Appendix to report:

SBJ-33-C5-OON-22-RE-013-APPF

K12 - SHIP IMPACT, GLOBAL ASSESSMENT

Appendix title:

APPENDIX F – GIRDER-COLUMN CONNECTION

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CONCEPT DEVELOPMENT FLOATING BRIDGE E39 BJØRNAFJORDEN

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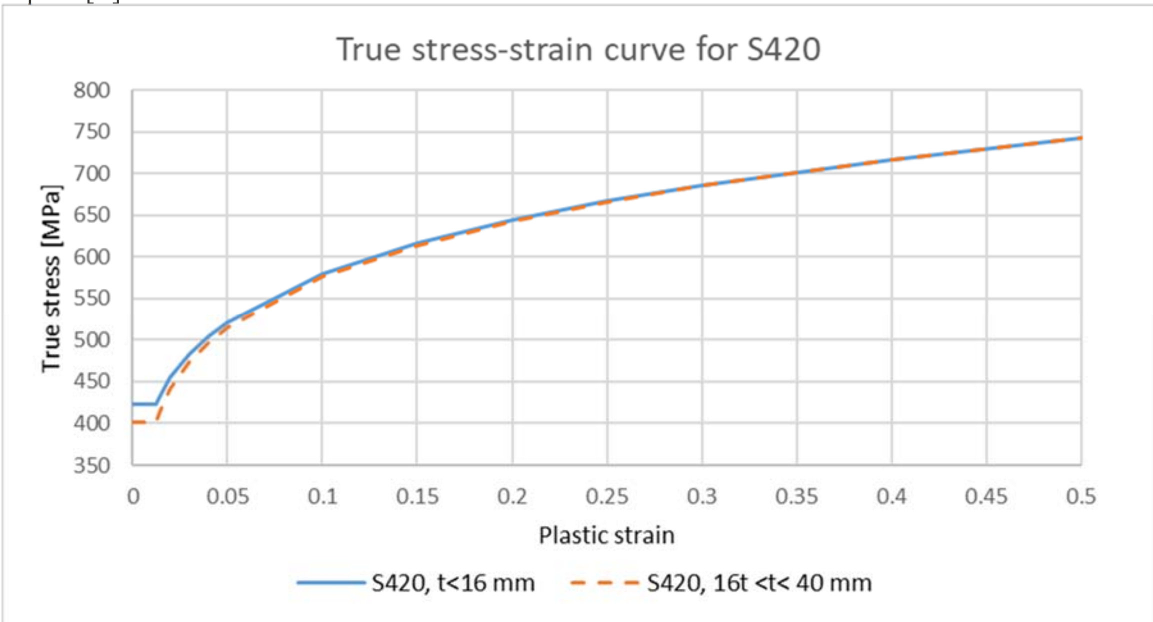
F.1 Analysis setup

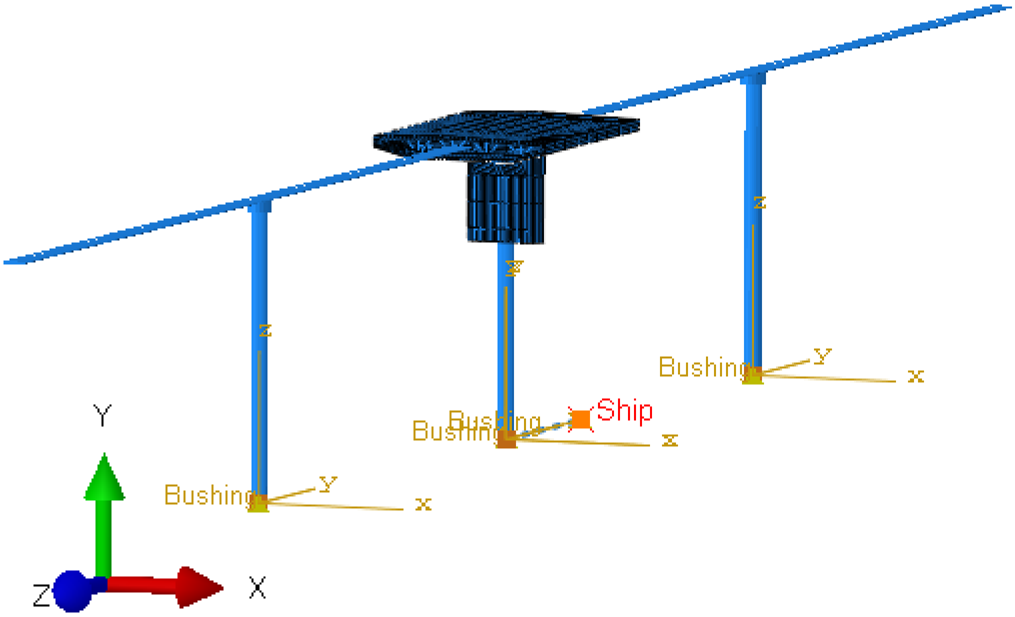
The bridge design is sensitive to the weak axis strength of the column, and especially the connection between the column and the girder. For the side impacts (90-deg) on pontoon, centric and eccentric, the weak axis bending (and torsion) moments exceeds the elastic bending capacities.

To evaluate the effects of this, there has been established a local model with shell elements in the critical area to get approximate plastic capacity of the chosen girder- and column design, and to evaluate the distribution of energy dissipation between girder, column and pontoon-ship.

Plastic material curve for S420 is utilized, see stress strain curve below. The material is described further and curve can be seen in Figure 4-6 in the "K12 Ship impact, Bridge girder" report [1].



The FE-model of the girder-column connection of the high bridge is shown below. Note that the geometry of the voute itself is simplified in these analysis – in a final design it will be extent to cover the entire column width.

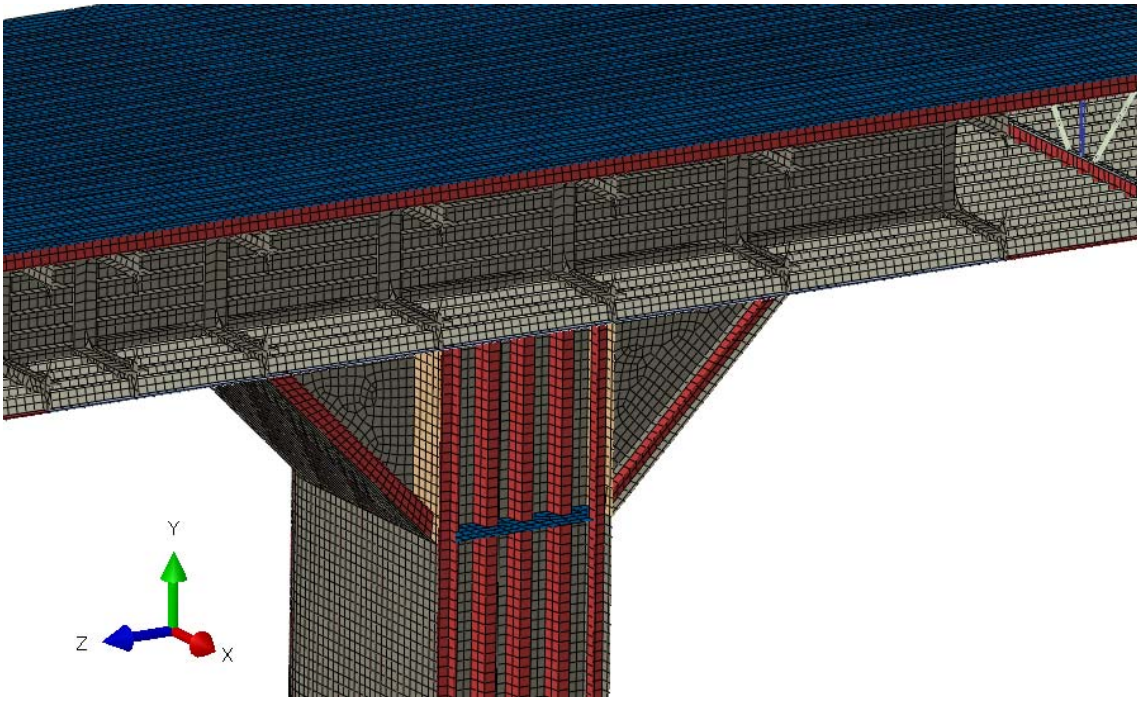


> *Figure F-1 FE-model of girder-column connection, high bridge*

The short column-analysis is set up the same way.

The analysis setup is similar to the global model, with a point mass with an initial velocity and a connector who transfers the forces from the ship and dissipates energy. The reason for this "complex" setup is mainly computational, as a static implicit analysis does not converge as good as a dynamic, and therefore is not able to do the "pushover exercise". At the same time, this analysis can be used to evaluate the maximum indentation in the pontoon and the distribution between the different plastic dissipations in a good way, at the bridge itself is very stiff in the longitudinal direction. The eccentric impact is set up the same way with the impact point at the pontoon end.

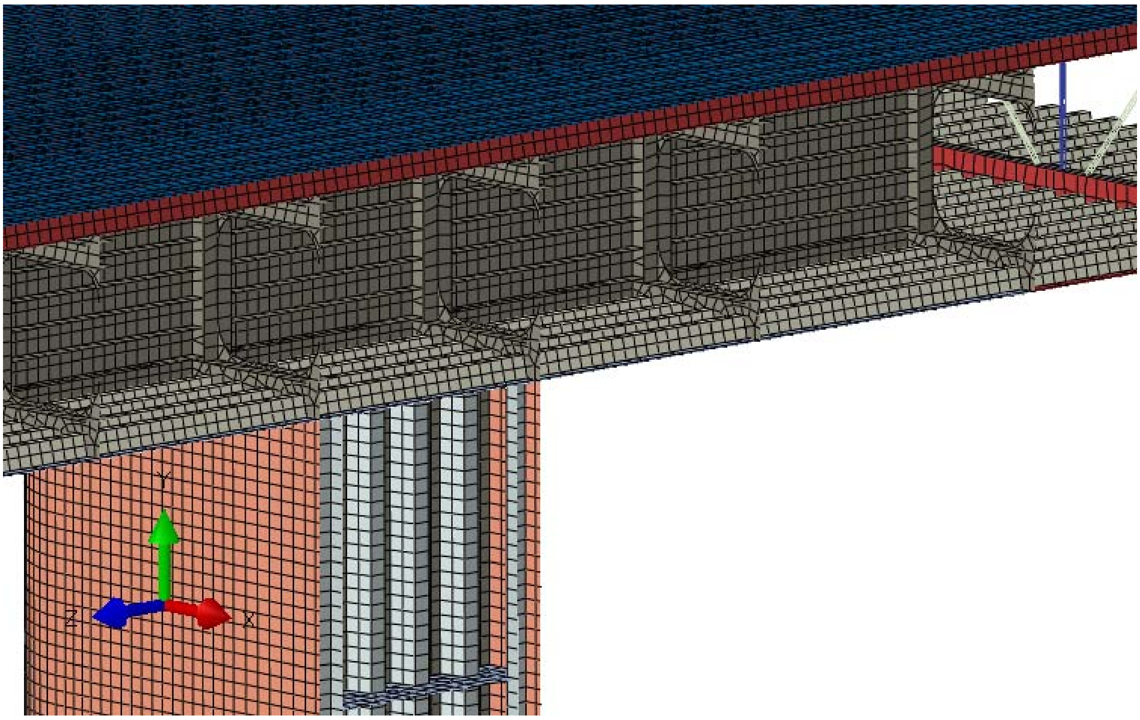
The mesh for the final model of the high bridge is shown below. The model is very sensitive to the mesh size, and 0.20 m is the finest mesh that is possible to evaluate in a practical point of view. The element types are S4R and S3R for the shell, B31 for the wires.



> *Figure F-2 FE-model of girder-column connection, high bridge. Mesh size is approximately 0.20 m.*

Active	Sections	Color
☑	PL8	
☑	PL10	
☑	PL12	
☑	PL14	
☑	PL15	
☑	PL16	
☑	PL20	
☑	PL25	
☑	PL30	
☑	PL35	
☑	Pontoon_44_B_high_4-6	
☑	RHS150x5	
☑	RHS150x8	
☑	Ship_pontoon3	
☑	column_ormen	
☑	girder_ormen	
☑	rigmat	

> *Figure F-3 Color codes to describe the shell thicknesses used for the high bridge analyses, see Figure F-2.*



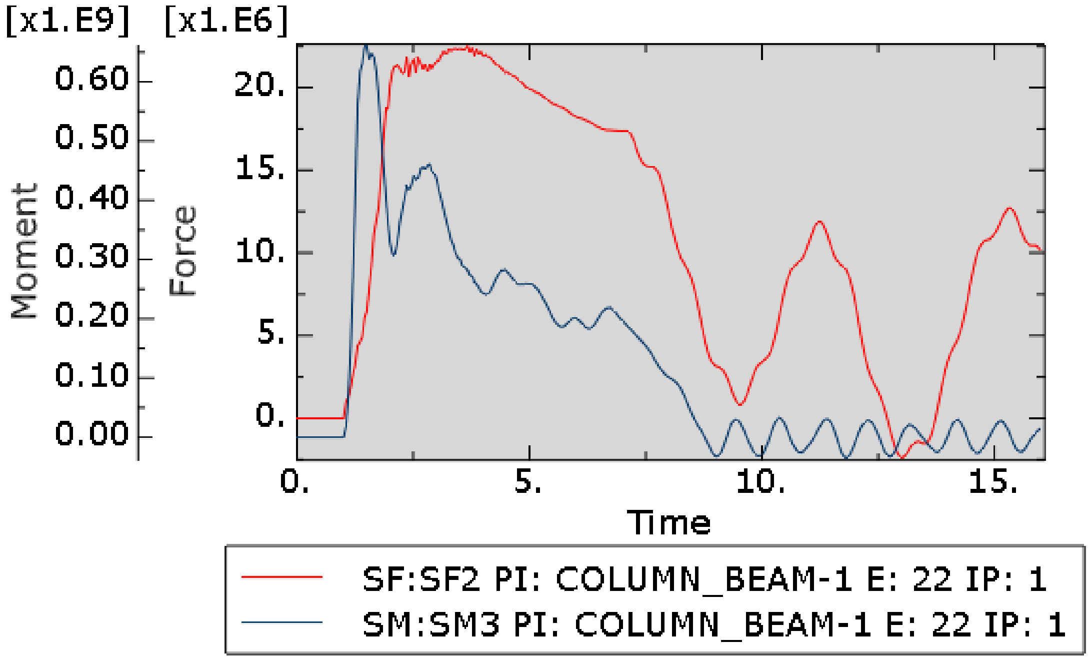
> *Figure F-4 FE-model of girder-column connection, low bridge. Mesh size is approximately 0.20 m.*

