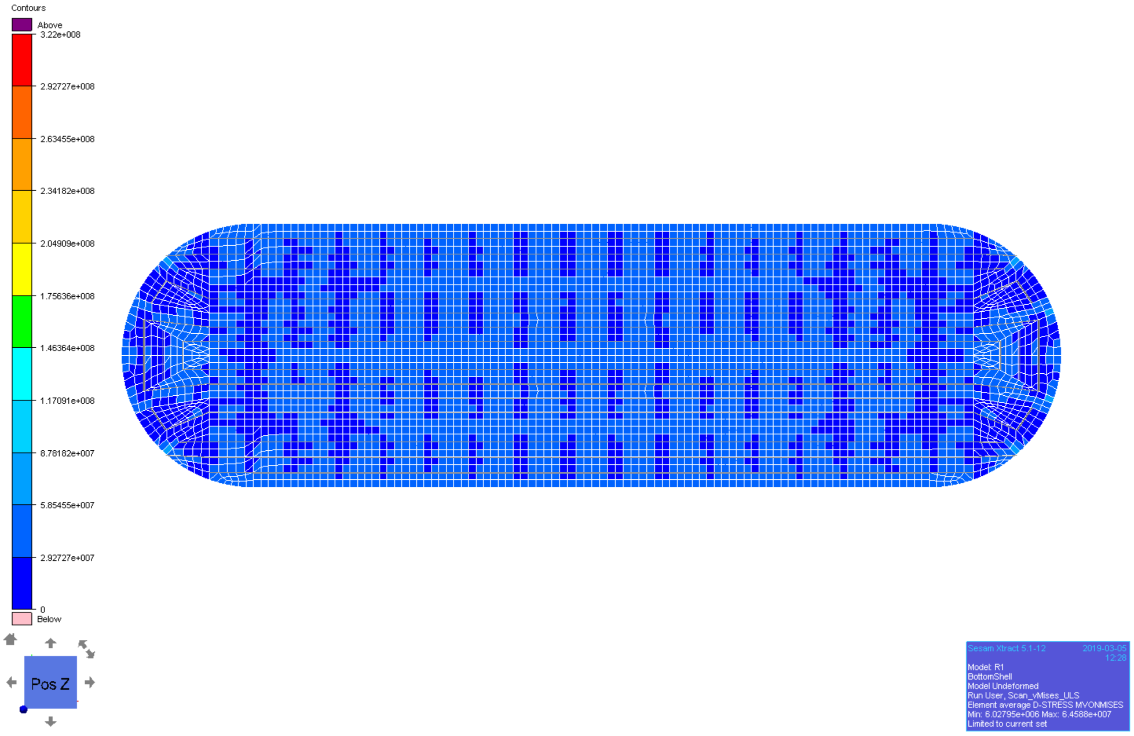


Figure 5-24 von Mises stresses for ULS load combinations [N/m^2] outer bottom shell

