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Calculation note

NDC_Note reference CP_FEA_Rev06

Associated spreadsheet: ASME CP19 F09-00 Rev02

Subject	**Ref. no.**
Calculation note FEA stress analysis of CP40 -200 plates	FEA-CP21-24561-01 Rev00

SUMMARY

The present document covers the design analysis of the panels of a CP40 200 plates.

The design pressure and temperature are:

- Side A: 1.04 MPa and 120 °C (151 Psi and 248 °F)
- Side B: 1.04 MPa and 120 °C (151 Psi and 248 °F)

The exchanger is calculated with panels including nozzles.

The results show that the design of those parts fulfils the requirements of the division 1 of the section VIII ASME Code.

Remark: if there are different design temperatures, the maximal value is chosen.

Reference World Energy tag number on this sheet.

Note that design pressures exceed specification

00	**Original issue**
Rev.	**Description of revision**

00	**19/07/21**	N.ROSSIGNOL NRL	**19/07/21**	T.SINTHOMEZ TSZ	**19/07/21**	Pascal VERNAY
Rev.	**Date**	**Prepared**	**Date**	**Reviewed**	**Date**	**Approved**

CONTENTS

1. INTRODUCTION

The document presents the validation of the design of panels and nozzles of CP40-200 plates Compabloc heat exchanger according to the division 1 of the section VIII ASME Code [1].

Alfalaval Compabloc ® has a design that differ from these covered in ASME VIII div.1 and the following calculation way is defined:

- Use of the chapter UG-16 for these designs with the alternative by using Mandatory Appendix 46.
- Use of the chapter 4.12 of [2] as allowed by Mandatory Appendix 46.3.
- If the design by rule is not possible, use of Part 5 of [2] by using a FEA calculation as allowed by Mandatory Appendix 46.4.

Indeed, The design of the Compabloc (panels and heads) corresponds directly to the chapter 4.12 of [2]: “Design rules for non circular vessels”. But in the “scope” in the paragraph 4.12.1.2 and in the “General design requirement” in the paragraph 4.12.2.8, for vessel other than described in 4.12 and for “Bolted full side or end plates…” “Part 5 shall be used”. Moreover, for openings in kind of vessel, the Part 5 is referenced again in the paragraph 4.12.2.9 (b): “rules for specific designs are not provided and the design shall be in accordance with Part 5”.

The design of panels, heads and openings are checked according to Part 5 of [2] in accordance with the requirement of Mandatory Appendix 46 of [1].

2. INITIAL DATA

2.1. References

[1]	ASME Code section VIII div.1	Boiler and Pressure Vessel Code. Section VIII Edition 2019 Rules for construction of Pressure Vessels Division 1
[2]	ASME Code section VIII div.2	Boiler and Pressure Vessel Code. Section VIII Edition 2019 Rules for construction of Pressure Vessels. Division 2 Alternative Rules
[3]	ASME Code section II	Section II part D Properties MATERIALS Edition 2019
[4]	Directive 2014/68/UE	Pressure Equipment directive
[5]	ANSYS V19.2	Finite element analysis software, developed by ANSYS Inc. (USA) and certified ISO 9001
[6]	Drawings	DWG-CP21-24561-01
[7]	Analytical note	NDC-CP21-24561-01 Rev00
[8]	FEA validation note	FEA-validation-CP19 Rev00
[9]	Complementary NDC	FEA_CP_Head Rev00

SI units are used in the calculation. US Customary units are converted from Si units for information.

2.2. Materials

The allowable stress values at maximal design temperature of the materials are reported in *Table 1* of this report.

		100°F	**40°C**	248°F	**120°C**
	Material	Ksi	**MPa**	Ksi	**MPa**
Carbon steel plate	SA-516 gr60N	17.1	**118.0**	17.1	**118.0**
Stainless steel pipe (Smls pipe)	SA-312 TP316L	16.7	**115.0**	16.7	**115.0**
Bolting (∅ < 64 mm)	SA-193 B7	24.9	**172.0**	24.9	**172.0**

Table 1: Material properties for the structural parts

		Yield stress (S_y) at Temperature			
		100°F	**40°C**	248°F	**120°C**
	Material	Ksi	**MPa**	Ksi	**MPa**
Carbon steel plate	SA-516 gr60N	32.1	**221.0**	28.9	**199.0**
Stainless steel pipe (Smls pipe)	SA-312 TP316L	24.9	**172.0**	20.2	**139.0**
Bolting (∅ < 64 mm)	SA-193 B7	105.0	**724.0**	96.0	**662.0**

Table 2: Yield stress for the structural parts

The panels are made in SA-516 gr60N

The heads are made in SA-516 gr60N

The pipes materials are defined in § 3.1.

The bolts are made in SA-193 B7

Supplementary data for FEA analysis according to [3] (CS: Carbon steel)

Material	Poisson ratio	Density (kg/m^3)
CS	0.30	7850
SS	0.31	7950

Table 3: Poisson ratio and density

Young Modulus MPa		
Material	40°C	120°C
CS	202 000	197 000
SS	195 000	188 000
Bolt CS	204 000	199 000

Table 4: Young modulus

To be notice, materials with allowable stress at the design temperature governed by time-independent properties.

2.3. Stress categorisation and criteria of the ASME VIII div.2 Code [2]

The criteria are based on the type of analysis which gives a realistic representation of the part behaviour. The linear elastic stress analysis method is chosen for each protection. In this case, the equivalent stress is equal to the Von Mises equivalent stress given by the equation 5.1 in Part 5 of the Code. In this chapter all references are made from [2].

2.3.1. Panels and nozzles

The stresses computed in those parts are then categorised in four basic equivalent stresses.

1 – General Primary Membrane Equivalent Stress (Pm)

2 – Local Primary Membrane Equivalent Stress (Pl)

3 – Primary membrane (General or Local) Plus Primary Bending Equivalent Stress (Pl + Pb)

4 – Secondary membrane + bending equivalent stresses (Q)

They are self-equilibrating stresses and are necessary to satisfy continuity of the structure. Those stresses occur at structural discontinuities and they can be due to mechanical load or by differential thermal expansion. This categorisation is described too for nozzle neck in § 5.6.

2.3.2. Protection against plastic collapse

In order to evaluate protection against plastic collapse, the computed equivalent stresses (Pl, Pm, Pm + Pb) are compared to their corresponding allowable values

$$\mathbf{Pm \leq S} \qquad 5.2\ (\text{part } 5)$$

$$\mathbf{Pl \leq 1.5S} \qquad 5.3\ (\text{part } 5)$$

$$\mathbf{(Pm + Pb) \leq 1.5S} \qquad 5.4\ (\text{part } 5)$$

S is the allowable stress (given in *Table 1*) based on the material of construction and design temperature.

2.3.3. Protection against local failure

In addition to demonstrating protection against plastic collapse, the applicable local failure criterion below can be satisfied for a component including geometrical discontinuity (criterion detailed in paragraph 5.3 of the part 5). This criterion is defined as the sum of the local primary membrane plus bending principal stresses.

$$\boldsymbol{(\sigma_1 + \sigma_2 + \sigma_3) \leq 4S} \qquad 5.5\ (\text{part } 5)$$

2.3.4. Protection against collapse from buckling

According to § 5.1.1.2 (a) the protection against collapse from buckling need to be done for compressive part like nozzle in external pressure. This analysis is made in [7]. For flat panels in traction and flexion, there is no collapse from buckling risk.

2.3.5. Protection against failure from cyclic loading

2.3.5.1. Screening criteria

The used paragraph is the § 5.5.2.3 Method A.

For integral construction the criterion is (Table 5.9):

$N_{\Delta FP} + N_{\Delta PO} + N_{\Delta TE} + N_{\Delta T\alpha} \leq 1000$

- $N_{\Delta FP}$ (step 2): Number of cycle for the full range pressure
- $N_{\Delta PO}$ (step 3): Number of cycle for the operating range pressures.
- $N_{\Delta TE}$ (step 4): Number of cycle for range temperature (by using the Table 5.8).
- $N_{\Delta T\alpha}$ (step 5): Number of cycle base on non homogenous welded material

1/ In first case with insulation the following analysis is made:

1. $N_{\Delta FP} = 1000$ Considering cycle : $0 \rightarrow Pd \rightarrow 0$ bar
2. $N_{\Delta PO} = 0$ Considering cycle : No. To be studied case by case only
3. $N_{\Delta TE} = 0$ Considering cycle : ∞ if temperature gradient between two adjacent points AB is less than 28 °C: $\Delta TE \leq 28$ °C. AB is through the thickness.
4. $N_{\Delta T\alpha} = 0$ Homogenous material.

To respect the point 3, insulation and slow ramp up and cooling from ambient temperature to steady state or from steady state to ambient temperature(1°C/mn) are needed.

In conclusion we have maximum 1000 cycles of full pressure range.

2/ In second case without insulation and considering unknown data for metal temperature faces the following analysis is made:

1. $N_{\Delta FP} = 47$ Considering cycle : $0 \rightarrow Pd \rightarrow 0$ bar
2. $N_{\Delta PO} = 0$ Considering cycle : No. To be studied case by case only
3. $N_{\Delta TE} = 47$ (cycles) × 20 (factor of table 5.8 of [2]). Gradient between two adjacent points AB is equal or greater to 250 °C
4. $N_{\Delta T\alpha} = 0$ Homogenous material.

In conclusion, we have maximum 47 cycles of full pressure range with 250 °C or more temperature gradient variation.

2.3.5.2. Ratcheting assessment

Even if the fatigue screening is satisfactory as per § 5.5.6.1 (no fatigue analysis), this analysis is mandatory to avoid ratcheting fracture.

When no transient and its associated cycles are given we consider the following criterion:

$$\mathbf{\Delta(Pl + Pb + Q) \leq max\{ 3S \; ; 2\, Sy\}} \qquad 5.78 \text{ (part 5)}$$

In our case the cycle is defined from 0 MPa to the design pressure, so we consider $\Delta(Pl + Pb + Q)$ like the maximal secondary stress of the result with the classic design loads below.

As described in the Code § 5.5.6.1, we consider only in this criterion the gross structural discontinuities but not local discontinuities (peak stress). And, as described in table 5.6, the bending stress at a gross structural discontinuities is a secondary stress.

Sy is the yield stress of the material. We focus only on the 3S criterion.

2.3.6. Environment loads

Wind and earthquake when applicable are used only for support in supplementary specific calculation. These loads are neglectable for panels and nozzles. These loads can affect the head of the attached support. A complementary note [9] is made in conservative conditions (maximal pressure at maximal temperature with the maximal bolting forces) to prove the mechanical strength of the head.

2.4. Test pressure

According to the § 4.1.6.2 of ASME VIII-2 [2], the allowable stress in test conditions is 0.95Sy. According to the ASME VIII div.1 UG-99 (b) allowable stress shall not exceed 90% of yield stress for bolting. In conservative way, in [7] the ratio 0.9Sy is chosen for all material. The minimal following ratio (0.9 Sy (at room temperature) / S (at design temperature) is equal to 1.35. This value is upper to f_{test} = 1.3 [7] or [1], the following calculations in design condition (with the assumption of linear mechanical behaviour versus the pressure) are more conservative than the calculation in test conditions. And so no supplementary calculation is needed.

2.5. Loads

2.5.1. Bolt load designs

The gasket is made of graphite material. The bolt load is calculated in [7] using an analytical calculation. If different, the maximal load between the side A and the side B is chosen. This value can be a bit bigger than the value from analytical note due the maximal value chosen for the height of liquid (see next §).

$$Fb = 36300 \text{ N}$$

2.5.2. Pressure

The design pressures are

- Side A: 1.04 MPa
- Side B: 1.04 MPa

We add 0.02 MPa pressure due to static height of the liquid. In conservative way, this value is equal or bigger than the value in analytical note [7].

2.5.3. Nozzle loads

The nozzle loads are given in [6].