Active	Sections	Color
☑	PL8	
☑	PL10	
☑	PL12	
☑	PL14	
☑	PL15	
☑	PL16	
☑	PL20	
☑	PL25	
☑	PL30	
☑	PL35	
☑	Pontoon_44_B_high_4-6	
☑	RHS150x5	
☑	RHS150x8	
☑	Ship_pontoon3	
☑	column_ormen	
☑	girder_ormen	
☑	rigmat	

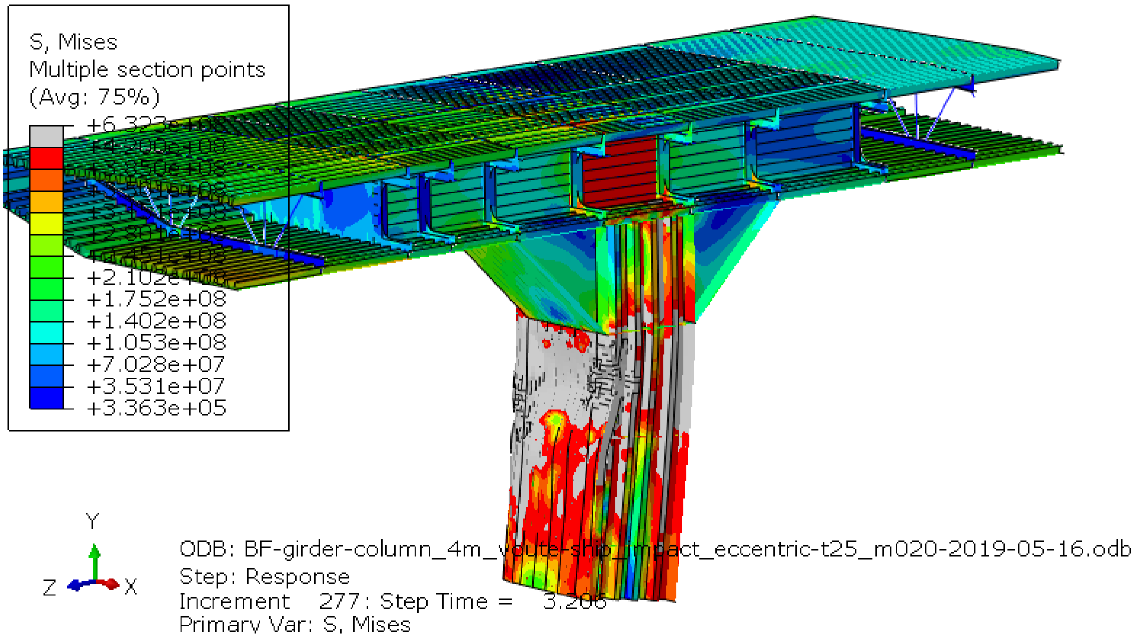
> *Figure F-5 Color codes to describe the shell thicknesses used for the high bridge analysis, see Figure F-4.*

F.2 Analysis results long column

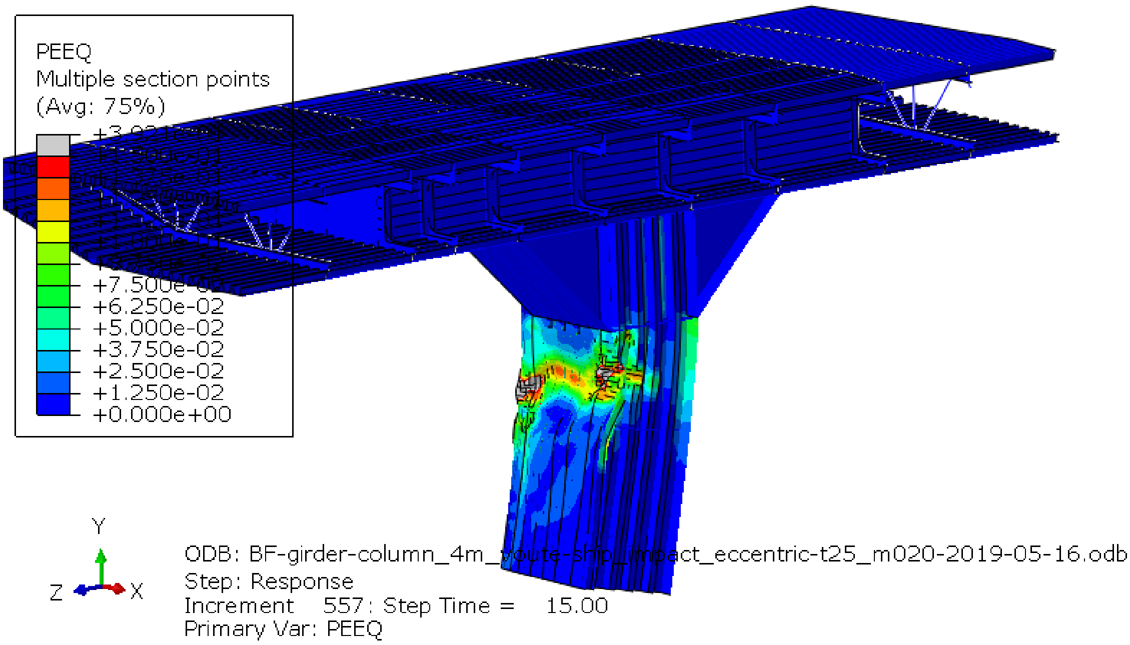
Section forces in column bottom: Shear force [N] and torsion moment [Nm]:



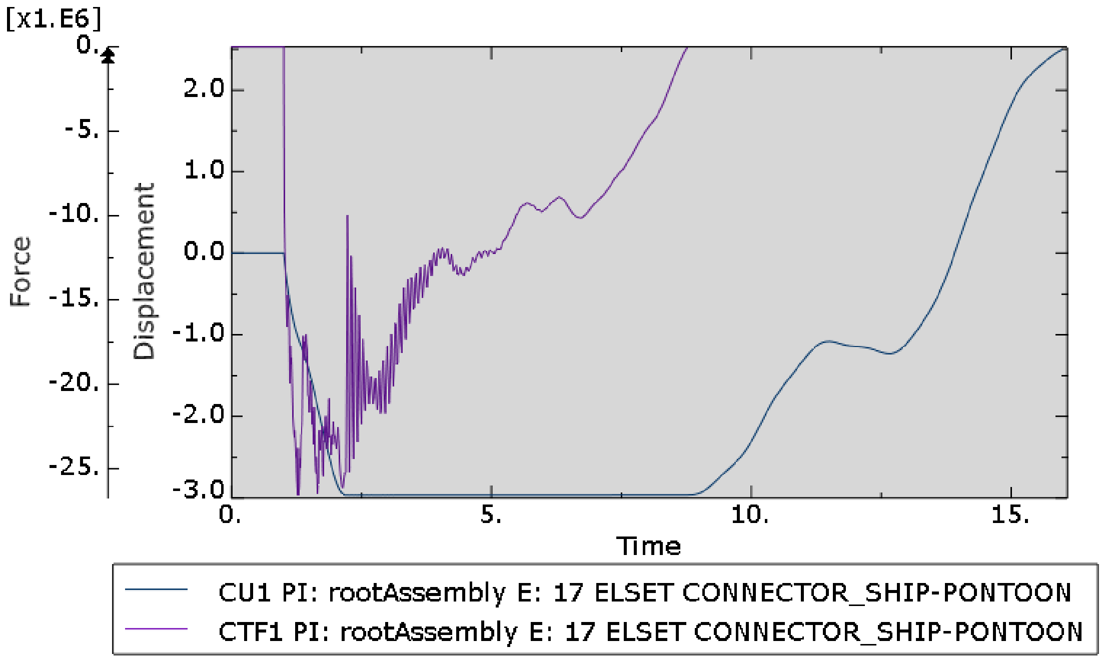
Stresses [Pa] in girder-column connection at approximately largest bending moment (step time 3 s, ref figure above):



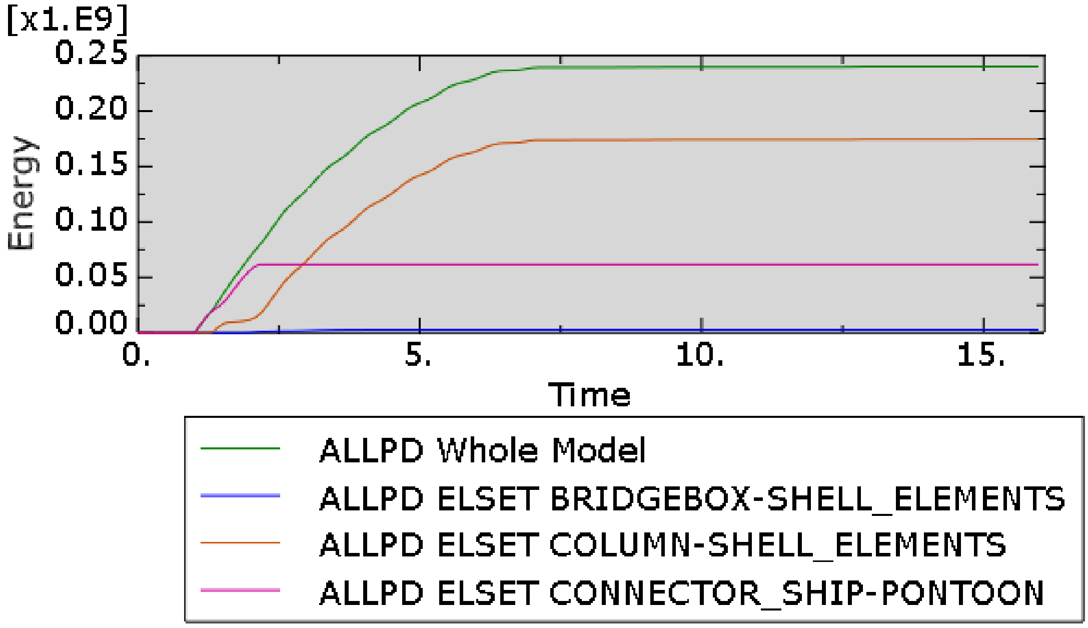
Plastic equivalent strain in connection post impact (grey color for strains above 0.15):



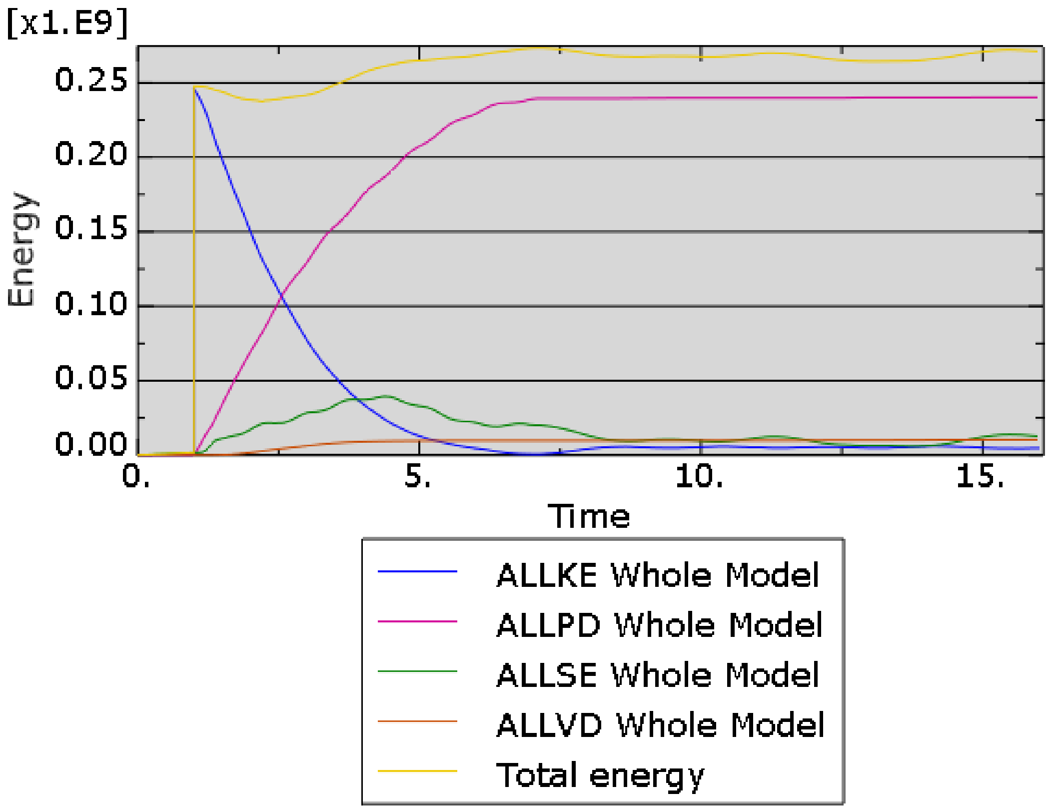
Force [N] and displacement [m] in connector between ship and pontoon:



Distribution of plastic dissipation between girder elements, column (and voute) elements and ship-pontoon damage:



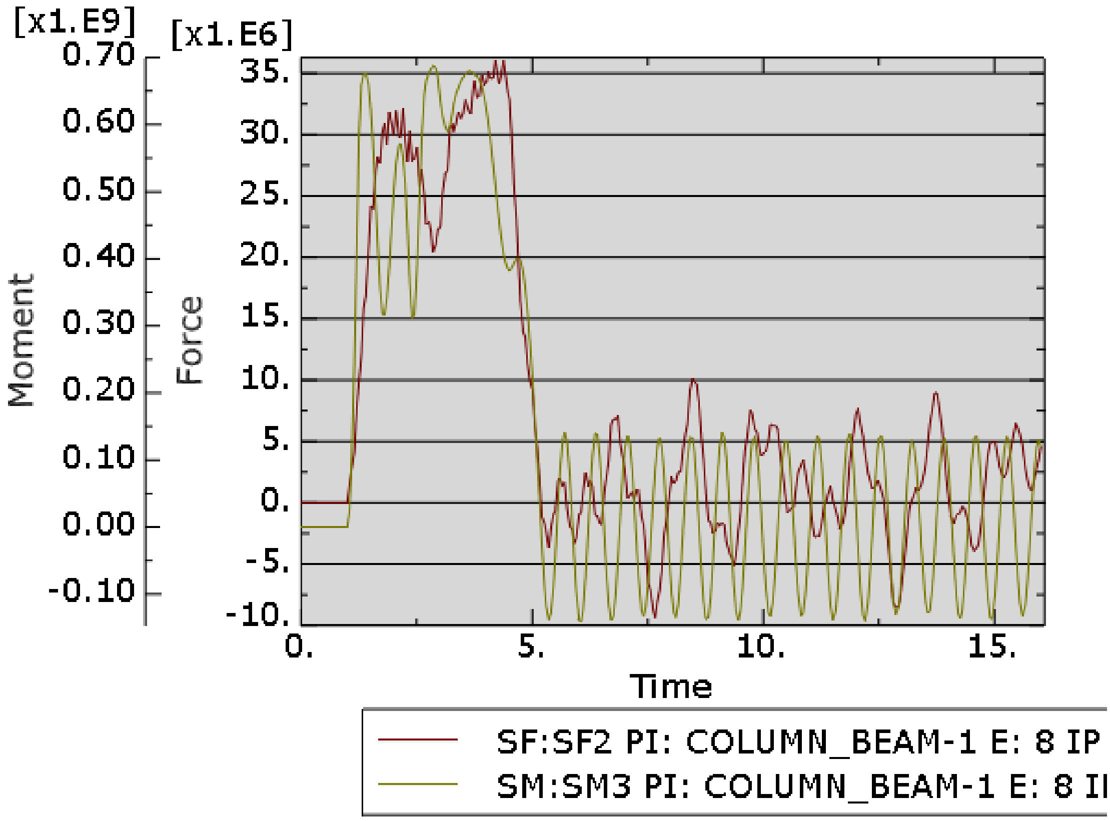
Energy distribution:



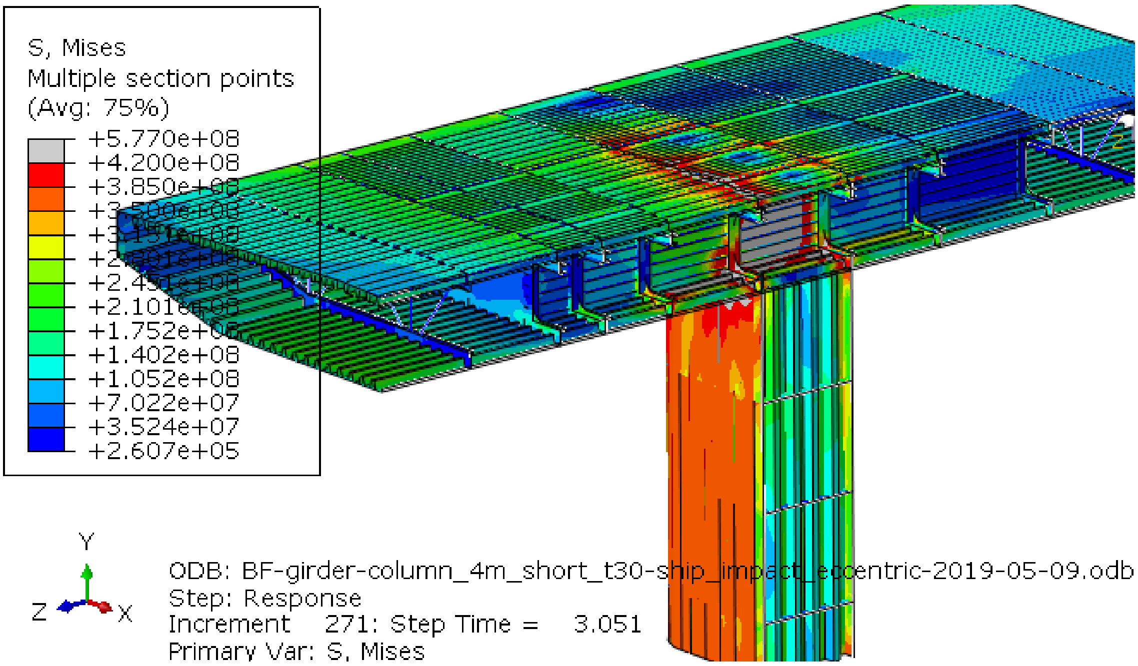
Theoretical capacities for bending and torsion of column detail.

F.3 Analysis results short column

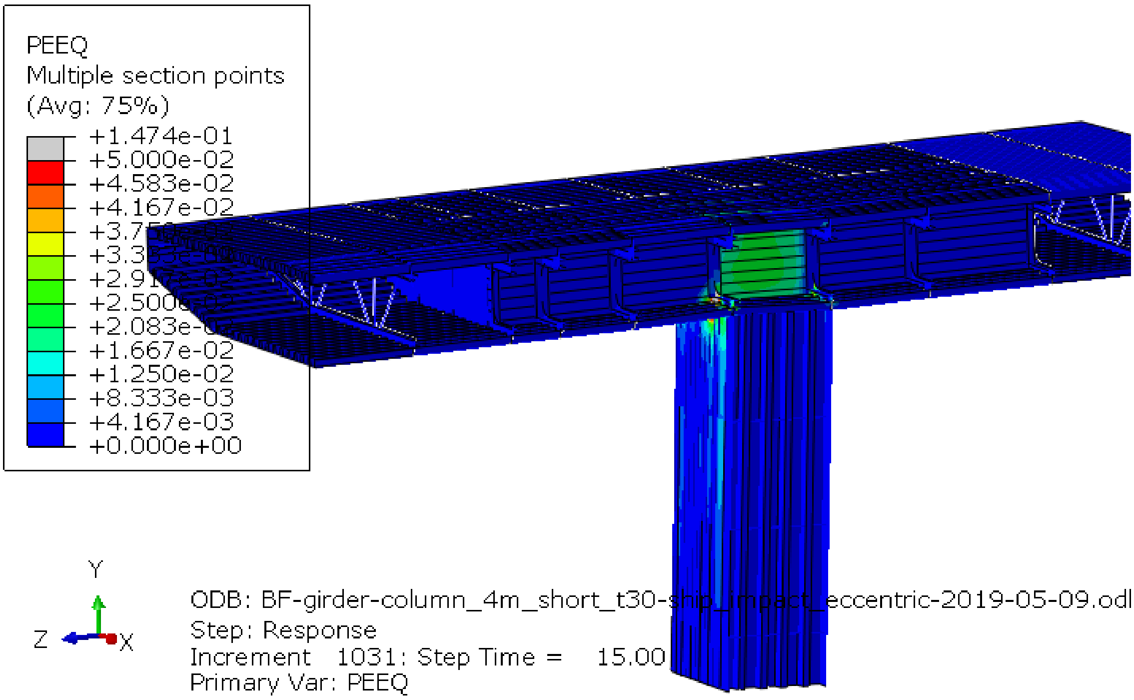
Section forces in column bottom: Shear force [N] and torsion moment [Nm]:



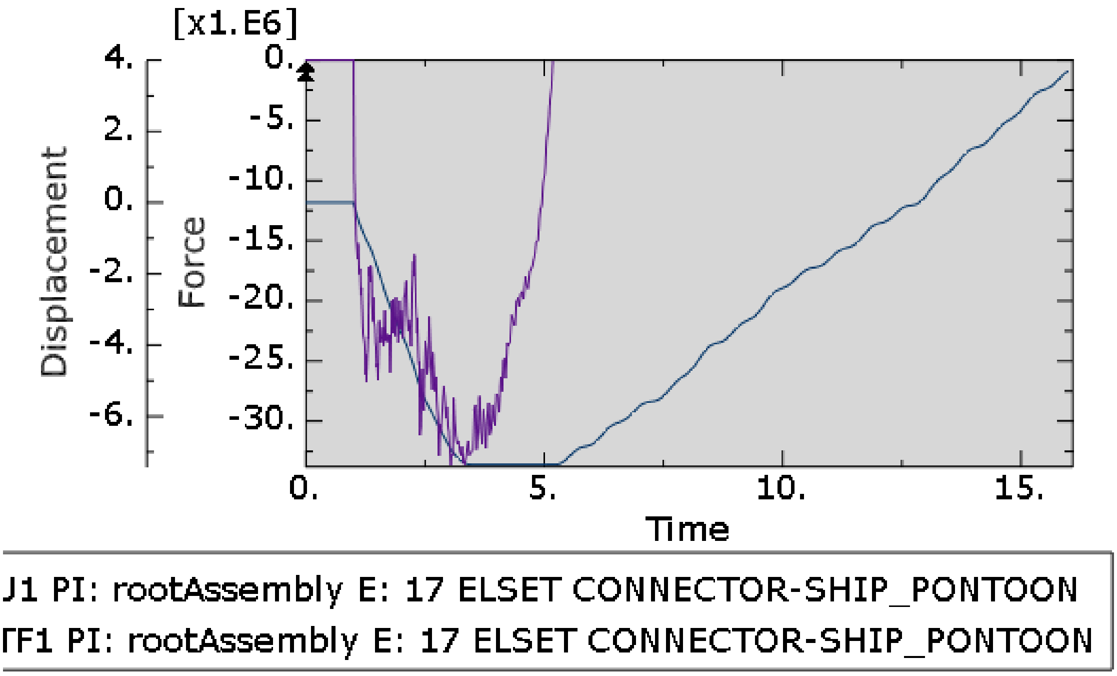
Stresses [Pa] in girder-column connection at approximately largest bending moment (step time 3 s, ref figure above):



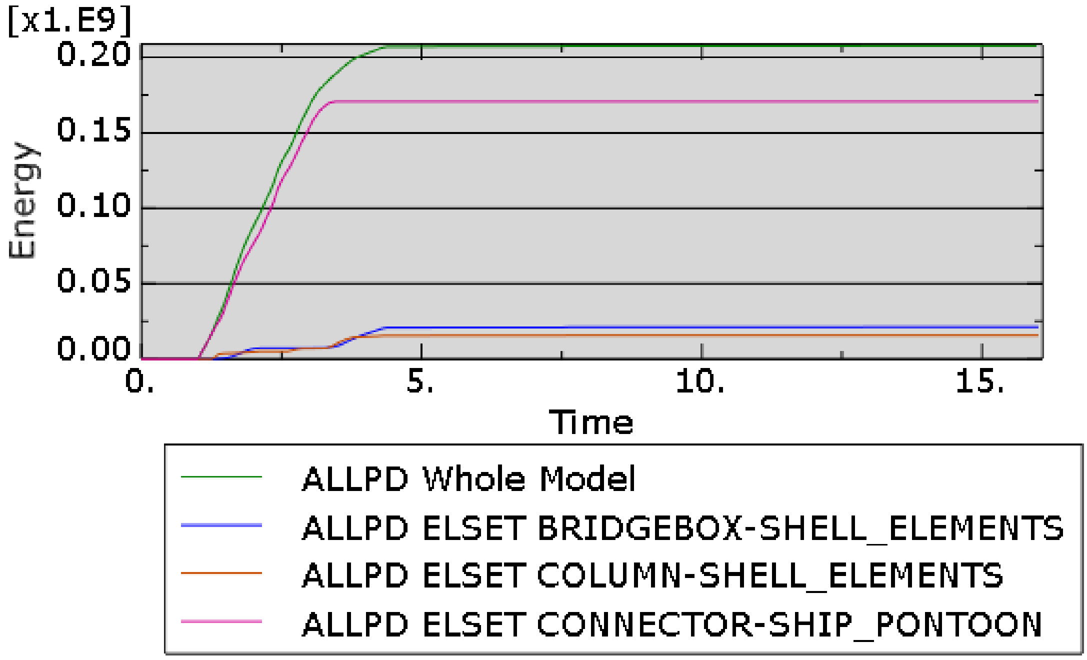
Plastic equivalent strain in connection post impact:



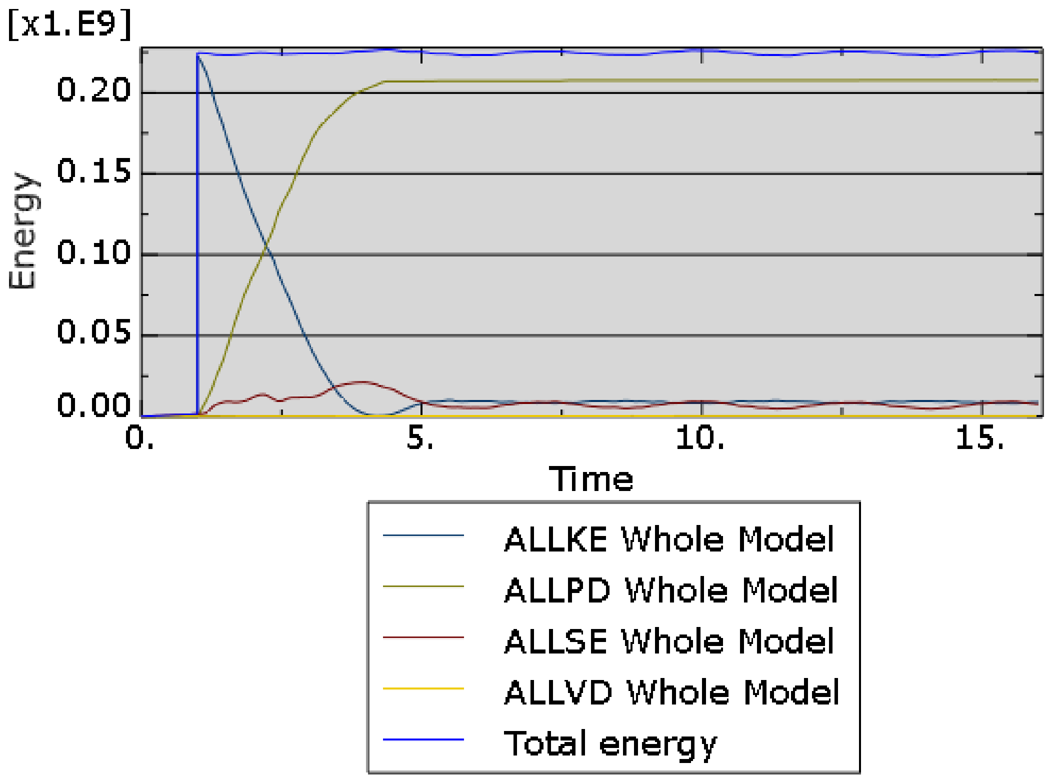
Force [N] and displacement [m] in connector between ship and pontoon:



Distribution of plastic dissipation between girder elements, column (and voute) elements and ship-pontoon damage:



Energy distribution:



F.4 Push-over analysis pure torsion and pure bending

There has been performed a local analysis of the column top only – as two separate push-over analysis. One for pure bending and one for pure torsion. These are considered as theoretical maximum capacities for the column, as the torsion-bending interaction will result in lower combined capacities.