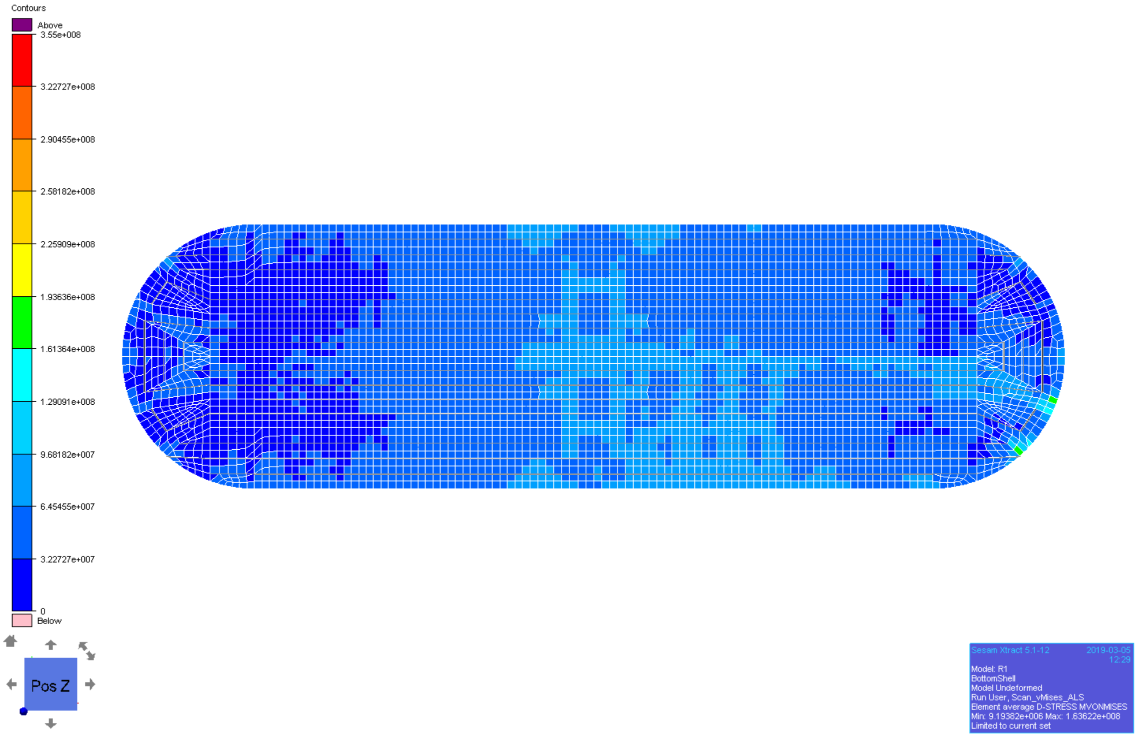


Figure 5-25 von Mises stresses for ALS load combinations [N/m^2] outer bottom shell

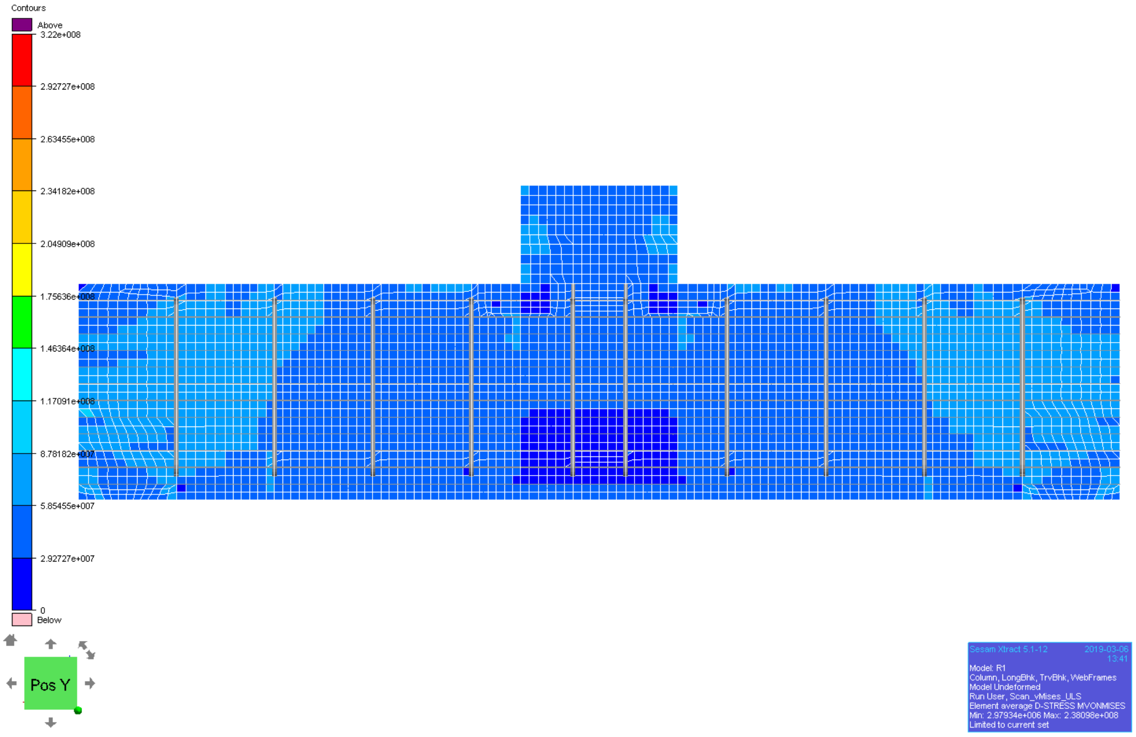


Figure 5-26 von Mises stresses for ULS load combinations [N/m^2] centreline bulkhead