Nozzle	DN	Class / PN	Fx (N)	Fy (N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
Panel 1 Nozzle 1	150	150	776	776	776	750	750	750
Panel 1 Nozzle 2	150	150	776	776	776	750	750	750
Panel 2 Nozzle 1	150	150	776	776	776	750	750	750
Panel 2 Nozzle 2	150	150	776	776	776	750	750	750

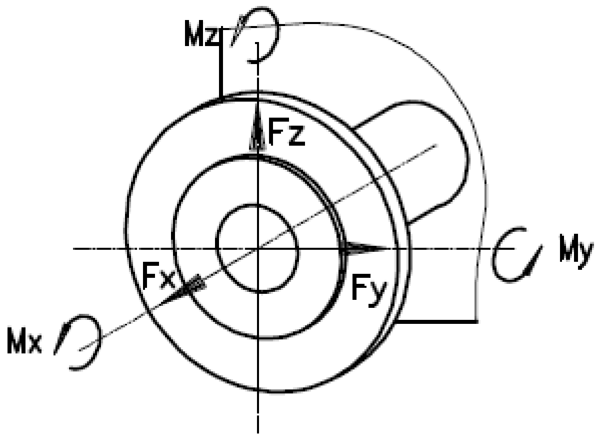

Figure 1: Nozzle sketch

2.5.4. Thermal loads

The thermal loads shall be considered for protection against failure from cyclic loading. If no cycling loads are defined in UG-22, no evaluation need to be performed.

3. MODEL

A complete model describes the full principal geometry of the Compabloc. The four panels are modelled in detail with all openings. The model includes panels with or without nozzles, 4 girders and two heads and the bolts in order to represent the actual assembly conditions. The full details of the drawing are not considered in the model, for example the link between the girders and heads is done like free (conservative model), details are therefore not necessary.

The dimensions of the Compabloc are defined according to [6].

In text description the number of panel corresponds to the following drawing panels:

- Panel 1 (X+): Panel Aa
- Panel 2 (Y+): Panel Ba
- Panel 3 (X-): Panel Ab
- Panel 4 (Y-): Panel Bb

3.1. Geometry

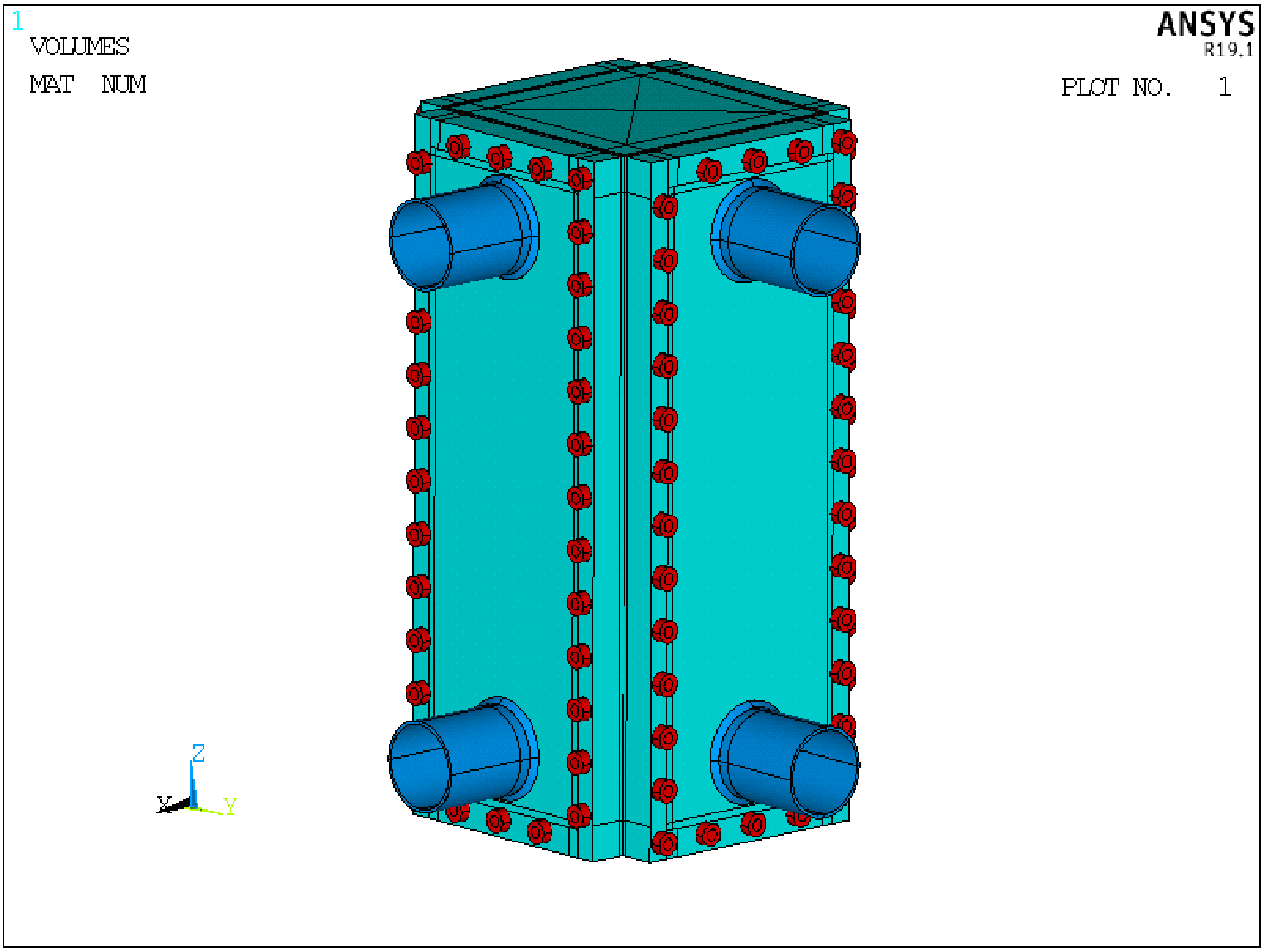

Figure 2: Design model

The following thicknesses correspond respectively to the nominal and the minimal values used in the calculation (2 mm external machining, 9 mm internal machining and 5 mm tolerance):

- Panel 1: 80 mm and 64 mm
- Panel 2: 80 mm and 64 mm
- Panel 3: 70 mm and 54 mm
- Panel 4: 70 mm and 54 mm

For the head, the following thicknesses correspond to the minimal value used in the calculation:

68 mm

The minimal thicknesses (at the location of the link with the panel) of nozzle used in the calculation are:

DN	Minimal thickness (mm)	Material	Nozzle
150	6.225	SA-312 TP316L	Panel 1 Nozzle 1
150	6.225	SA-312 TP316L	Panel 1 Nozzle 2
150	6.225	SA-312 TP316L	Panel 2 Nozzle 1
150	6.225	SA-312 TP316L	Panel 2 Nozzle 2

Table 5: DN and thicknesses

If corrosion allowances are defined in the analysis, the following values are used directly in the FEA model for the corresponding thicknesses of the carbon steel parts:

- Internal corrosion: c_i = 0 mm
- External corrosion: c_e = 0 mm

3.2. Mesh

The panel and the nozzle are meshed using 3D solid elements (SOLID185). Tetrahedral 3D elements are used for the mesh of the rest of the model (bolts, head and girders with SOLID187). Contact elements (CONTA173 and TARGE170) are used to model the links between the different parts. A friction coefficient of 0.2 is chosen (classic value), this value has a low influence on results. To validate the model according to the § 5.1.2.3 of [2], an accurate analysis is made in [8].

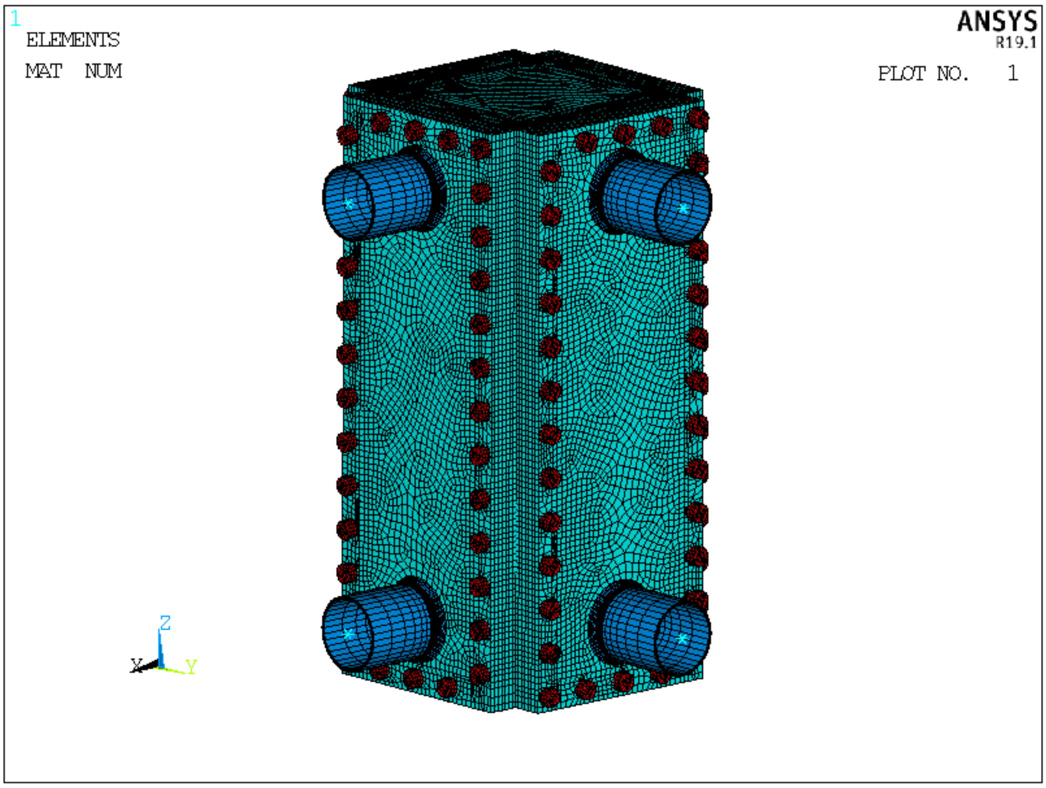

Figure 3: meshing

Remark: In the model, the length of the nozzle takes into account the length flange plus the nozzle length of the drawing [6].