This is performed on the same column with a voute, but without the girder and ship. The top and bottom shell edge nodes are constrained to separate reference points. The top reference point is fixed and the bottom node is used for applying displacement and rotation. There has been applied a horizontal displacement for the pure bending analysis and a rotation or the pure torsion analyses. See the model in the figure below.

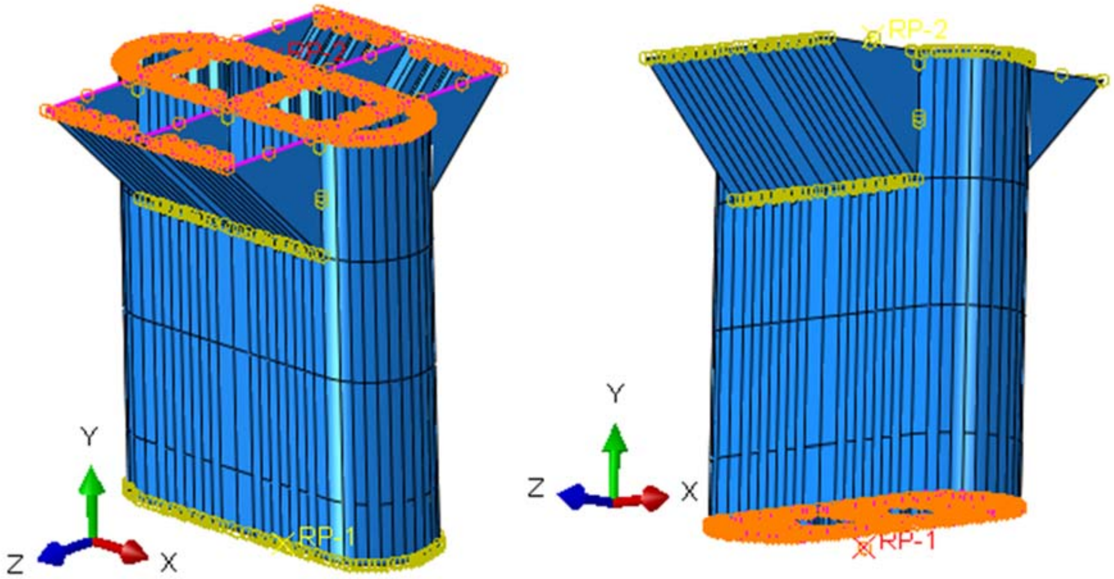


Figure F-6 Column model for push-over analysis. Left: MPC-constraint between column top shell edges and fixed reference point. Right: MPC-constraint between column bottom shell edges and displacement/rotations reference point. Note that the geometry of the voute itself is simplified in these analyses – in a final design it will be extent to cover the entire column width.

As the columns on the low bridge are lower than the high bridge columns, the 90-degree impacts are stiffer – resulting in higher torsional moment for the low bridge columns. Therefore the skin thickness is 30 mm for the short columns compared to 25 mm for the long columns. The short columns do not have a voute, but as the plastic hinge develops beneath the voute anyway both analysis for short and long columns are done with the voute model. It is the moment-rotation curve obtained from these analyses that are of interest, not the detailed stresses in the column top. The evaluated skin thicknesses are presented below.

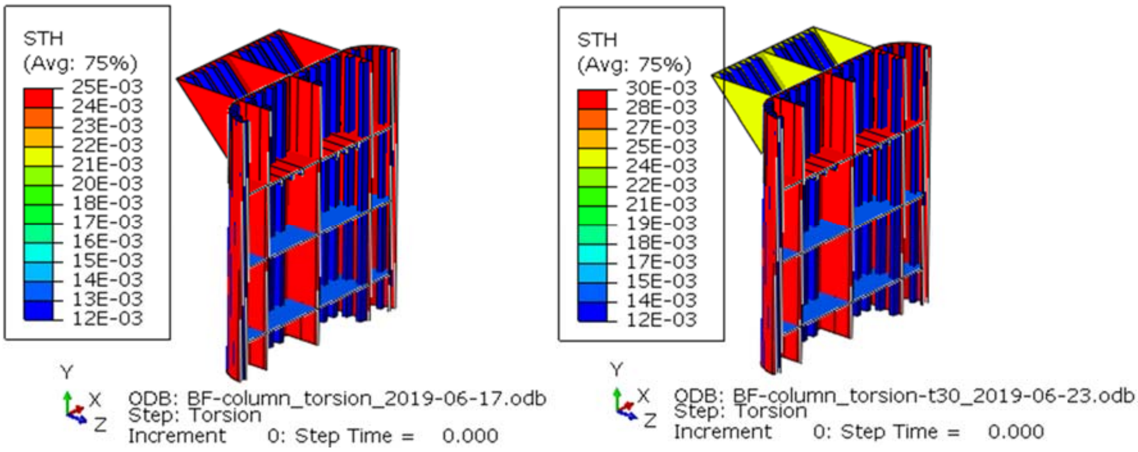


Figure F-7 Column model for push-over analysis – plate thicknesses [m]. Left: High bridge column. Right: Low bridge column.

The results are presented below. The results will be used to evaluate the results from the global analysis to see if the given section forces are within the elastic area, or if the energy dissipation in plastic hinges are acceptable.

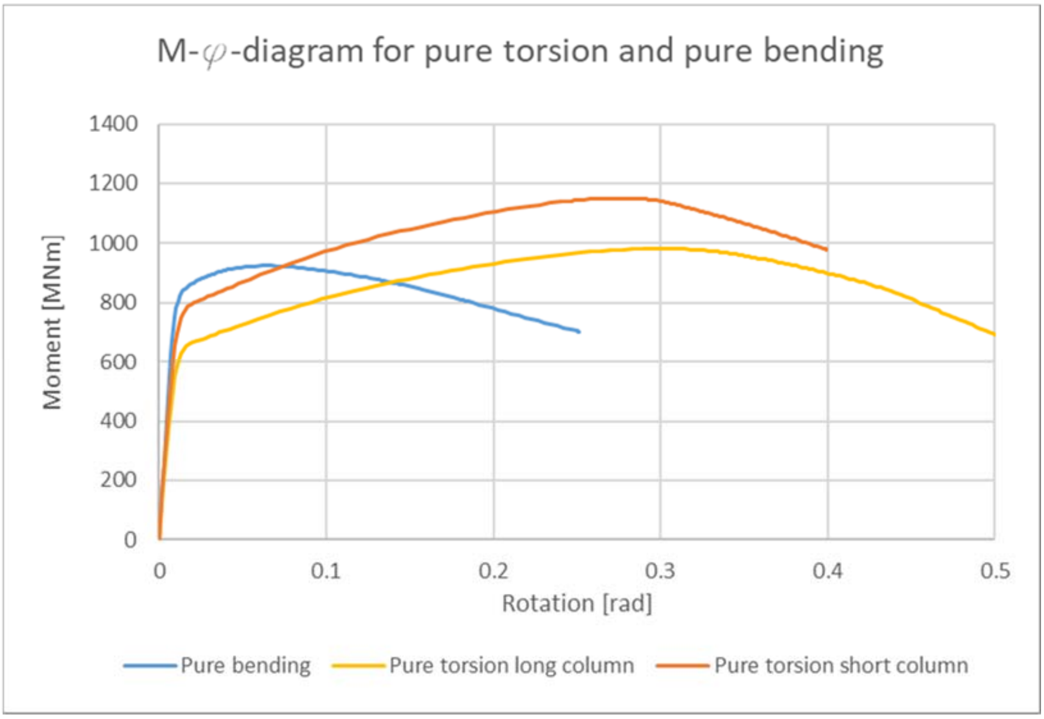


Figure B-1 M-phi-diagrams column, pure torsion and pure bending.

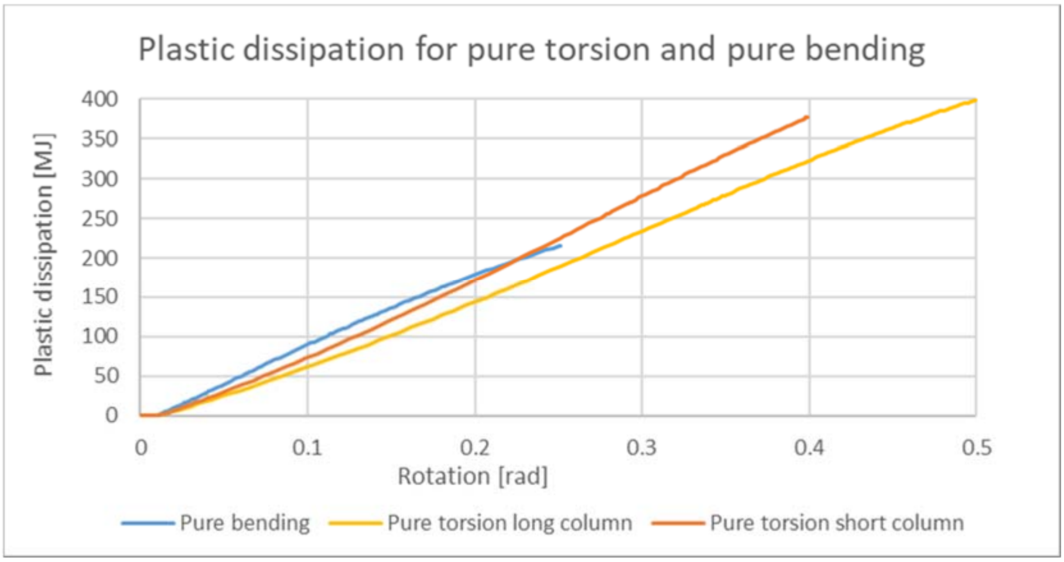
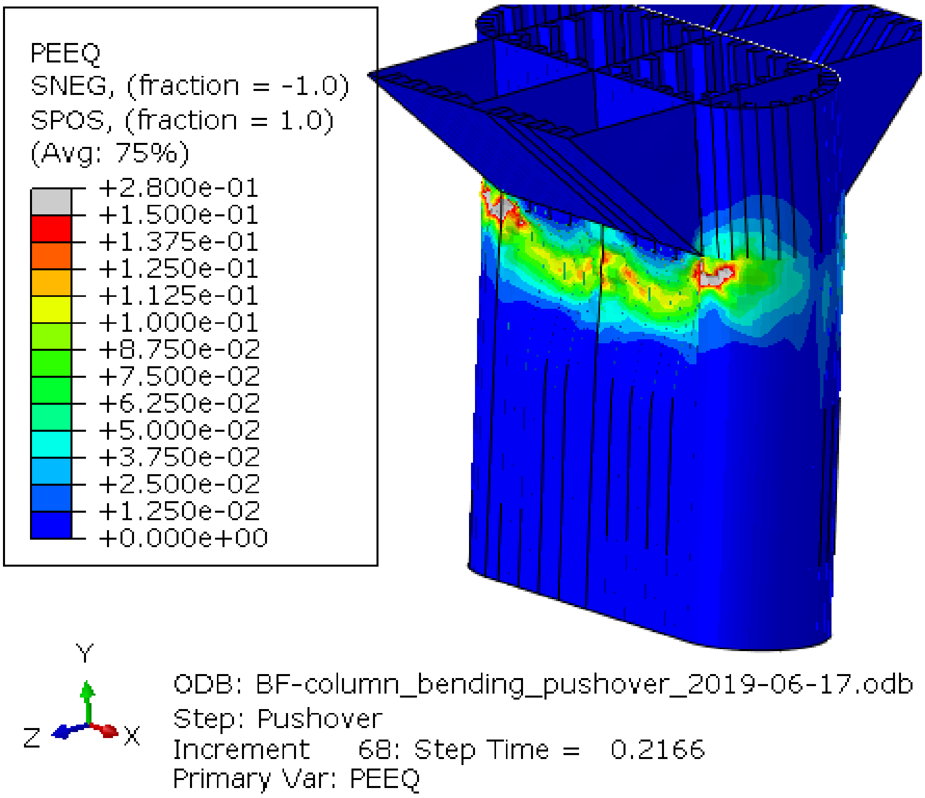
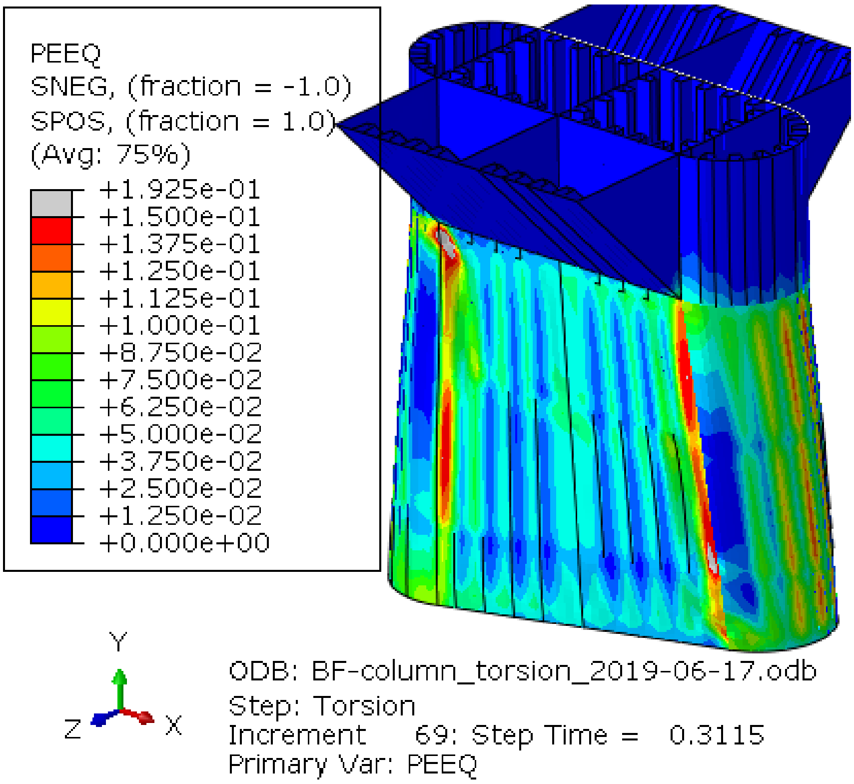


Figure F-8 Plastic dissipation in column for pure torsion and pure bending.