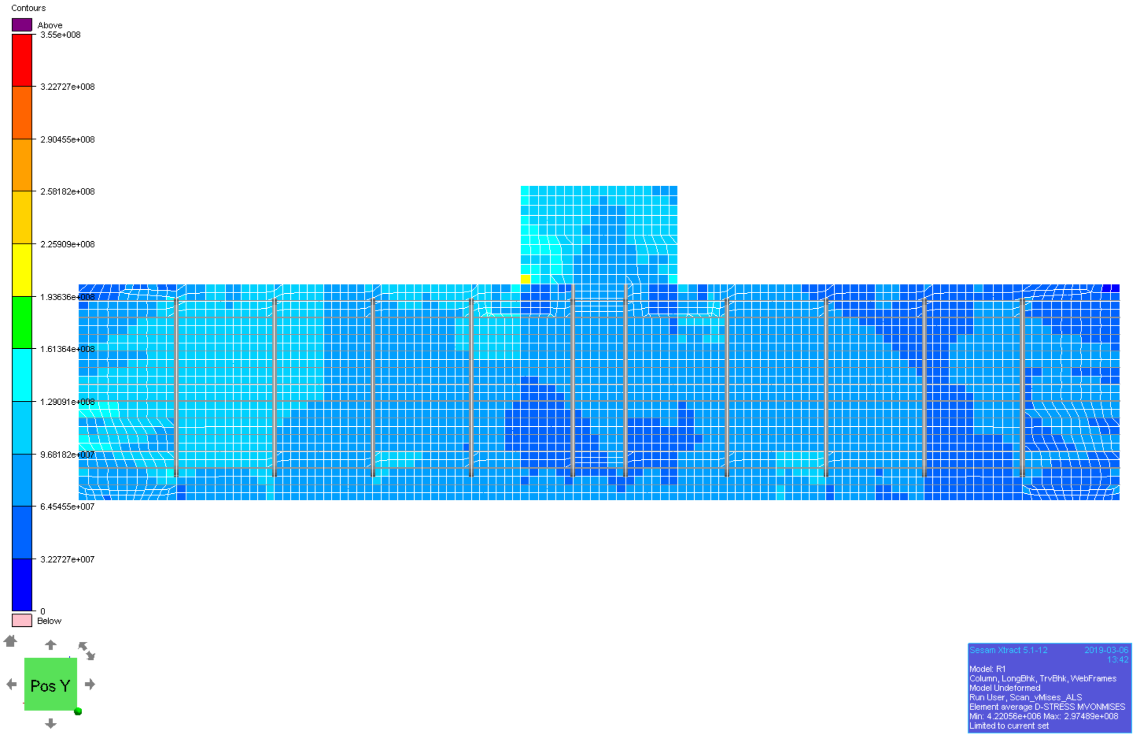


Figure 5-27 von Mises stresses for ALS load combinations [N/m^2] centreline bulkhead