There are four principal contact zones:

- Between each bolt head and the panels: bonded initial contact. The bolts are linked with the girders and the heads
- Between the gaskets (in purple in *Figure 6* and *Figure 7*) and the girders and heads. The gaskets are linked with the panels in the model.
- On the locking parts: between panels and girders and between panels (*Figure 7*) and heads (*Figure 6*)
- Between the girder and the heads in the corners

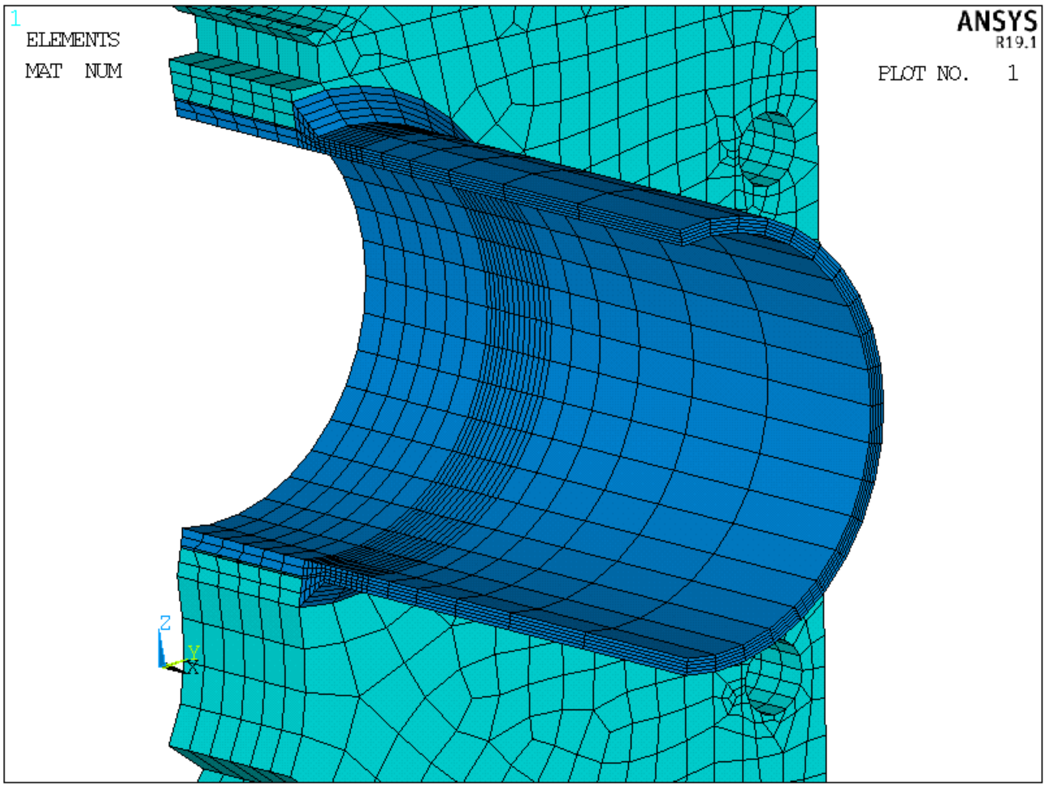

Figure 4: Nozzle connection

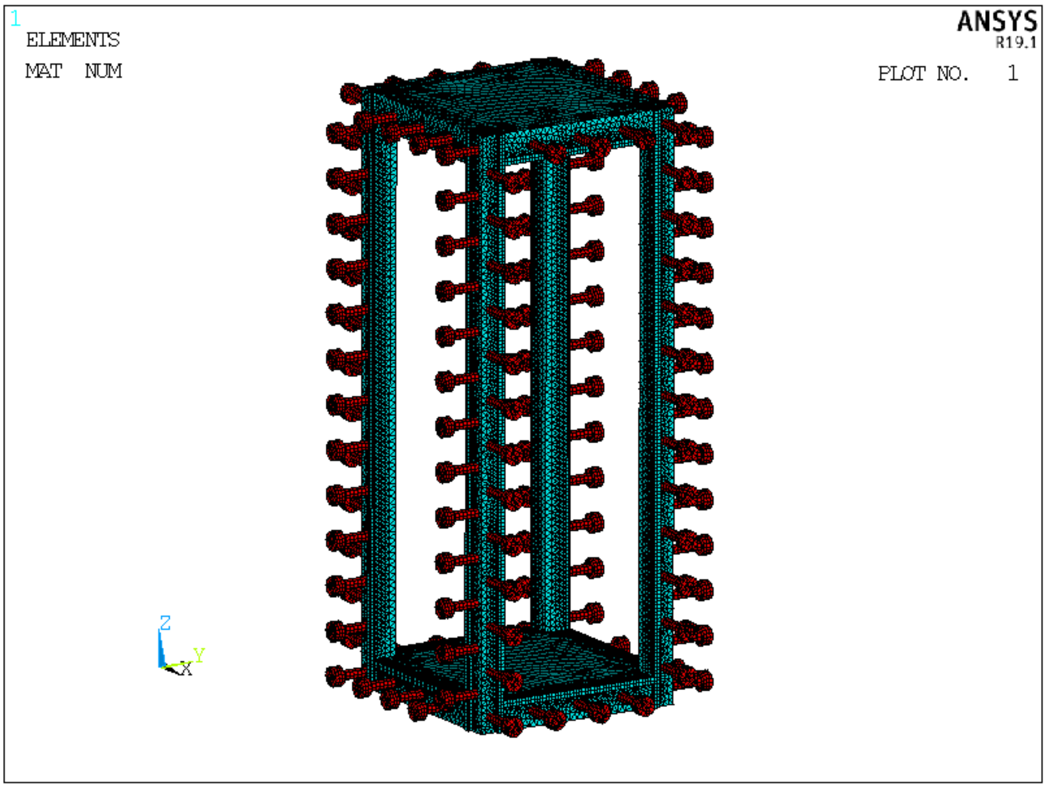

Figure 5: Mesh of the girders, heads and bolts

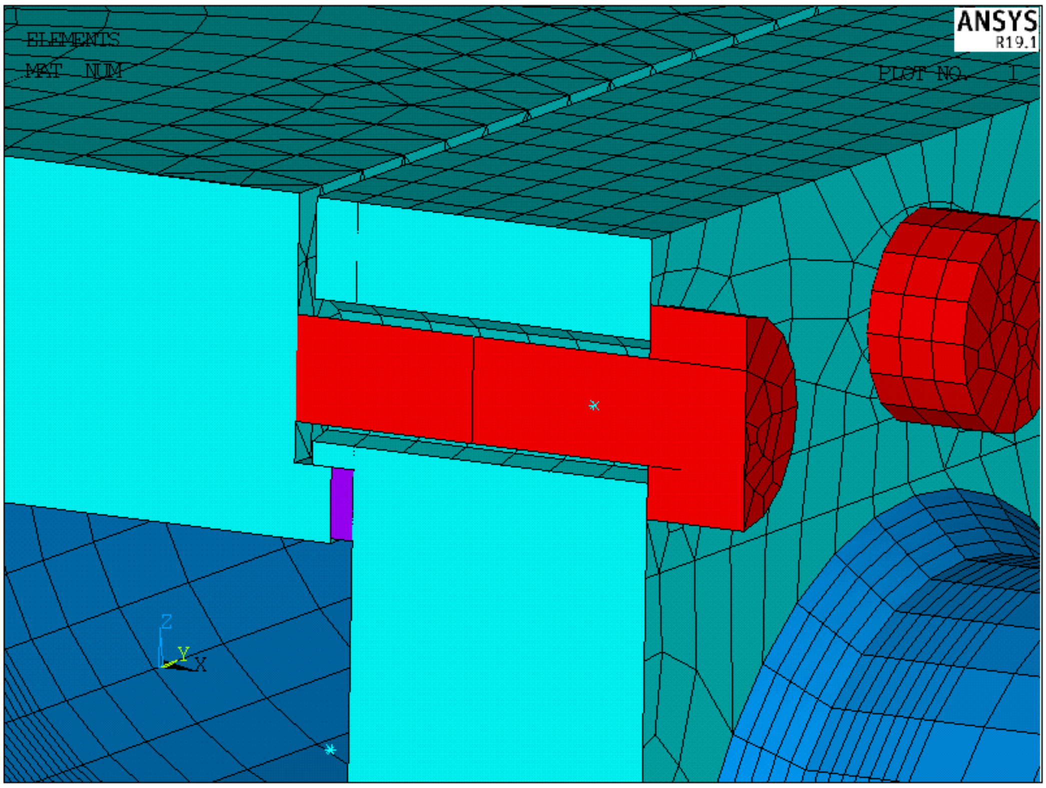

Figure 6: Gasket and head locking

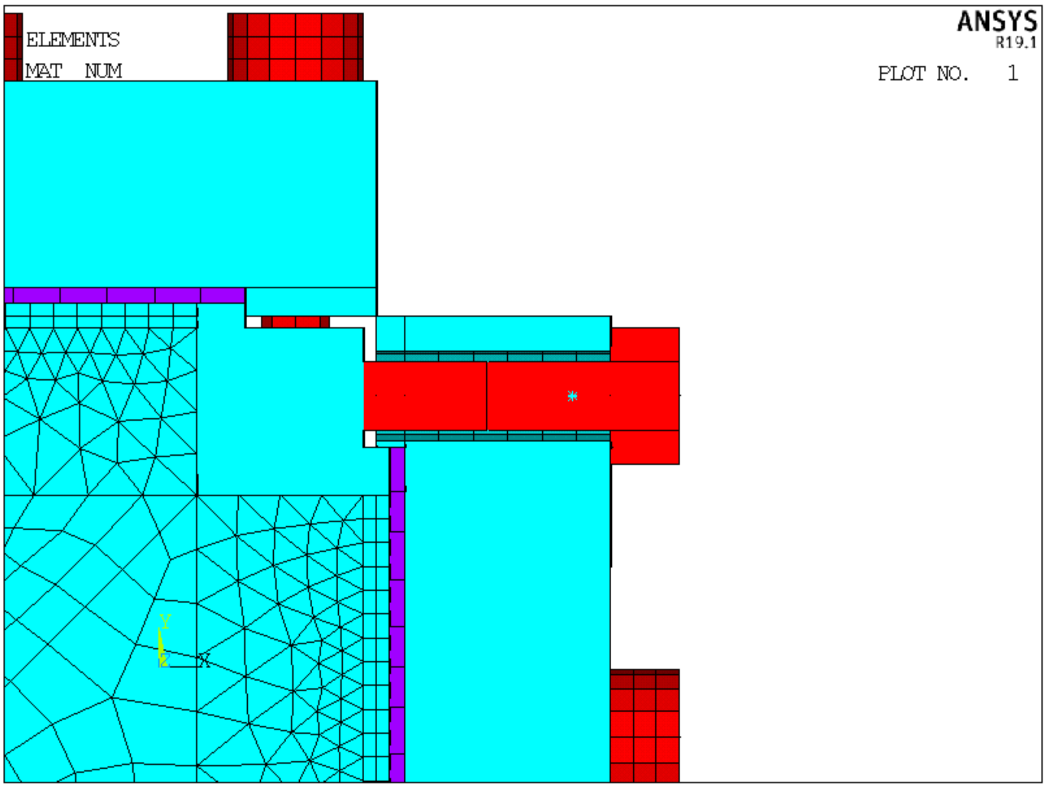

Figure 7: Gasket and girder locking

The head locking and the girder locking are modelled without gap and a linear gasket is modelled with a young modulus Eg = 4000 MPa (in compressive condition). This assumption is checked in [8].

3.3. Boundary conditions

Four areas on the bottom head are fixed on X, Y and Z directions in order to simulate the vertical supports.