PEEQ
SNEG, (fraction = -1.0)
SPOS, (fraction = 1.0)
(Avg: 75%)
+2.800e-01
+1.500e-01
+1.375e-01
+1.250e-01
+1.125e-01
+1.000e-01
+8.750e-02
+7.500e-02
+6.250e-02
+5.000e-02
+3.750e-02
+2.500e-02
+1.250e-02
+0.000e+00
Y
Z
X
ODB: BF-column_bending_pushover_2019-06-17.odb
Step: Pushover
Increment 68: Step Time = 0.2166
Primary Var: PEEQ


PEEQ
SNEG, (fraction = -1.0)
SPOS, (fraction = 1.0)
(Avg: 75%)
+1.925e-01
+1.500e-01
+1.375e-01
+1.250e-01
+1.125e-01
+1.000e-01
+8.750e-02
+7.500e-02
+6.250e-02
+5.000e-02
+3.750e-02
+2.500e-02
+1.250e-02
+0.000e+00
Y
Z
X
ODB: BF-column_torsion_2019-06-17.odb
Step: Torsion
Increment 69: Step Time = 0.3115
Primary Var: PEEQ

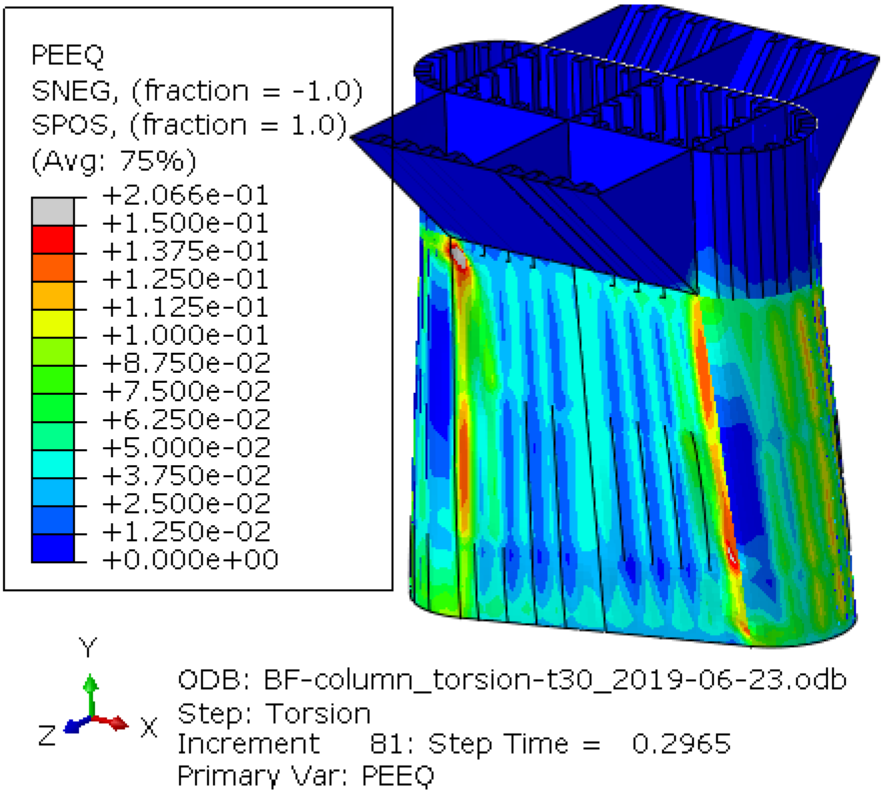


Figure F-9 Plastic equivalent strain in column subjected to pure bending and pure torsion, at approximate step where the strain exceeds 0.15 in a larger area. Top: bending. Middle: Torsion long column. Bottom: torsion short column. Step time 0.22 in bending corresponds to 0.11 rad bending or 100 MJ plastic dissipation. Step time 0.31 for long column torsion corresponds to 0.31 rad rotation, or 240 MJ plastic dissipation. Step time 0.29 for short column torsion corresponds to 0.29 rad rotation, or 270 MJ plastic dissipation.

F.5 Analysis setup for design of girder-column crown

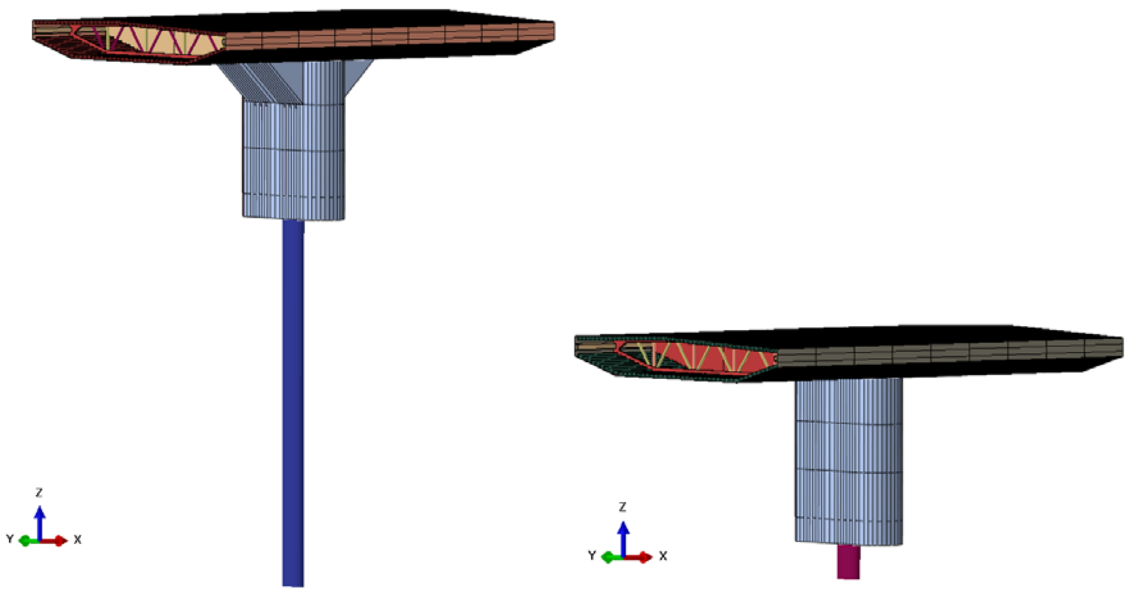
The analysis model in appendix 0-F.4 focuses on the column such that the design of the column dissipates most of the energy that is required for ship impact. The governing load case is the 90-degree impact on the pontoon (along the bridge length axis) with the container bow.

This section investigates the design of the "crown" in the bridge girder above the column. In the design philosophy with the column dissipating most of the energy, the crown shall preferably have stresses in the elastic range. However, a weight optimization is also necessary for the crown to minimize the effect of added structural mass in the girder-column connection on the global analysis of the bridge in 3D float.

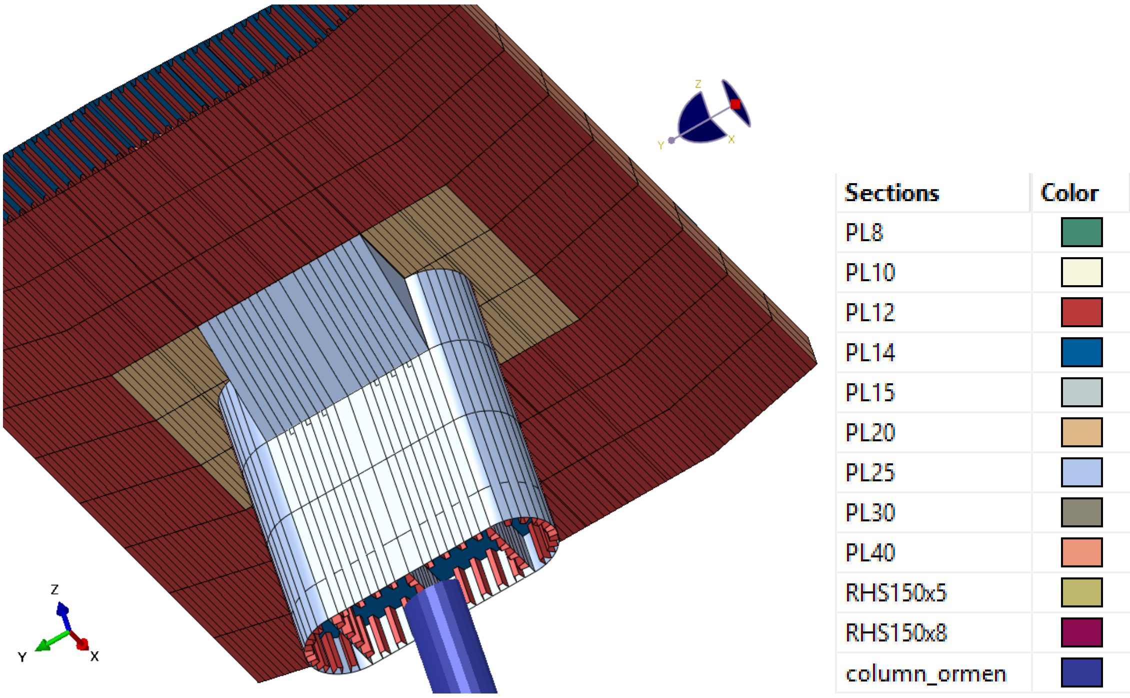
The local shell model established in this section utilizes the same column as in appendix 0-F.4. The lower part of the column is modelled as a wire with beam properties. The total length of the column includes the height to the assumed center of impact 2.5 m below the water line. The total modelled column length of the high bridge model is therefore 46 m and of the low bridge model 17 m.

An updated bridge girder cross section is modelled according to drawing no. SBJ-33-C5-OON-22-DR-141-B [2] and SBJ-33-C5-OON-22-DR-142-B [3]. The modelled length of the bridge section is 36 m (9 sections between transverse girders). The crown spans over 5 sections or 20 m.

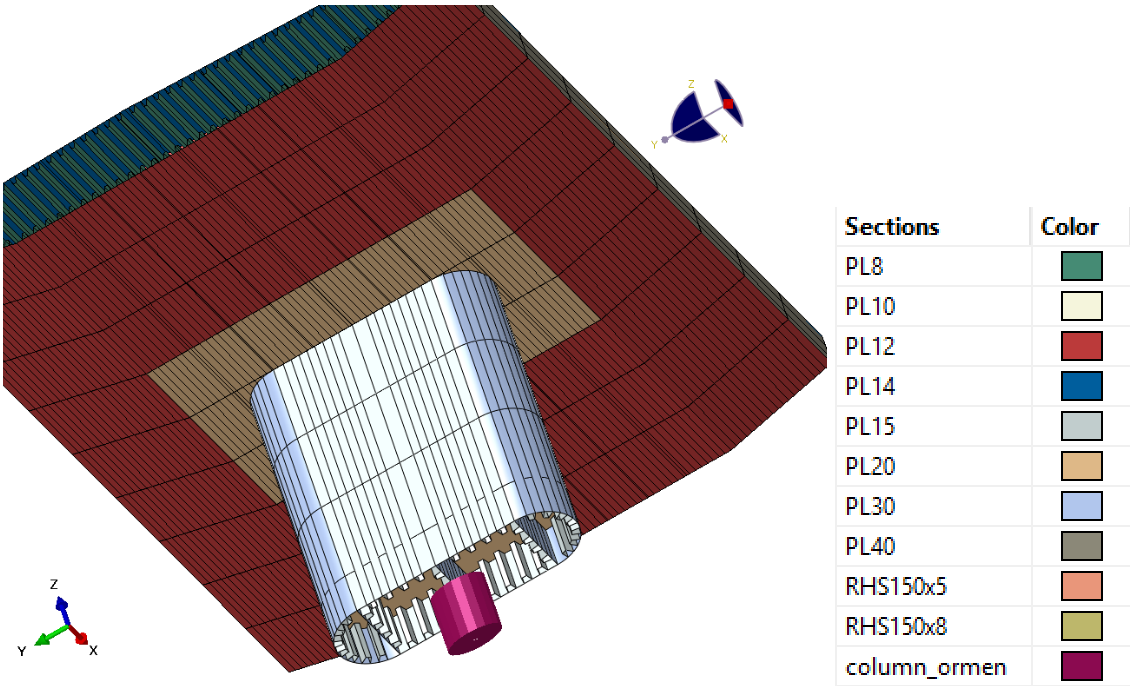
Plastic material curve for S420 is utilized. The material curved can be seen in Figure 4-6 in the "K12 Ship impact, Bridge girder" report [1]. The column beam elements are modelled elastic.