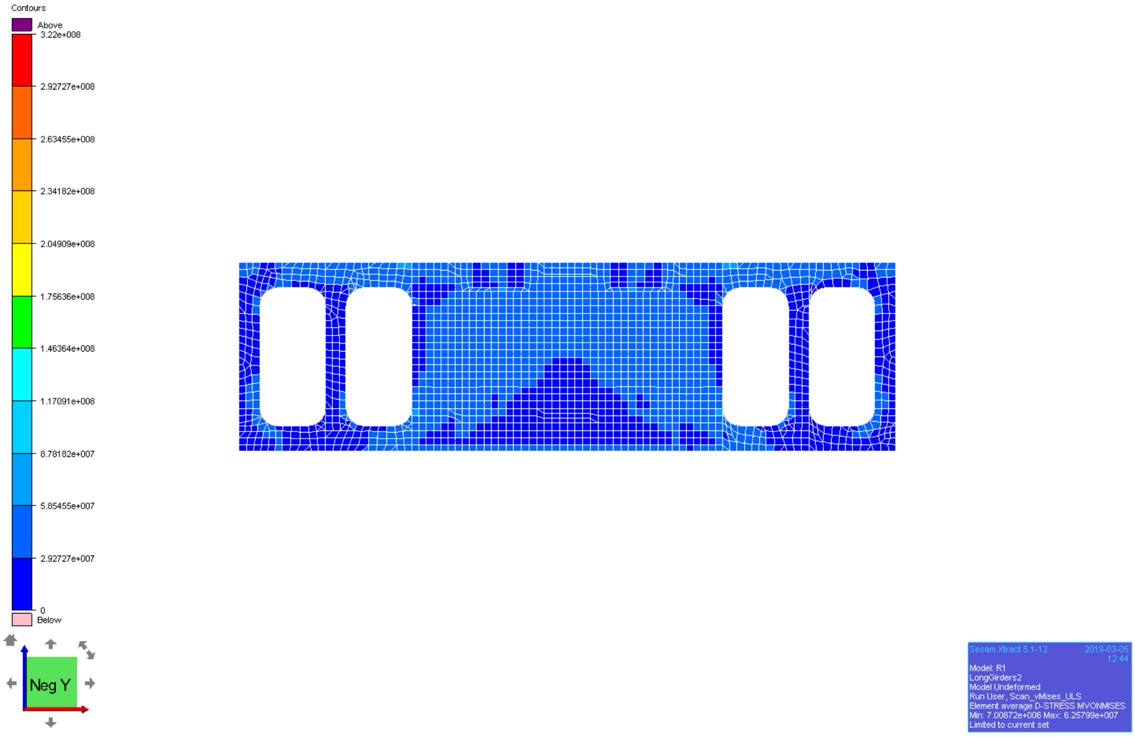


Figure 5-28 von Mises stresses for ULS load combinations [N/m^2] bulkhead 4.0 m of centreline