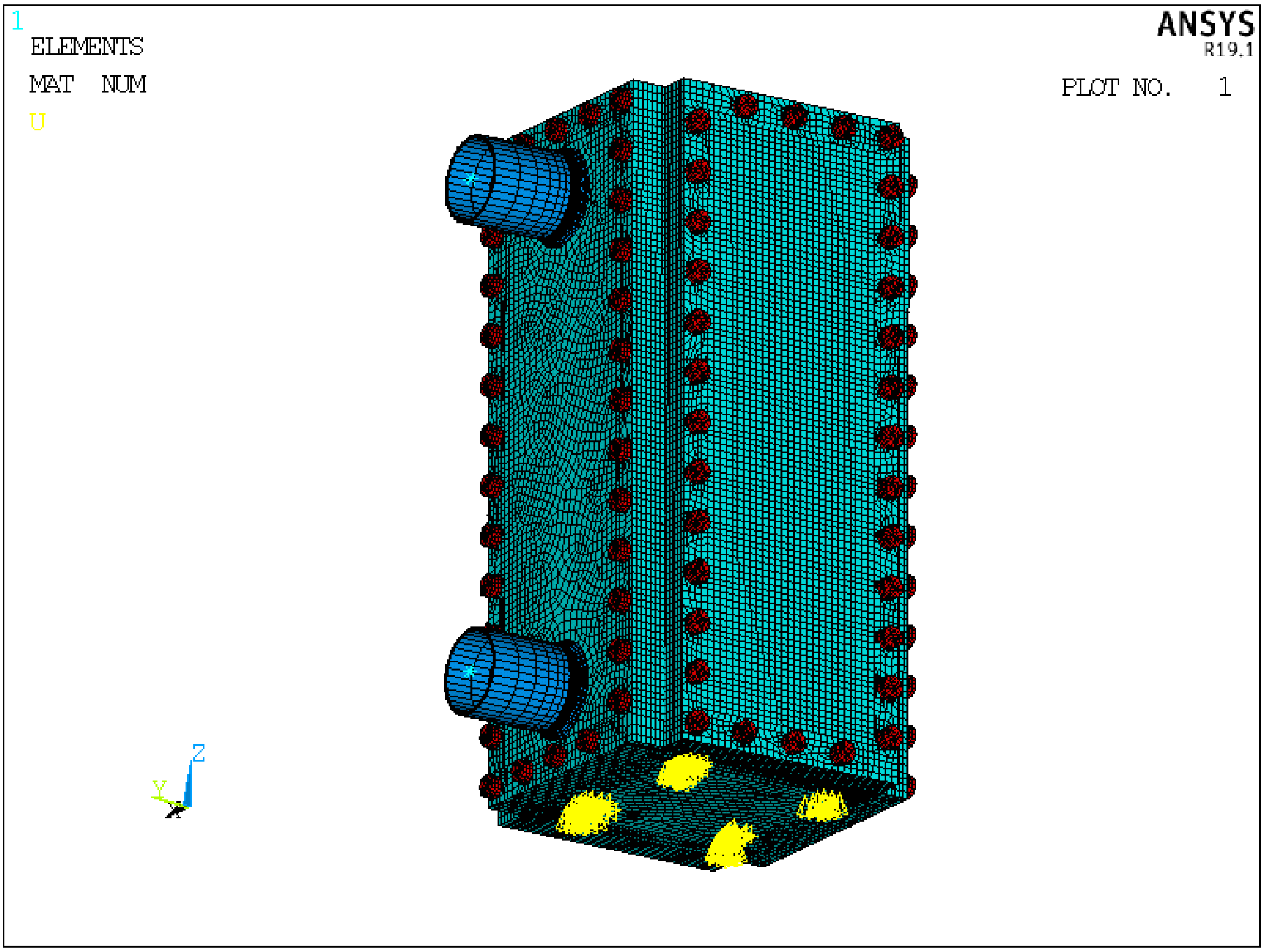

Figure 8: Boundary conditions

3.4. Loads

3.4.1. Bolts

The minimal bolt load value is then implemented in the finite elements model using the "pretension section" command of ANSYS (*Figure 9*).

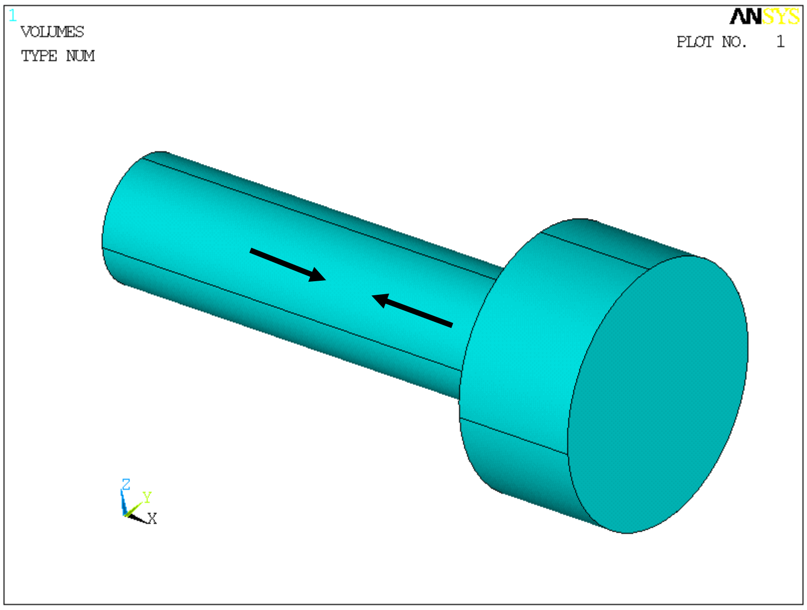

Figure 9: Representation of the pre-load

3.4.2. Design pressure

The pressure values used for the model are:

- Side A: 1.06 MPa
- Side B: 1.06 MPa

This pressure is applied as a surface load on the pressurized areas presented in *Figure 10*.

The cover effect is also considered when applying the pressure in additional load of the axial nozzle loads and applied like described in next § 3.4.3.

Three sets of area pressure are defined:

- Simultaneous pressure
- Differential pressure with full pressure on side A (panels 1 – 3)
- Differential pressure with full pressure on side B (panels 2 – 4)

For the simultaneous pressure, the maximal pressure between the side A and the side B is applied on the heads (see *Figure 10*).

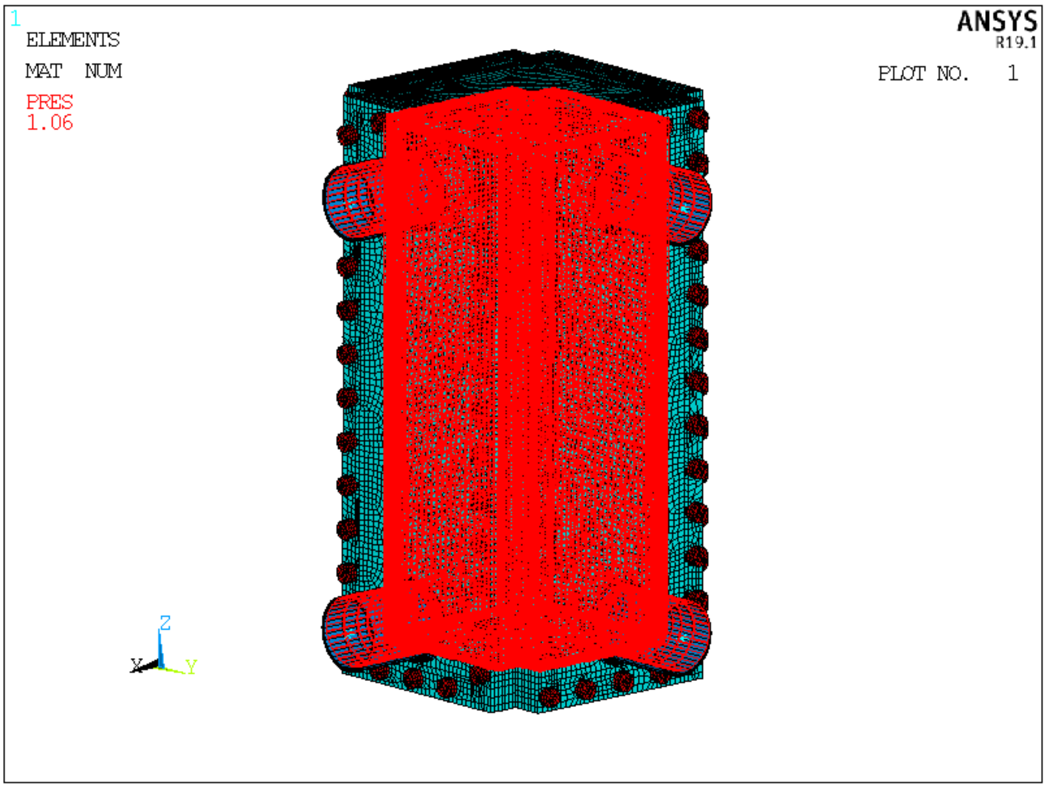

Figure 10: Simultaneous pressurized areas (MPa)

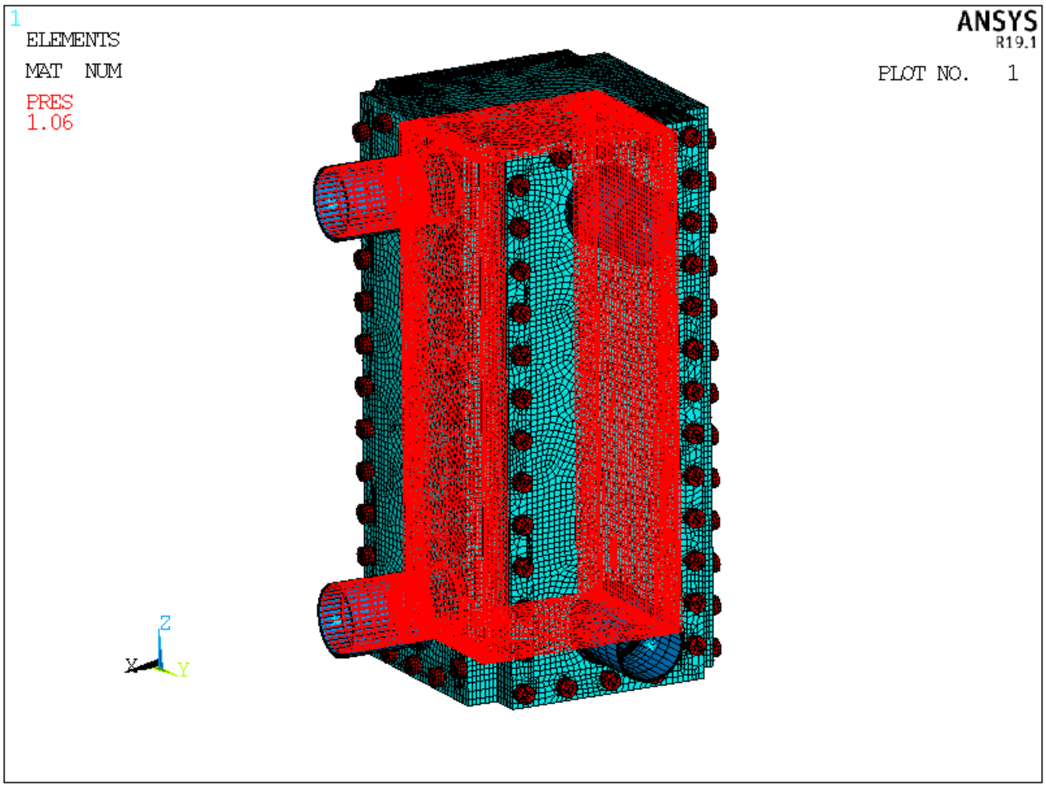

Figure 11: Differential pressurized areas side A (MPa)

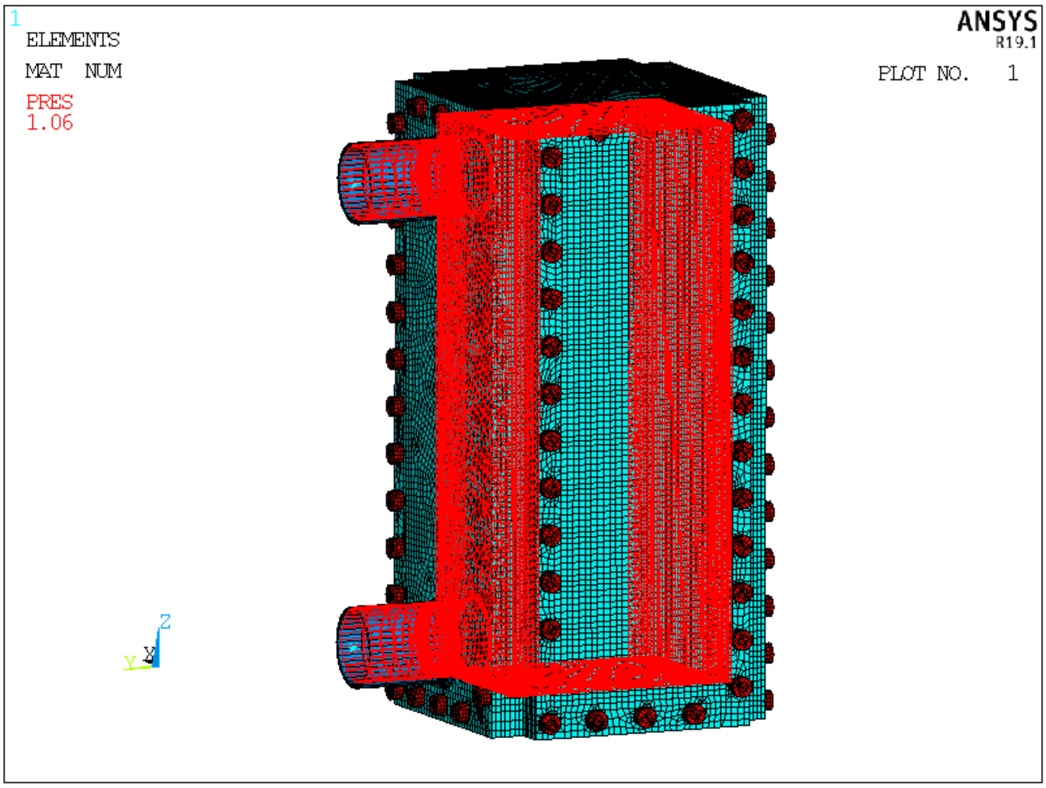

Figure 12: Differential pressurized areas side B (MPa)

3.4.3. Nozzle loads

The nozzle loads defined in § 2.5.3 are applied in the flange centre (*Figure 13*).