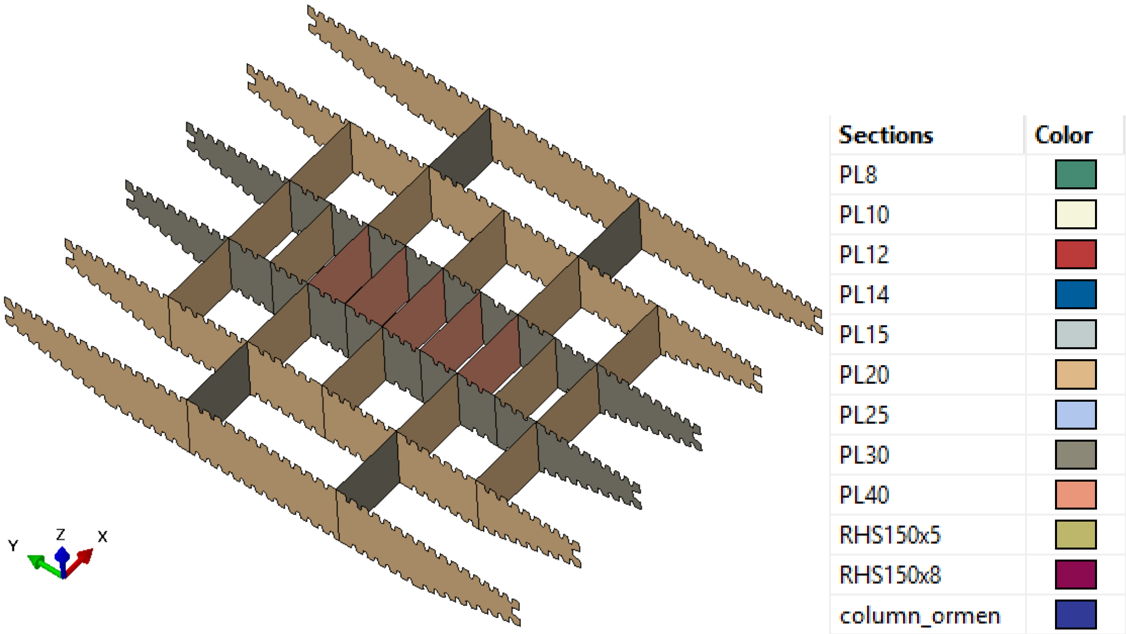
> *Figure F-10 Finite element model of high and low bridge girder-column connection for crown design*



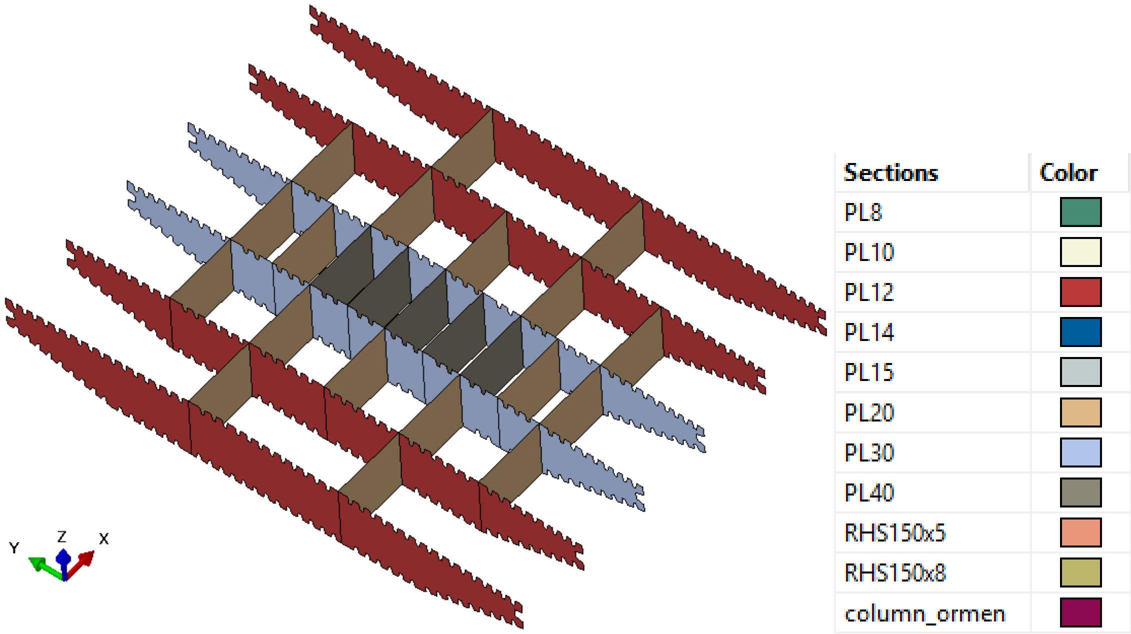
> *Figure F-11 Shell thicknesses for high bridge girder-column connection*



> *Figure F-12 Shell thicknesses for low bridge girder-column connection*



> *Figure F-13 Shell thicknesses for crown above long column*

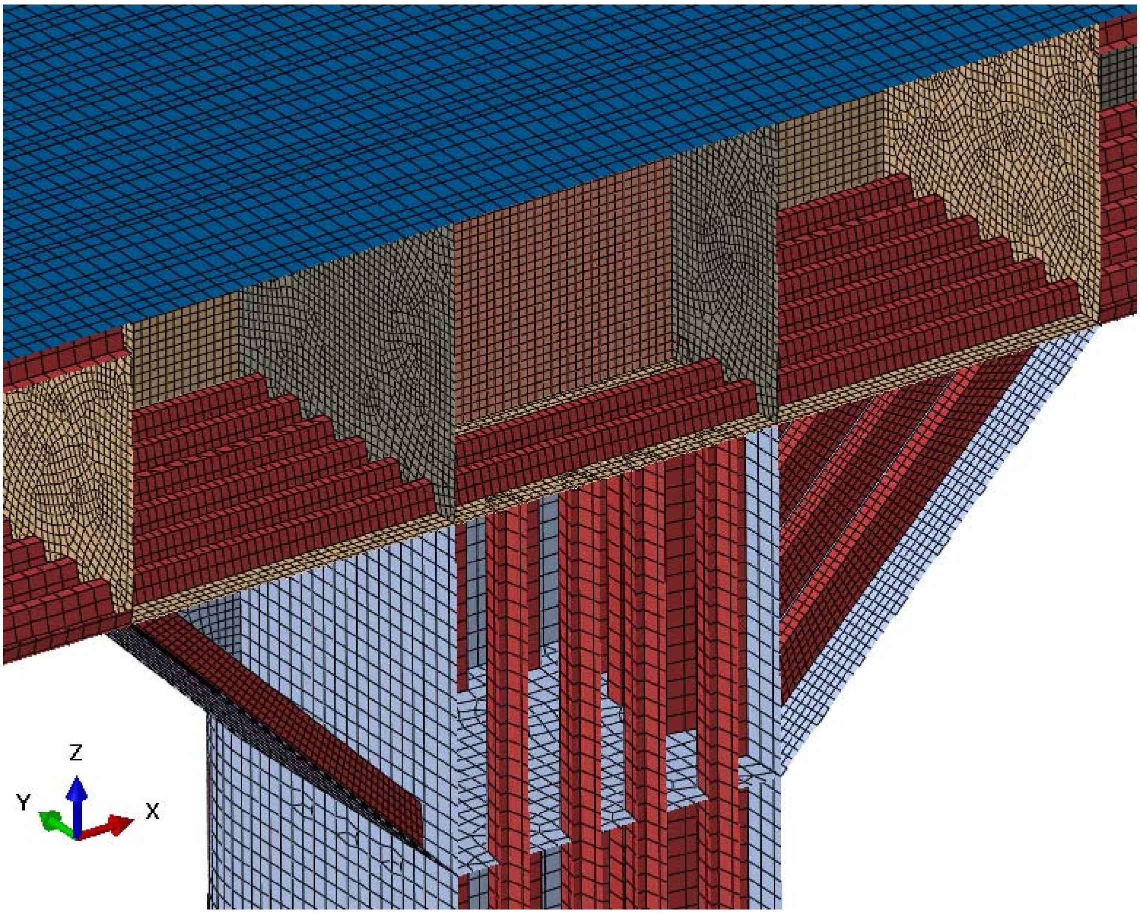


> *Figure F-14 Shell thicknesses for crown above short column*

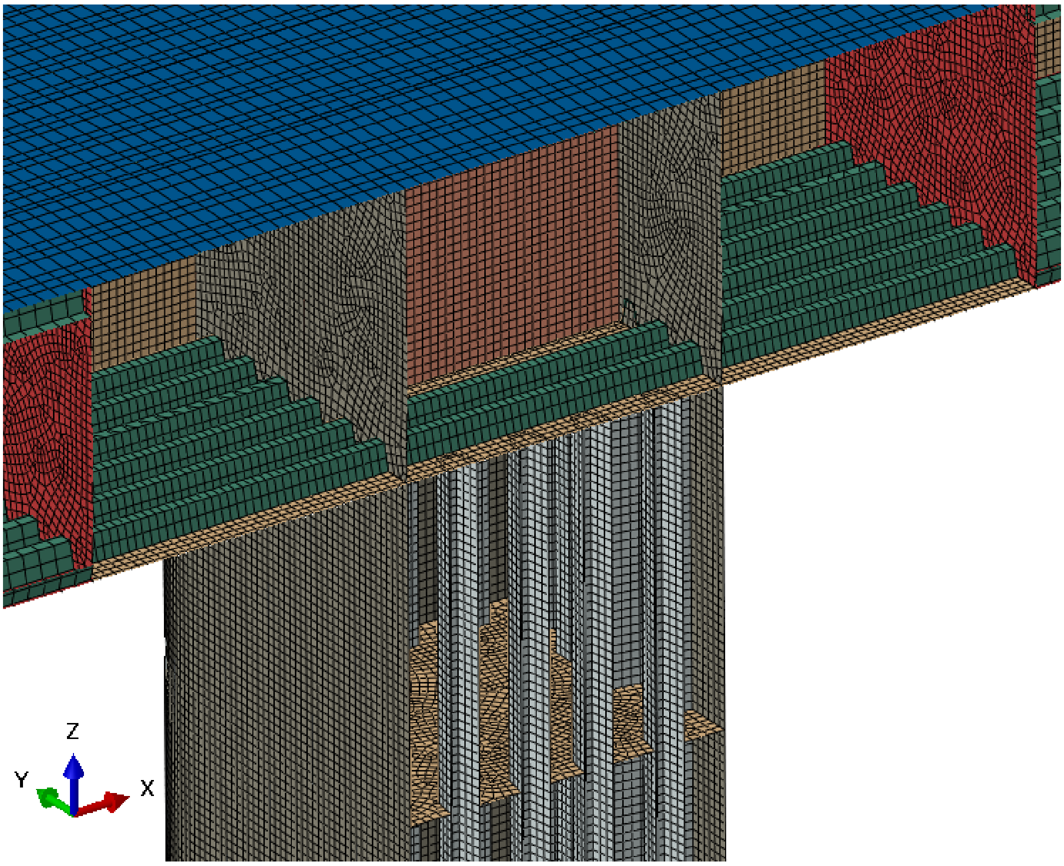
> *Table F-1 Mass of reinforced girder-column connection*

Model girder-crown-column connection	Mass of crown	Total mass of reinforced girder-column connection
High bridge	146 ton	165 ton (reinforced girder bottom plate and voute included; 6 normal bulkheads withdrawn)
Low bridge	123 ton	107 ton (reinforced girder bottom plate included; 6 normal bulkheads withdrawn)

The characteristic element size is 100 mm, except for the bridge girder cross section and the column (shell part) in the high bridge model, which has characteristic element size 200 mm. The bottom plate in the bridge girder above the column and voute has element size 100 mm. The element types are S4R and S3R for the shell, B31 for the wires.



> *Figure F-15 Mesh of the high bridge girder-crown-column connection*



> *Figure F-16 Mesh of the low bridge girder-crown-column connection*

The bridge girder is modelled fixed at the boundary cut-offs. The bottom of the column is constrained for vertical and transverse translation.

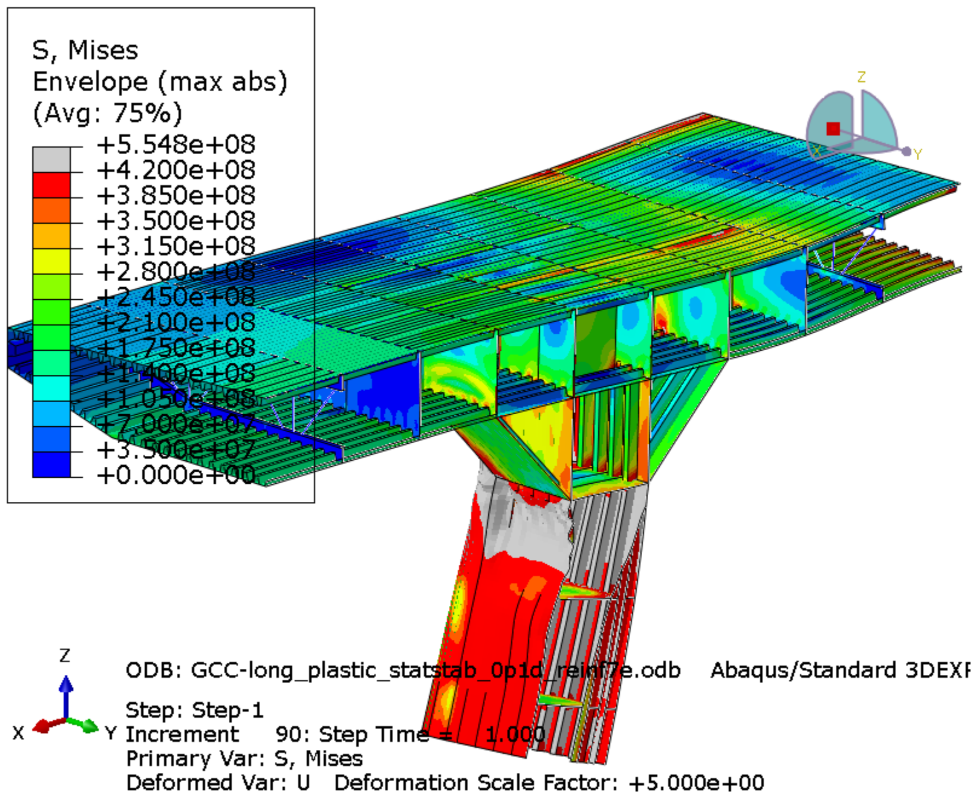
For this model, the ship impact load is applied in a simple manner with a static shear force (along the bridge length axis) and a static torsional moment at the bottom of the column. The values for the shear force are the approximate maximum forces in the connector for the results in appendices F.2 and F.3. The torsional moment is due to 23 m eccentricity of the shear force to the outer end of the pontoon.