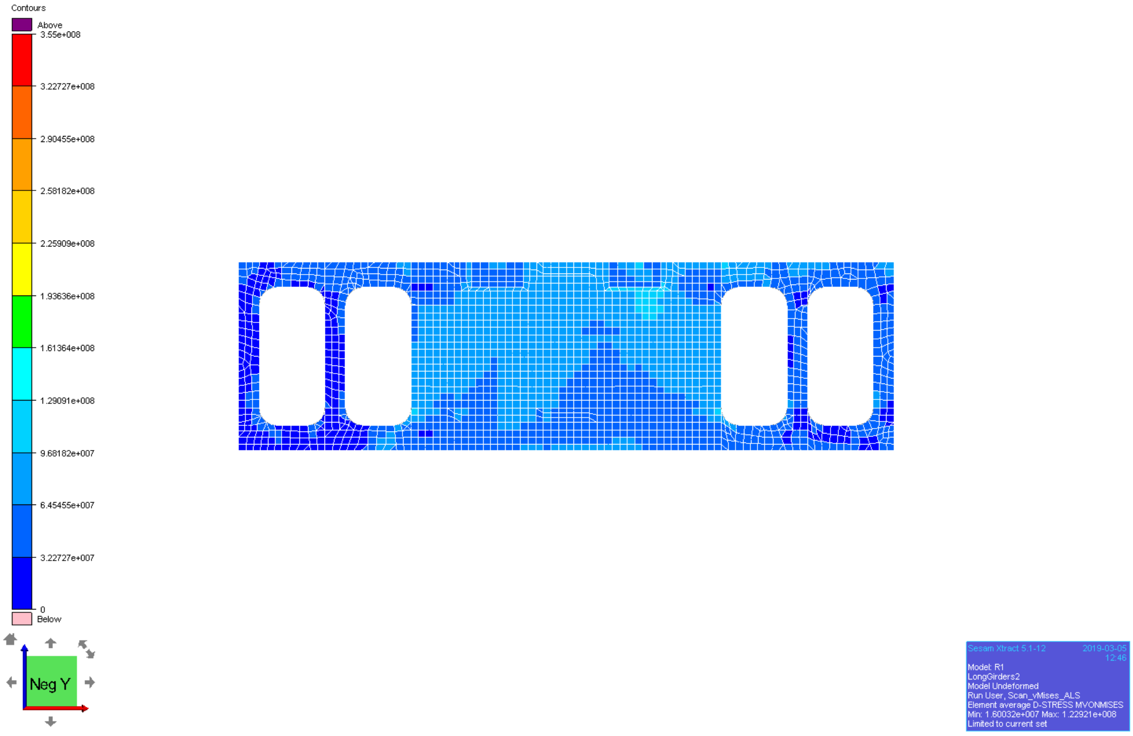


Figure 5-29 von Mises stresses for ALS load combinations [N/m^2] bulkhead 4.0 m of centreline

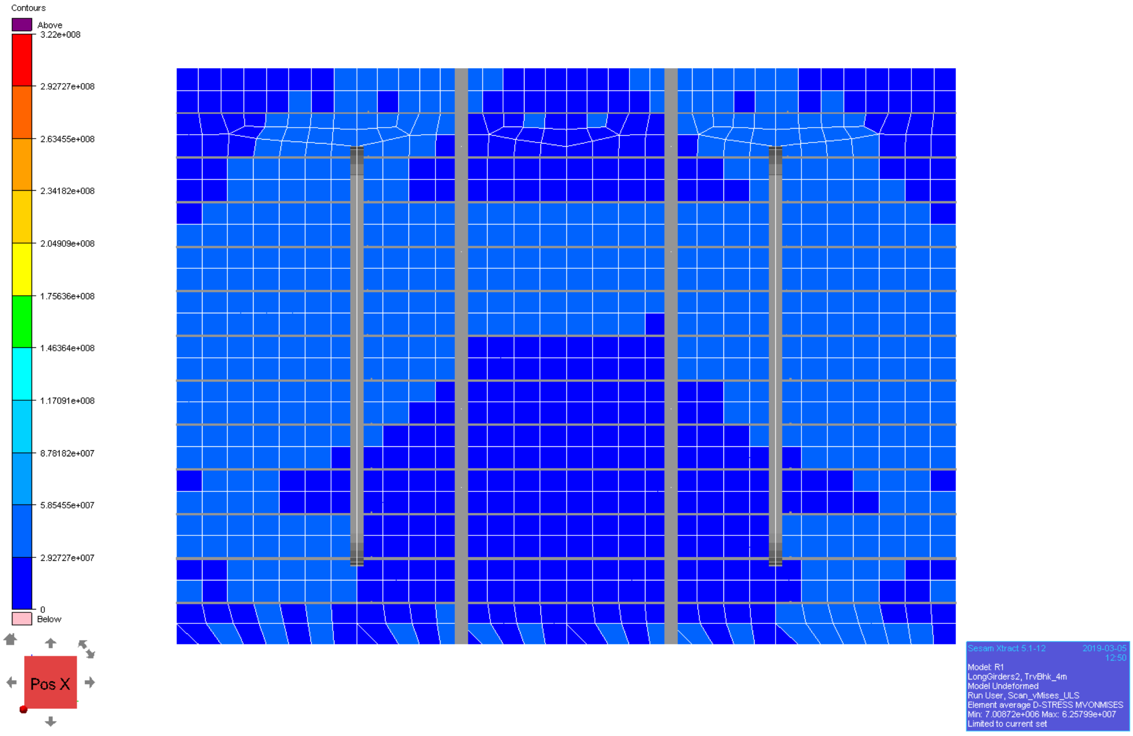


Figure 5-30 von Mises stresses for ULS load combinations [N/m^2] for transverse bulkhead supporting column