Forces and moments are applied on the flange centre. The nodes between the flange centre and the nozzle end are linked.

The cover effect is automatically calculated with the following equation (Di: internal diameter of the corresponding nozzle): $Fc = P \times \pi \, Di^2 / 4$

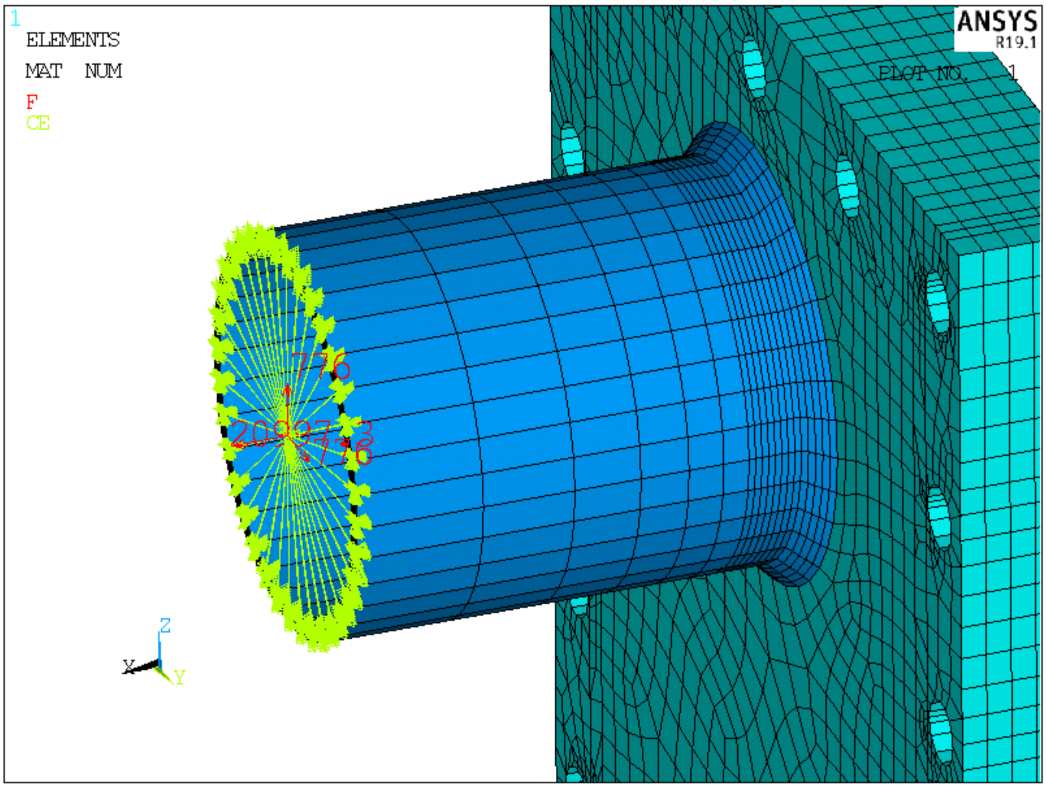

Figure 13: Cover effect on nozzle plus force nozzle loads

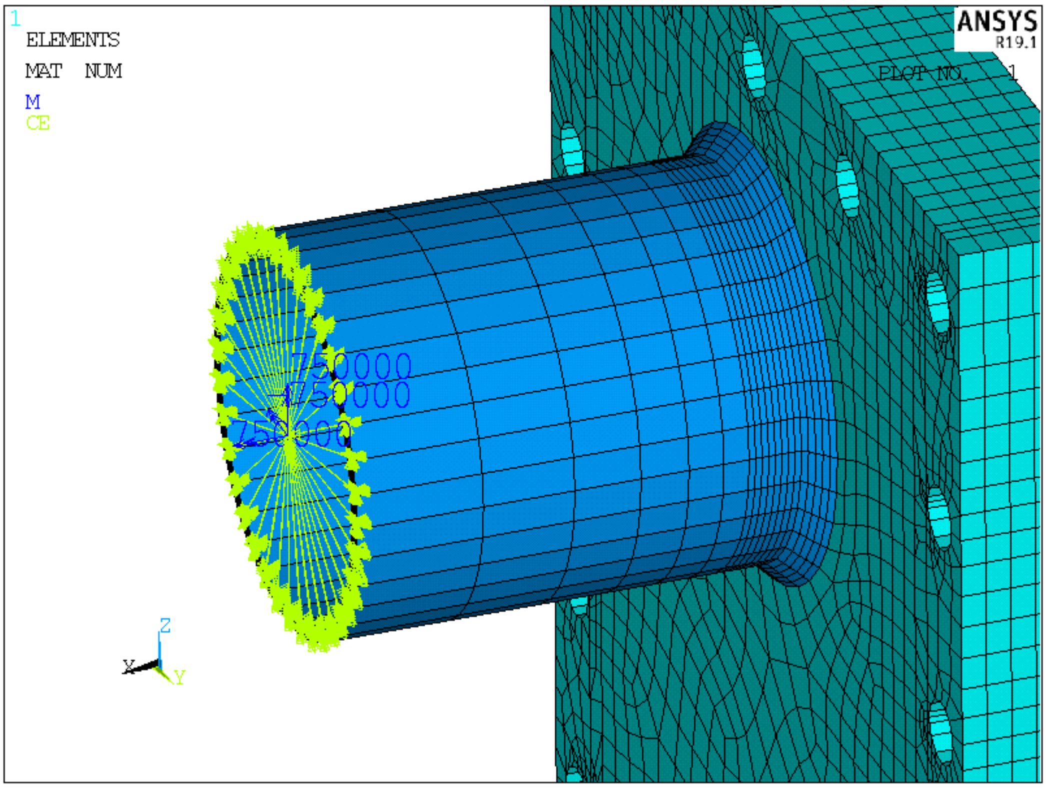

Figure 14: Moment nozzle loads

4. RESULTS

The next figures represent the stress distribution (Von Mises stress in MPa) throughout the Compabloc exchanger for the following combine loads:

- Set 1: pre-load (tightening)
- Set 2: pre-load + simultaneous pressure + all nozzles loads.
- Set 3: pre-load + differential pressure panels 1 – 3 + nozzle loads panels 1 - 3.
- Set 4: pre-load + differential pressure panels 2 – 4 + nozzle loads panels 2 - 4.

For all figures with the Von Mises distribution, the maximum value of the stress legend is adjusted to the criterion membrane + bending value 1.5 S of the analysis material (177 MPa for steel SA-516 gr60N). Thus, the stresses greater than the criterion appear in grey in the pictures. The maximal panel peak stresses are along the locking between panels and heads and between panels and girders. These high peak stresses are due to numerical issues of the contact with coarse mesh and are not taken into account in this analysis.

In order to verify the criteria, we define a path through thickness in the maximal stress area (more explanation is detailed in figures presented below).

4.1. Stress distribution

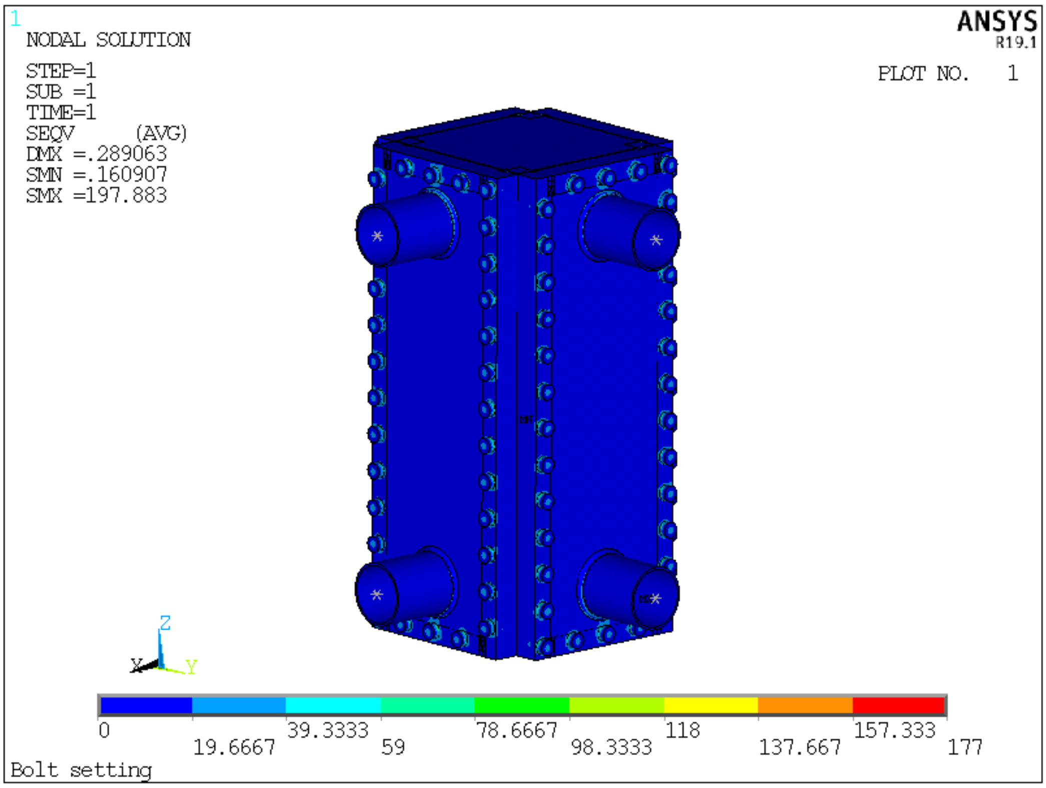

Figure 15: Stress distribution tightening (MPa)