> *Table F-2 Applied loads to the girder-crown-column models*

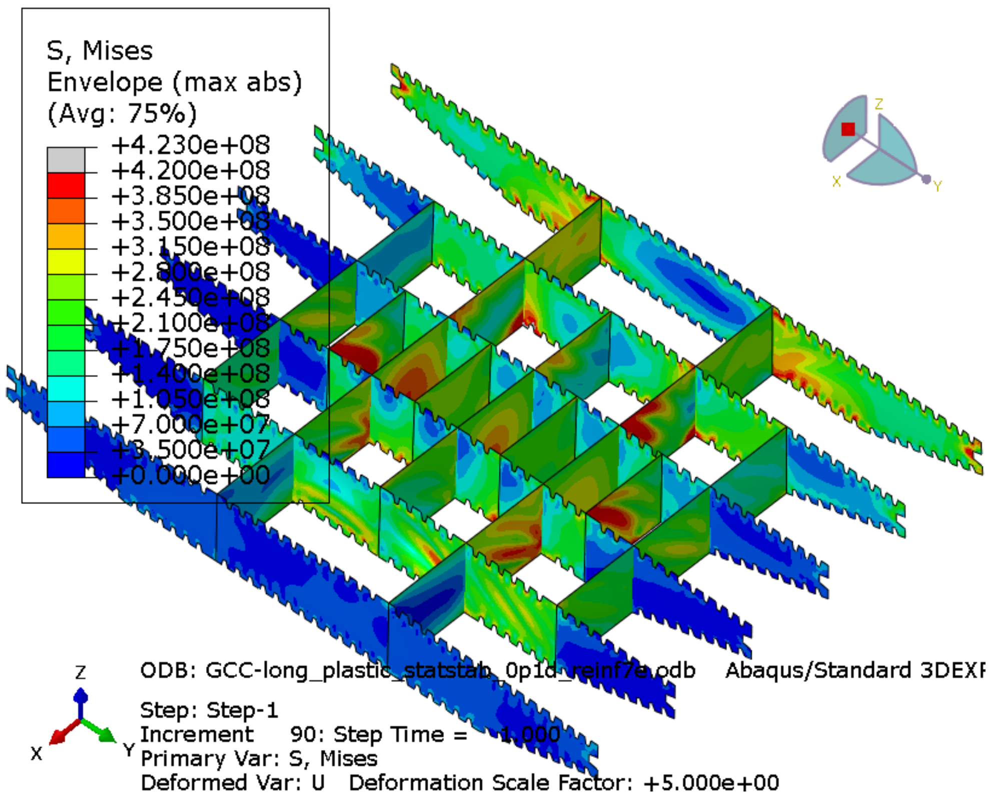
Model girder-crown-column connection	Shear force	Torsional moment
High bridge	22 MN	506 MNm
Low bridge	35 MN	805 MNm

F.6 Analysis results crown above long column

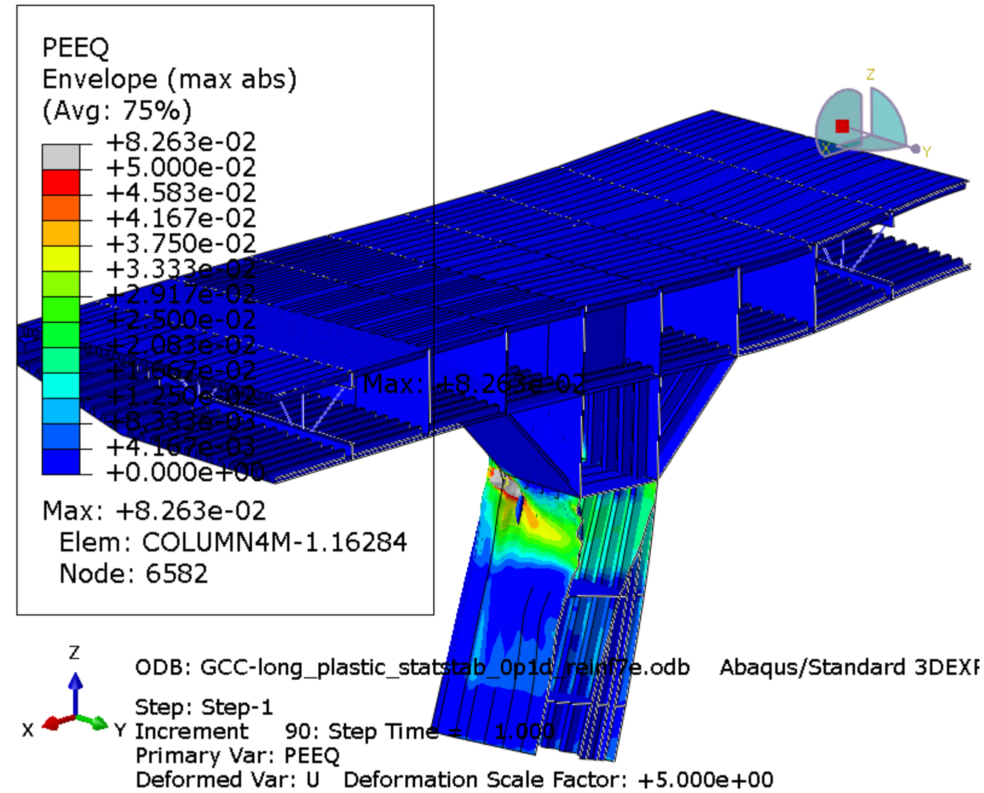
The results for the column are in the range of the results shown in appendix F.2-F.3. The crown displays higher stresses than preferred, but this is mainly due to buckling of the plates. The plates are modelled with equivalent thicknesses and buckling will be reduced if stiffeners are included. The plastic strains in the crown is low.



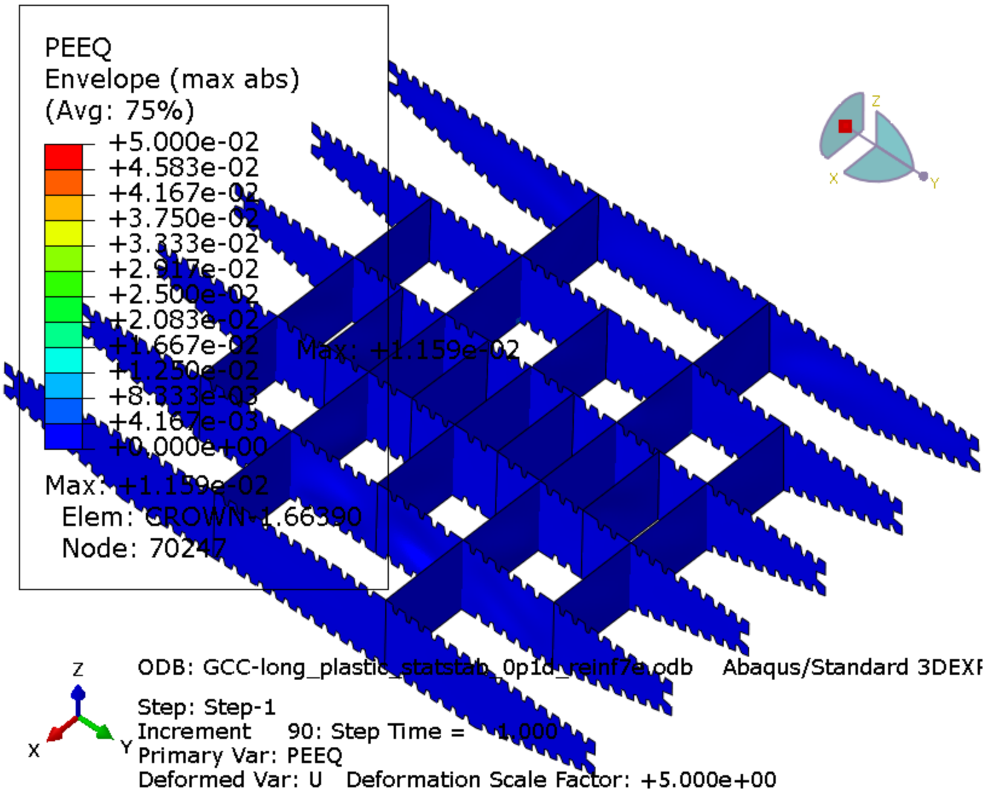
> *Figure F-17 von Mises stress [Pa] in high bridge girder-crown-column connection*



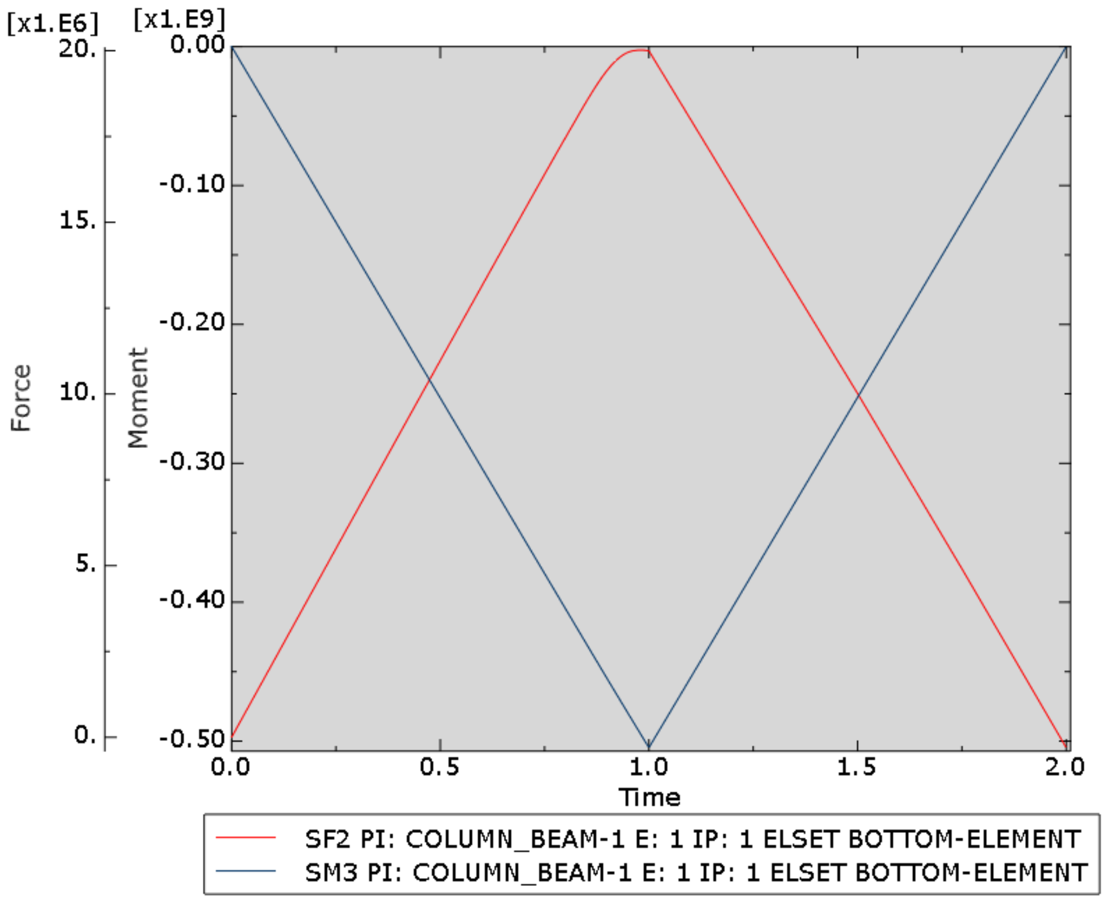
> *Figure F-18 von Mises stress [Pa] in crown above long column*



> *Figure F-19 Plastic equivalent strain [-] in high bridge girder-crown-column connection*



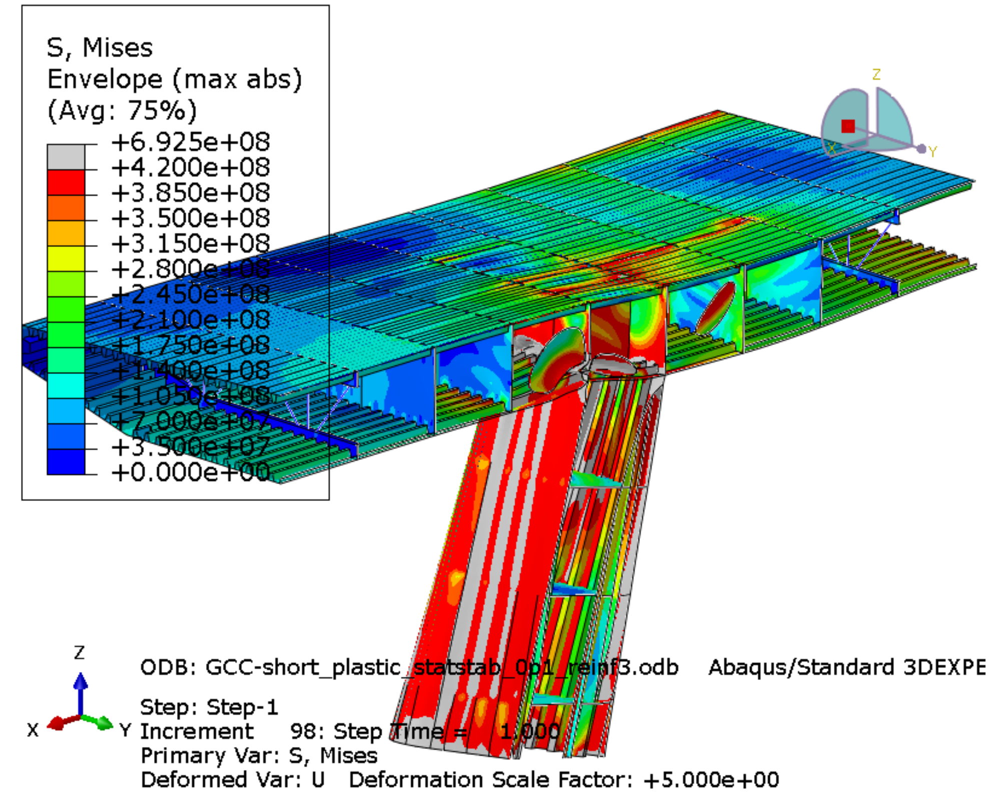
> *Figure F-20 Plastic equivalent strain [-] in crown above long column*