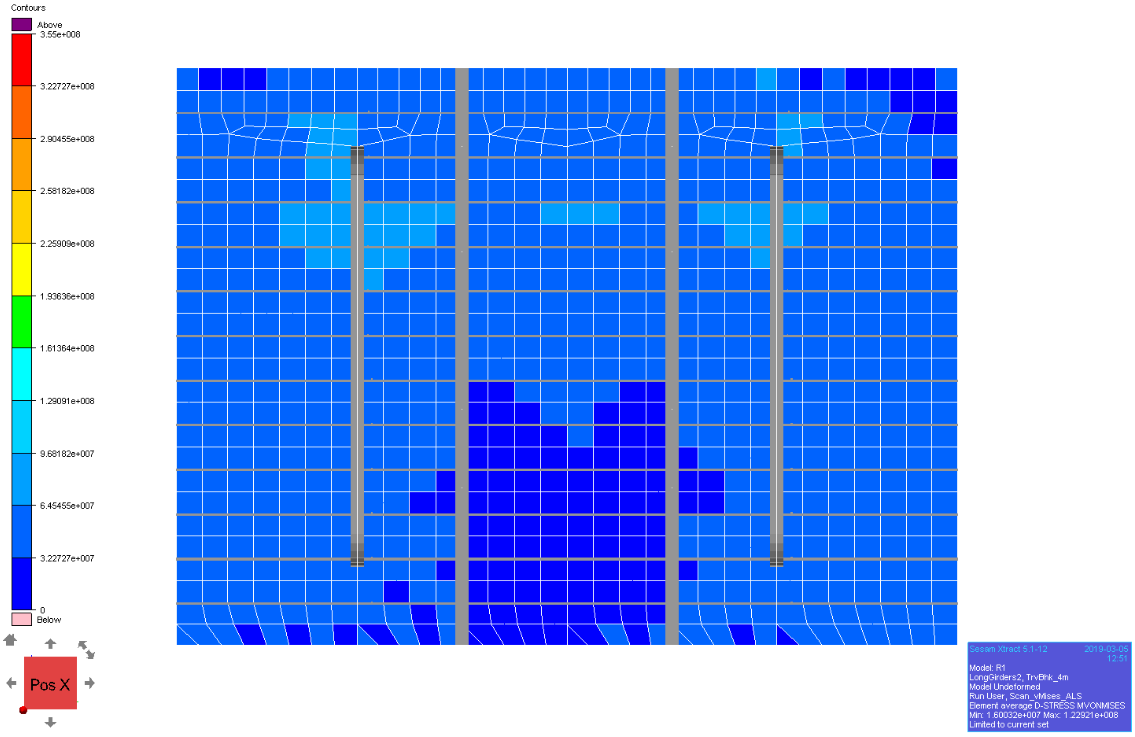


Figure 5-31 von Mises stresses for ALS load combinations [N/m^2] for transverse bulkhead supporting column