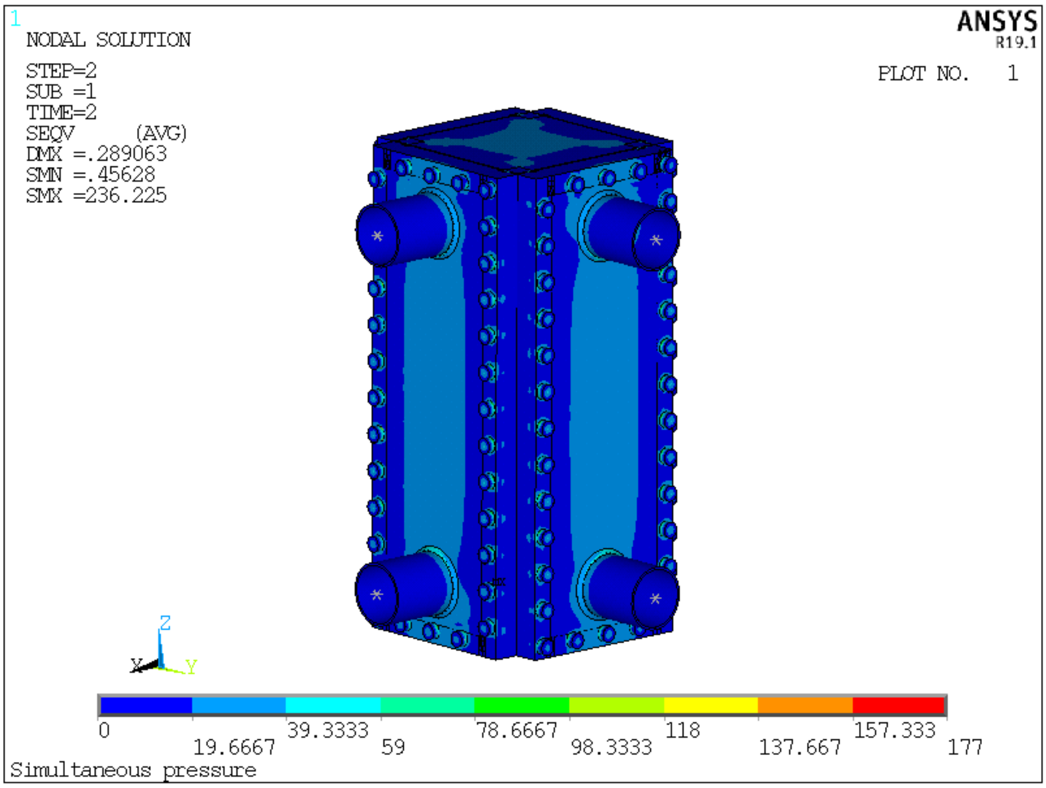

Figure 16: Stress distribution simultaneous pressure (MPa)

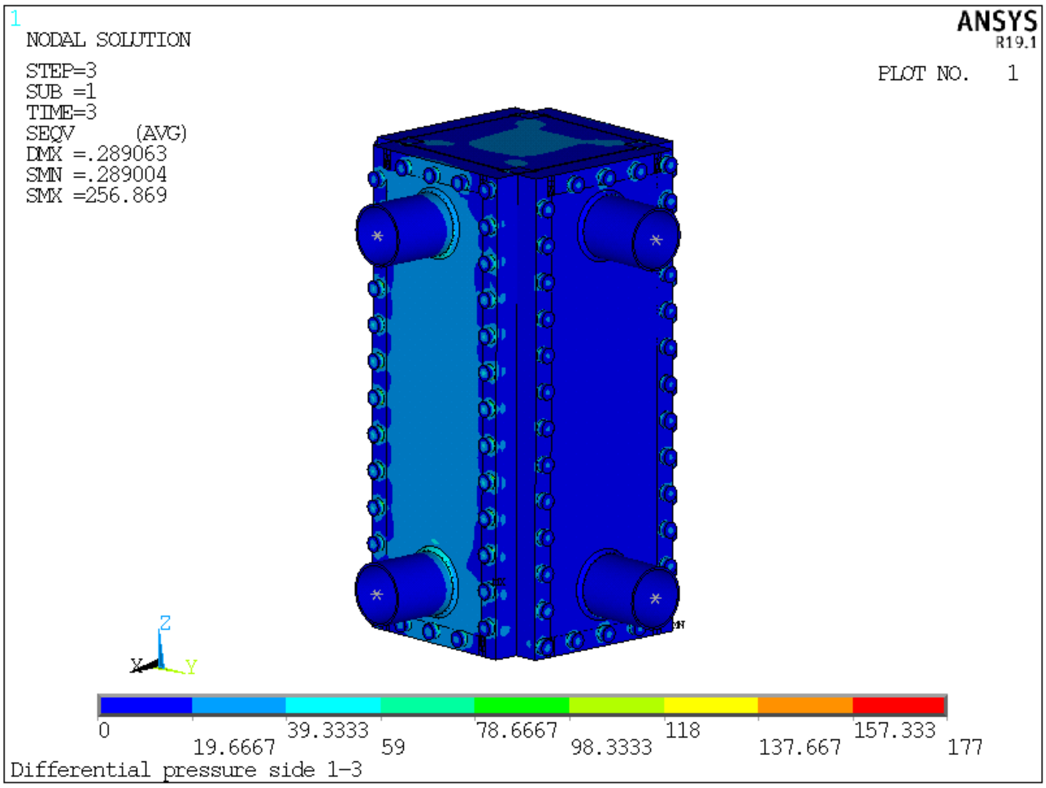

Figure 17: Stress distribution differential pressure side A (MPa)

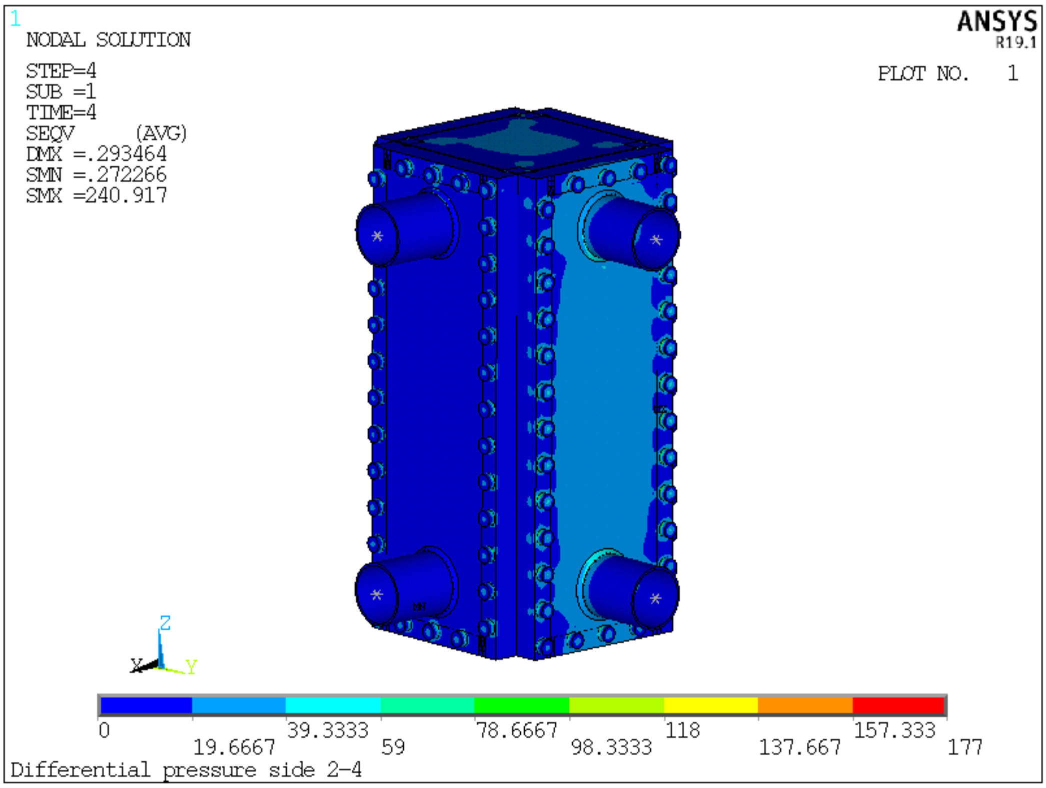

Figure 18: Stress distribution differential pressure side B (MPa)

On the previous figures, the stress distributions show that the set 3 (differential pressure side A) is the most severe conditions for panels 1- 3 and its nozzles, and the set 4 (differential pressure side B) is the most severe conditions for panels 2- 4 and its nozzles. The following post processing focus on the two sets for the corresponding panels and nozzles.

For each panel a global path is defined at the maximal solicited area (automatically check by the ANSYS software). This path is often at the central position of panel (Path global panel).
For each modelled nozzle three paths are defined in the maximal zone on the corresponding circumference (automating check by the ANSYS software):

- Path global panel around nozzle: circumference at the link between the nozzle and panel (local zone but considering in conservative way like a global zone).
- Path global nozzle: circumference on nozzle at a distance √Rt of the link with the weld
- Path local nozzle: circumference on nozzle at the link with the weld