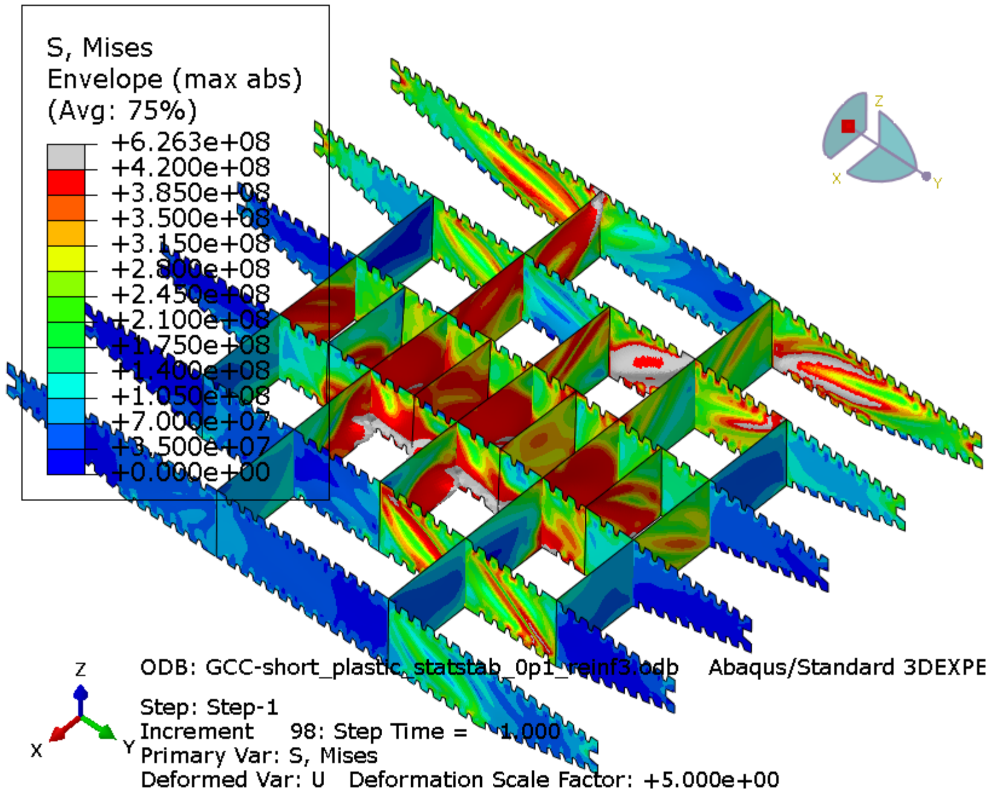
> *Figure F-21 Control of section forces at bottom of long column. SF2 [N] – shear force along bridge length axis. SM3 [Nm] – torsional moment. Step time 1.0 applied loading, step time 2.0 unloaded.*

F.7 Analysis results crown above short column

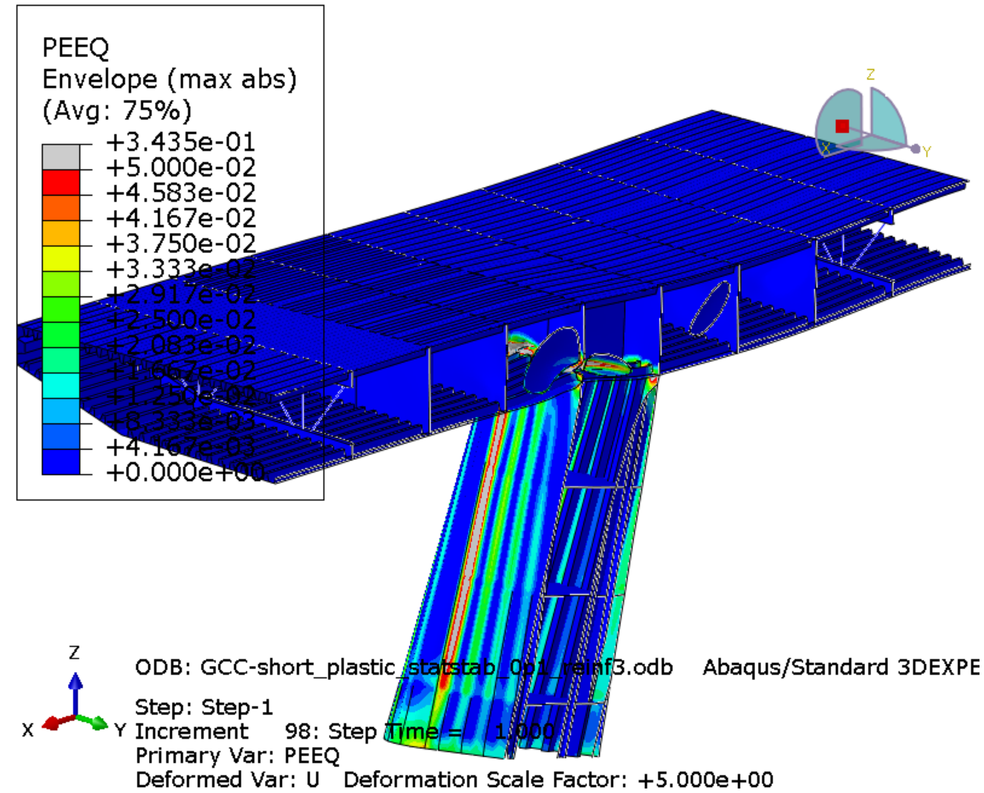
The results for the column are in the range of the results shown in appendix F.2-F.3. The crown displays very higher stresses, but this is mainly due to buckling of the plates. The plates are modelled with equivalent thicknesses and buckling will be reduced if stiffeners are included. The plastic strains in the crown is more moderate. Design optimization of the crown above the short columns should be pursued further.



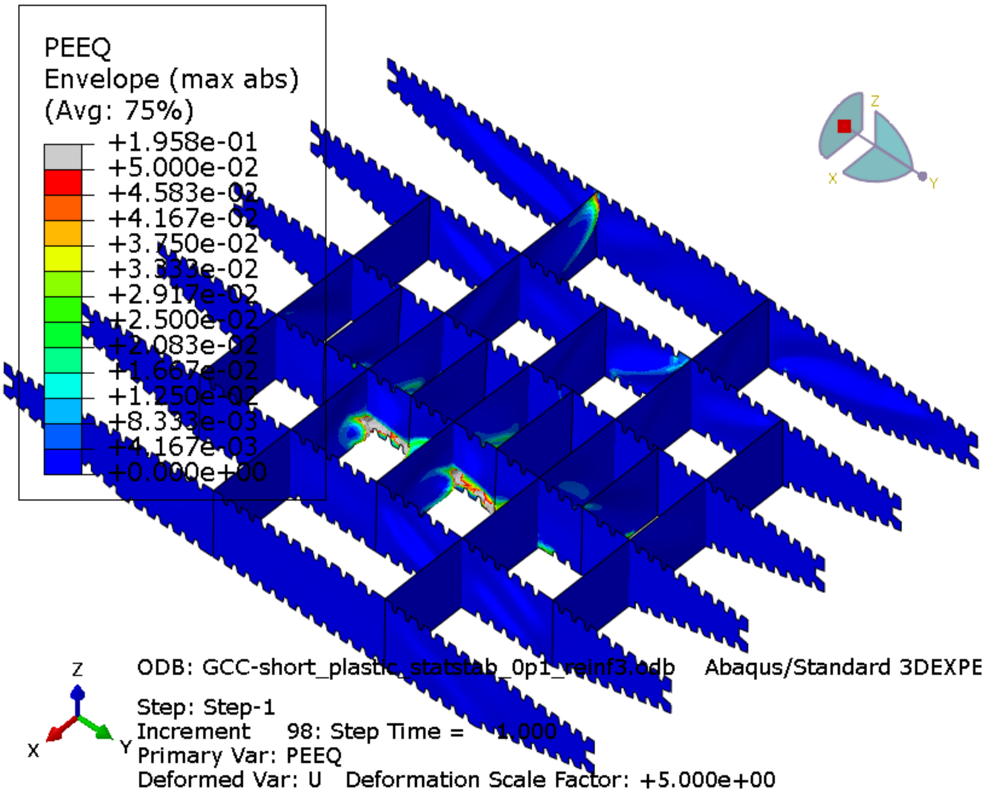
> *Figure F-22 von Mises stress [Pa] in low bridge girder-crown-column connection*



> *Figure F-23 von Mises stress [Pa] in crown above short column*



> *Figure F-24 Plastic equivalent strain [-] in low bridge girder-crown-column connection*



> *Figure F-25 Plastic equivalent strain [-] in crown above short column*

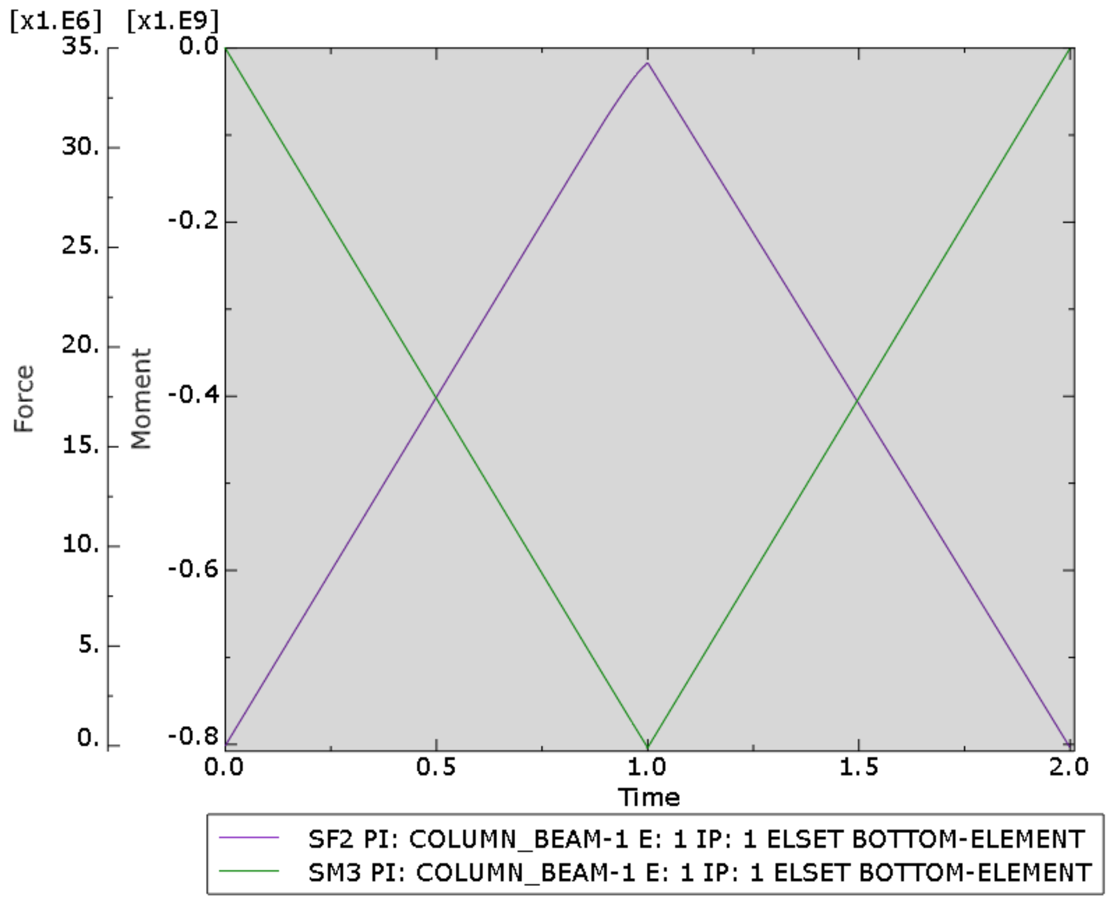


Figure F-26 Control of section forces at bottom of short column. SF2 [N] – shear force along bridge length axis. SM3 [Nm] – torsional moment. Step time 1.0 applied loading, step time 2.0 unloaded.

1 REFERENCES

[1] SBJ-33-C5-OON-22-RE-015-B, «K12 - Ship impact, Bridge girder,» 2019.

[2] Drawing no. SBJ-33-C5-OON-22-DR-141-B, «E39 Bjørnafjorden, Reksteren-Os, Concept developement floating bridge, Girder, Cross-sections 2, Concept study,» Norconsult, Dr. Techn. Olav Olsen, 2019.

[3] Drawing no. SBJ-33-C5-OON-22-DR-142-B, «E39 Bjørnafjorden, Reksteren-Os, Concept developement floating bridge, Girder, Cross-sections 1, Concept study,» Norconsult, Dr. Techn. Olav Olsen, 2019.

[4] SBJ-33-C5-OON-22-RE-012-B, «K12 - Structural response analyses,» 2019.

[5] SBJ-32-C5-OON-22-RE-003-B, «Analysis method,» 2019.

[6] SBJ-33-C5-OON-22-RE-014-B, «K12 - Ship impact, Pontoons and columns,» 2019.

[7] Statens vegvesen, «SBJ-01-C4-SVV-01-BA-001 Design basis MetOcean_rev_1,» 2018.