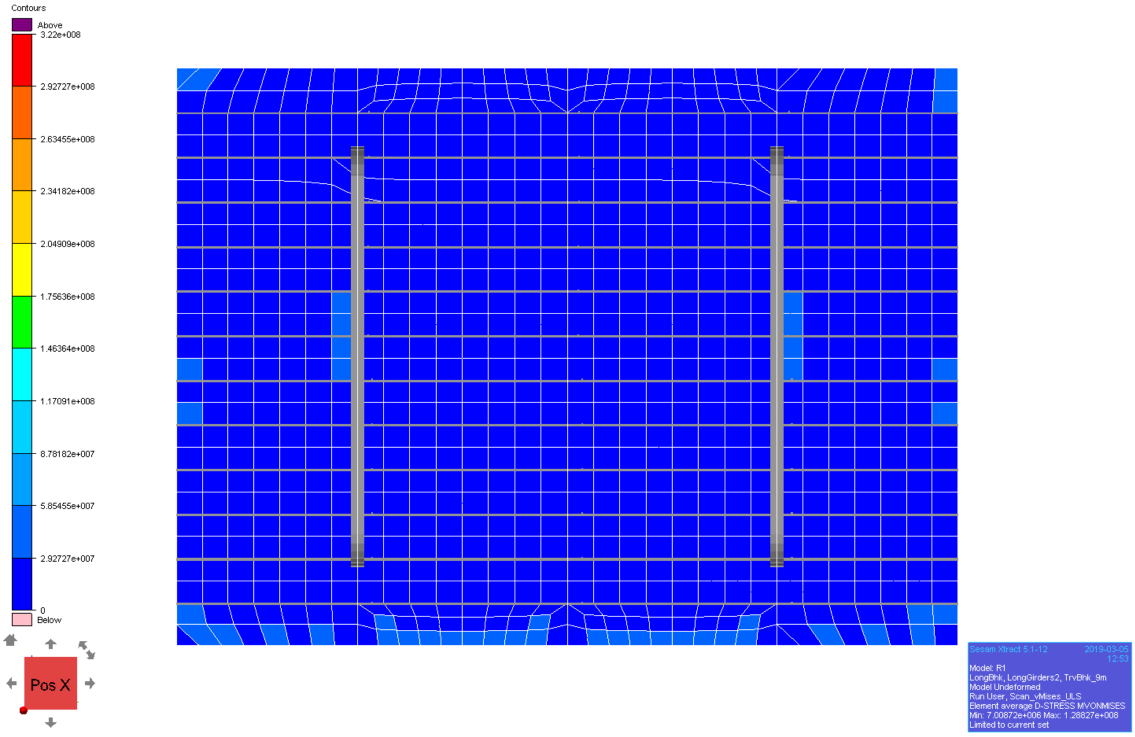


Figure 5-32 von Mises stresses for ULS load combinations [N/m^2] for a typical transverse bulkhead

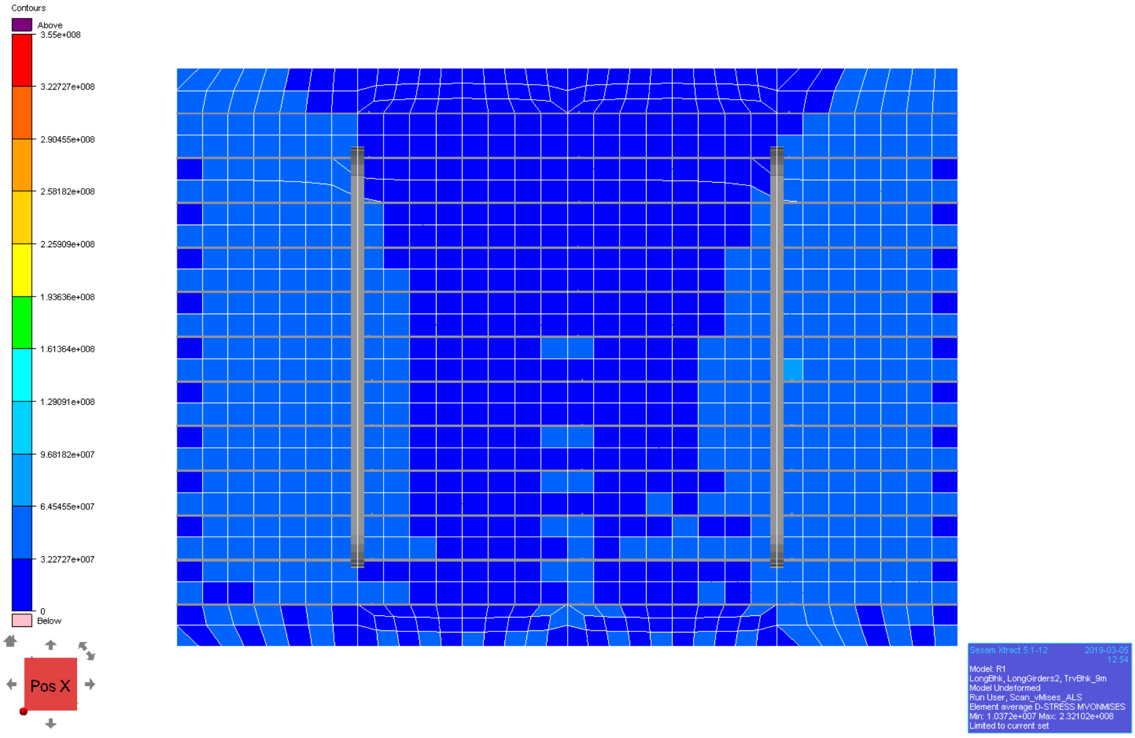


Figure 5-33 von Mises stresses for ALS load combinations [N/m^2] for a typical transverse bulkhead