4.2. Von Mises and 4S distributions per panel

4.2.1. Panel 1

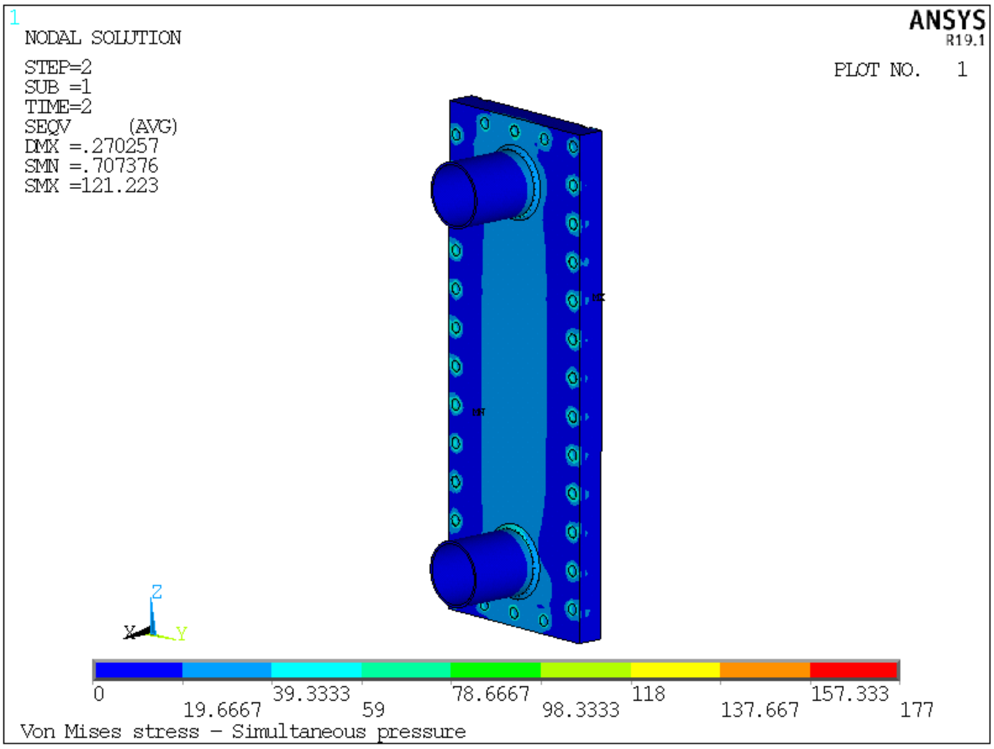

Figure 19: Von Mises stress - Simultaneous pressure

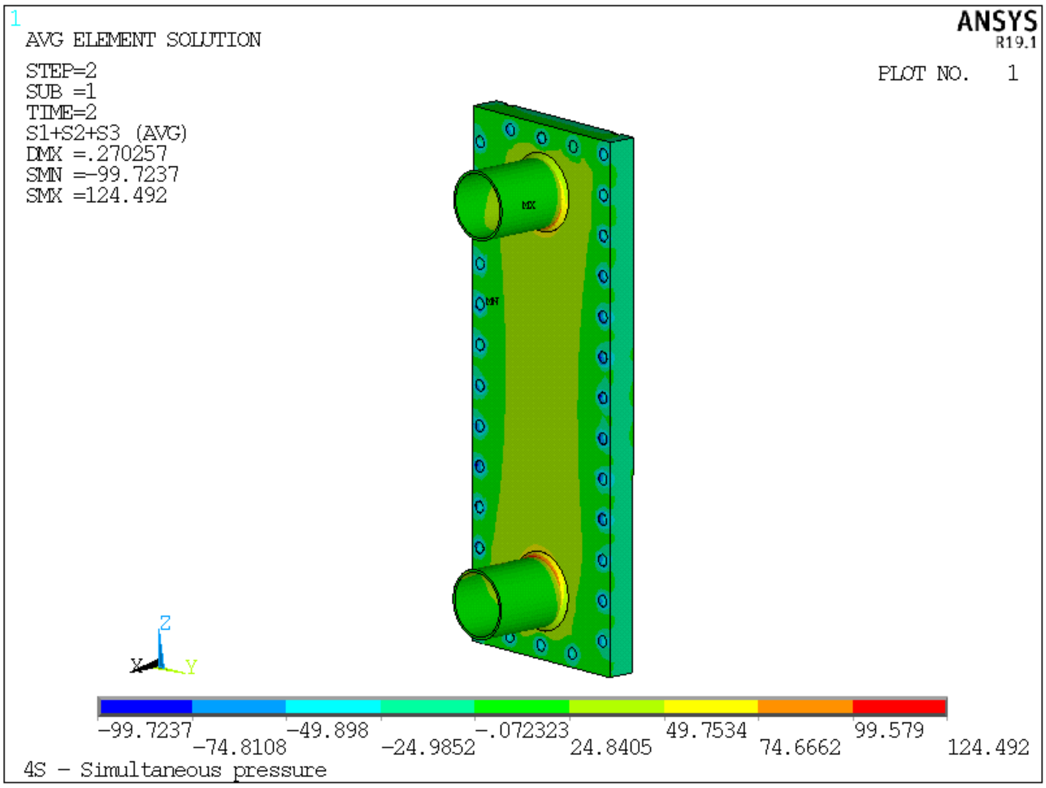

Figure 20: Sum of Principal stresses S1 + S 2 +S 3 - Simultaneous pressure

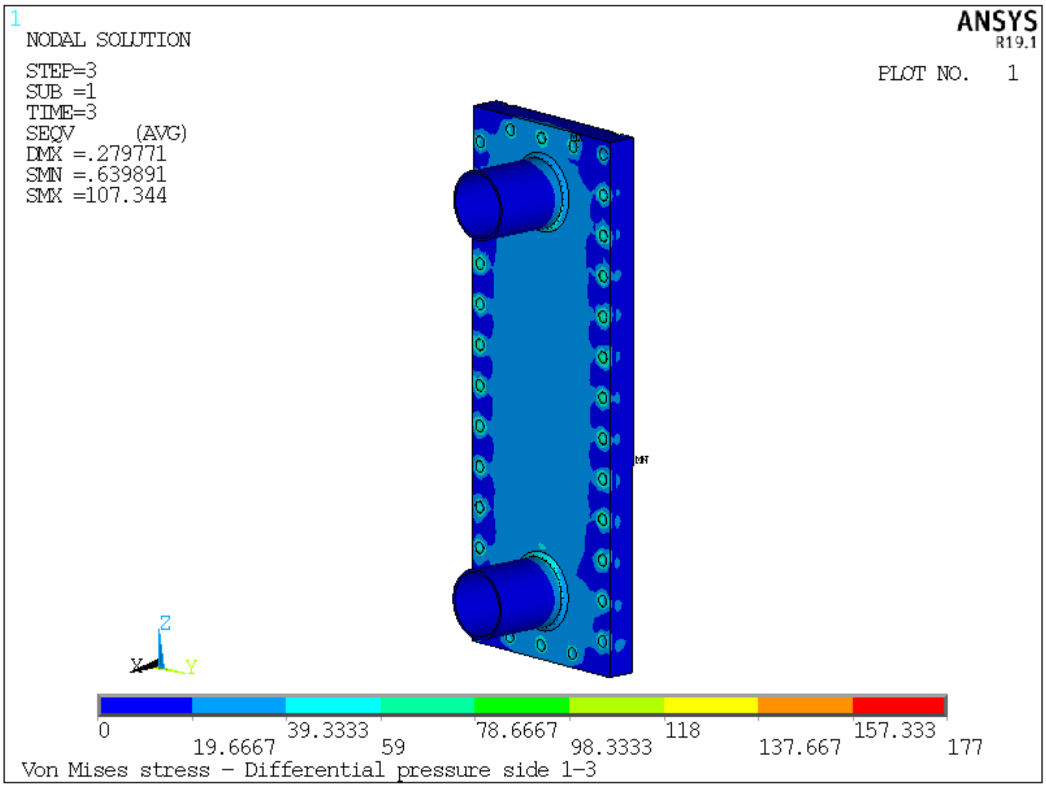

Figure 21: Von Mises stress - differential pressure side A

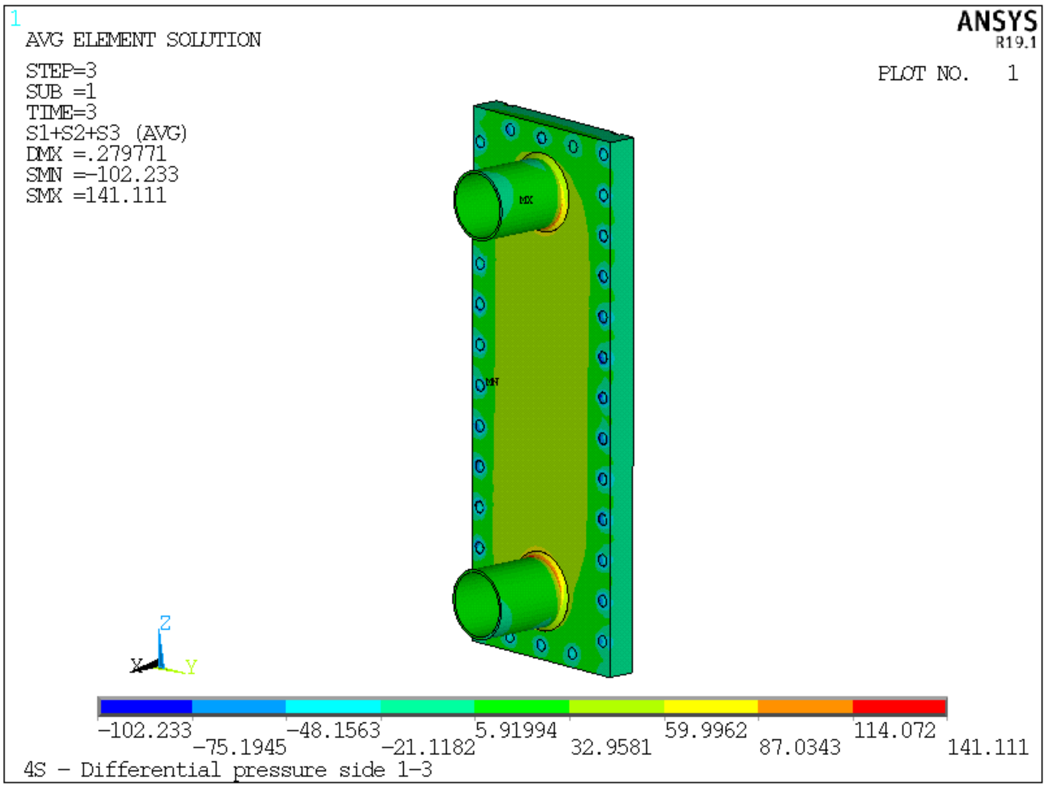

Figure 22: Sum of Principal stresses S1 + S 2 +S 3 - differential pressure side A

4.2.2. Panel 3

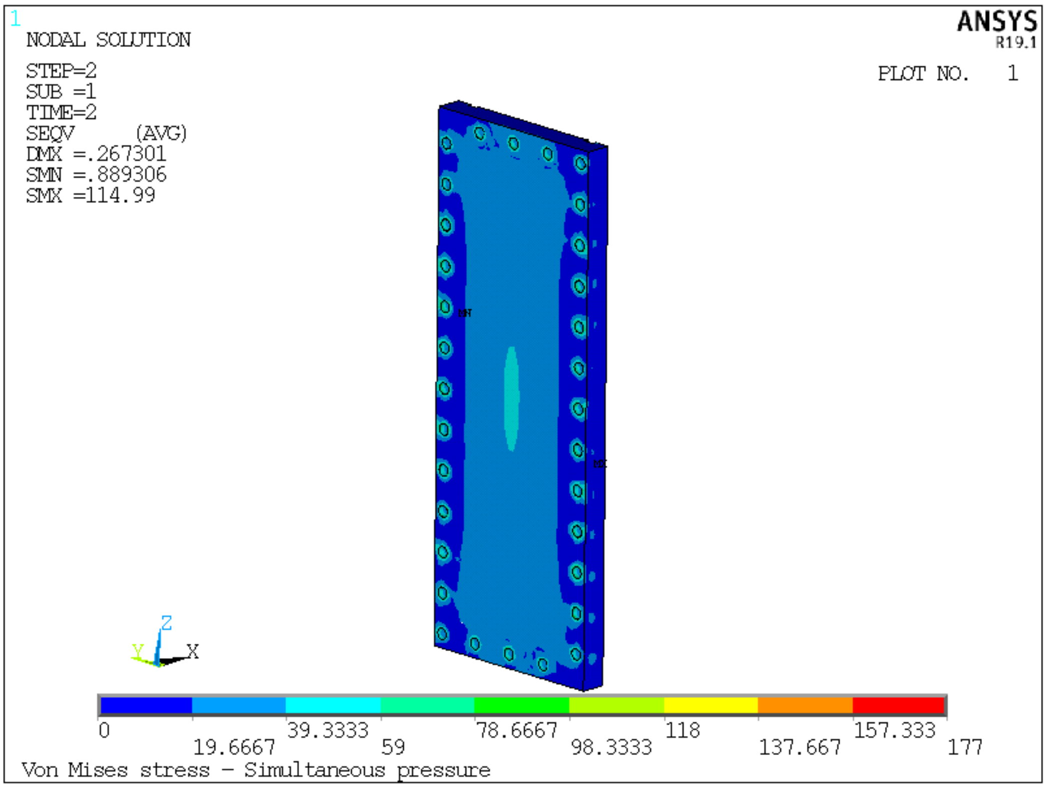

Figure 23: Von Mises stress - Simultaneous pressure

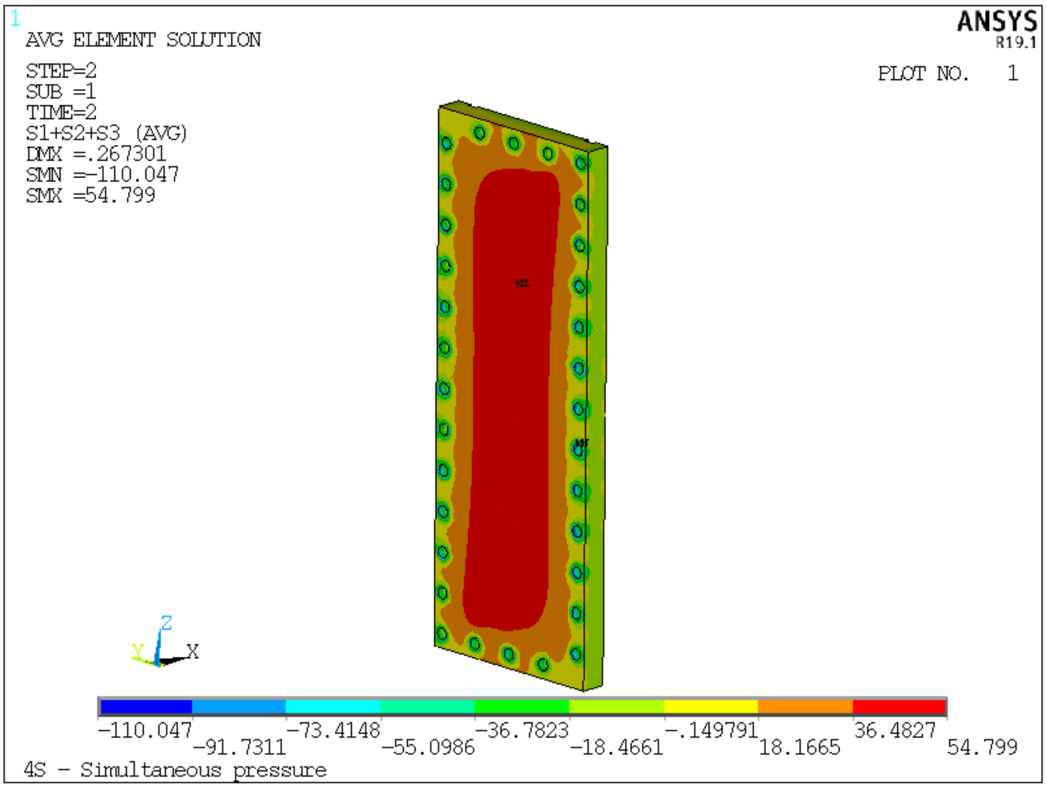

Figure 24: Sum of Principal stresses S1 + S 2 +S 3 - Simultaneous pressure

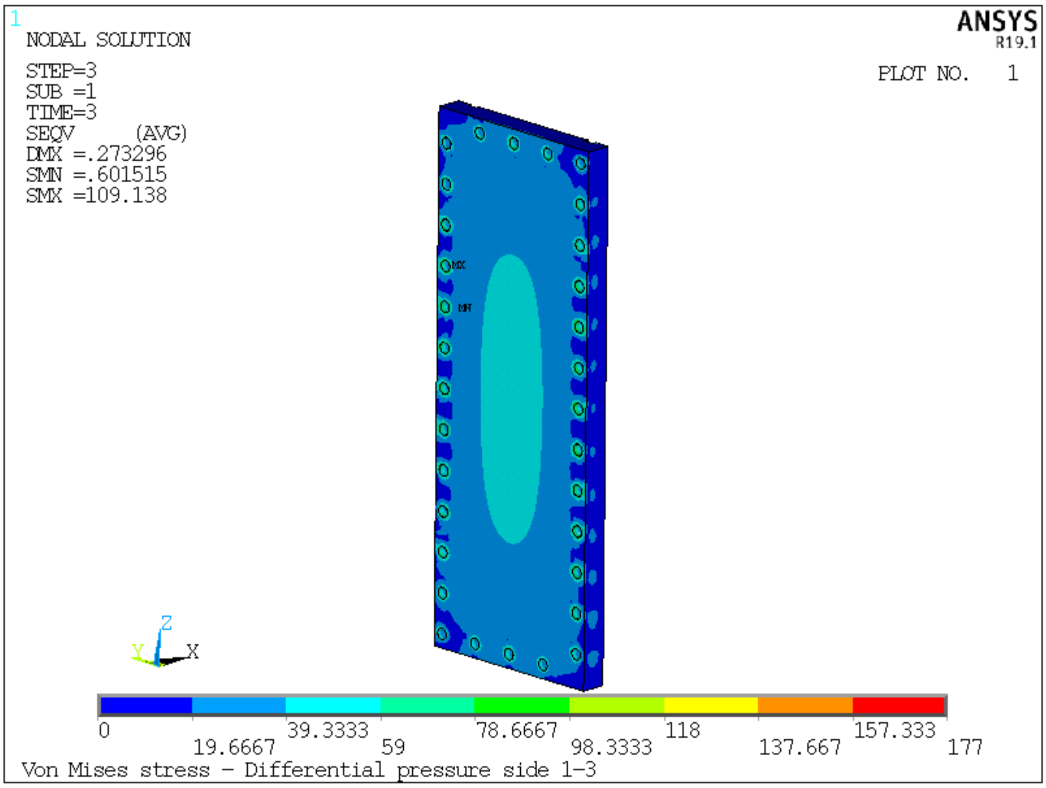

Figure 25: Von Mises stress - differential pressure side A

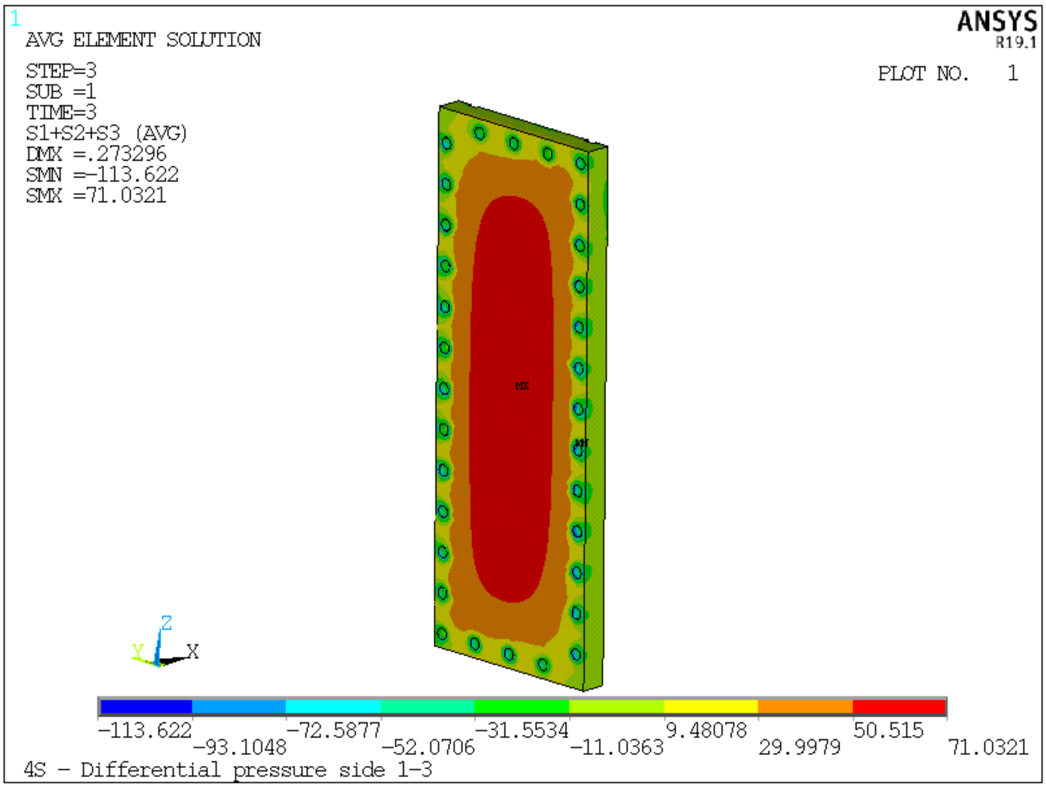

Figure 26: Sum of Principal stresses S1 + S 2 +S 3 - differential pressure side A

4.2.3. Panel 2

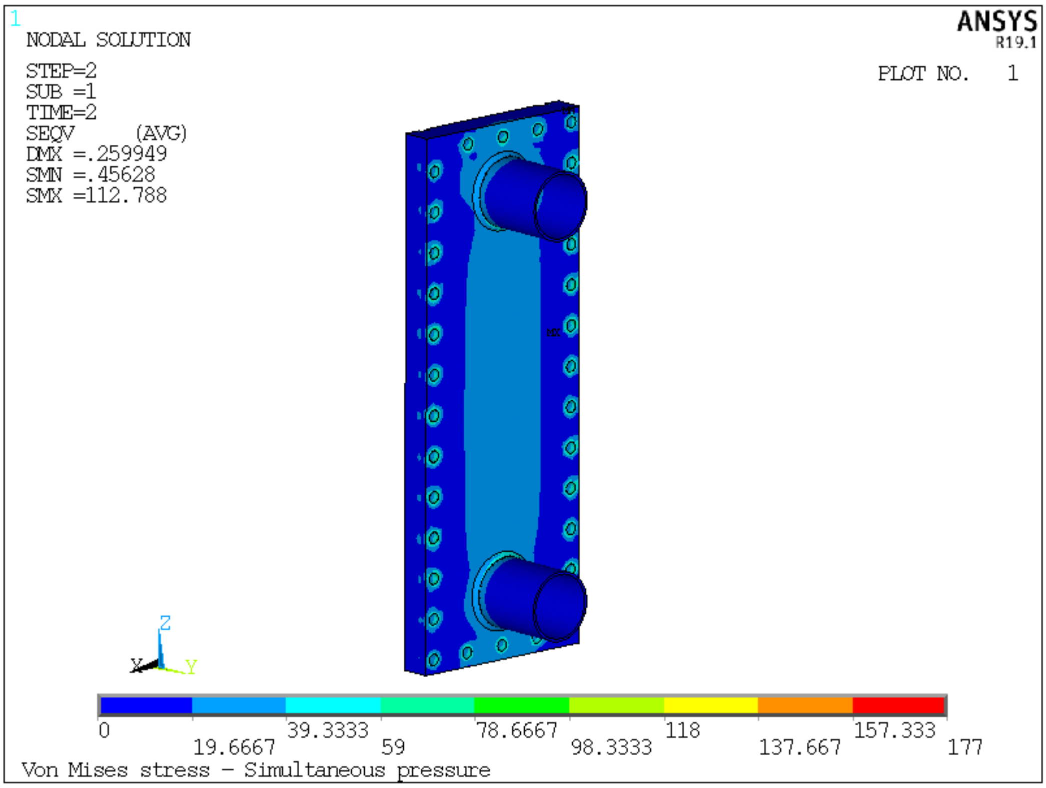

Figure 27: Von Mises stress - Simultaneous pressure

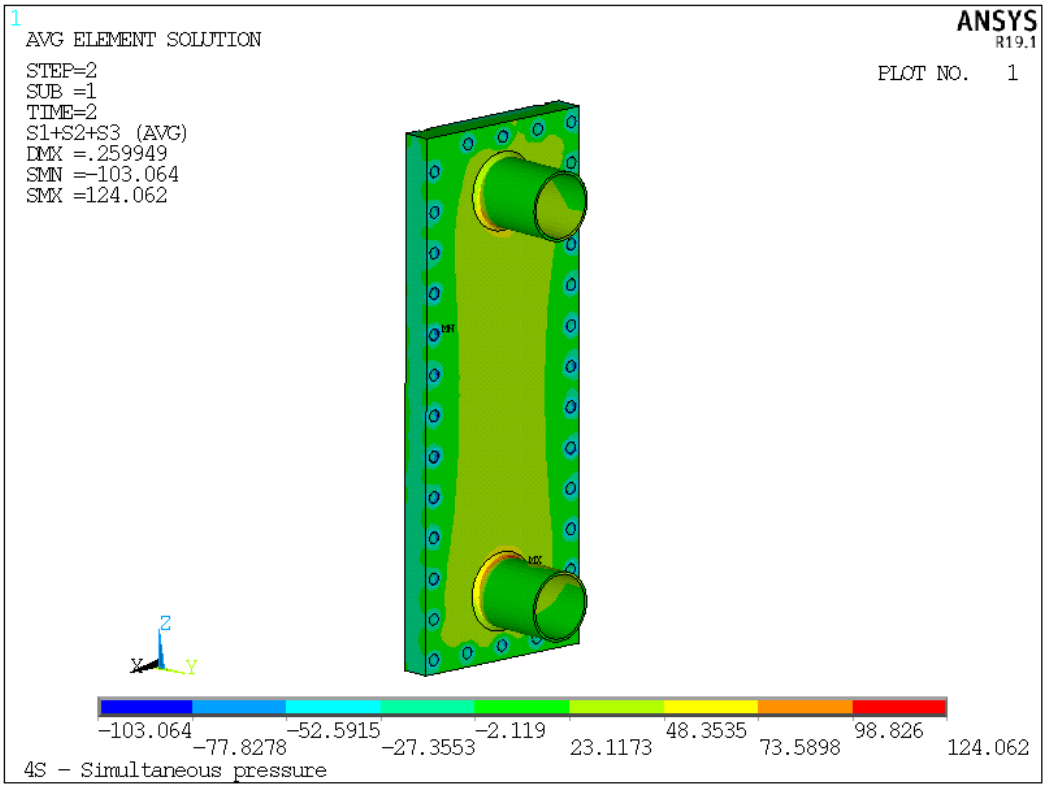

Figure 28: Sum of Principal stresses S1 + S 2 +S 3 - Simultaneous pressure

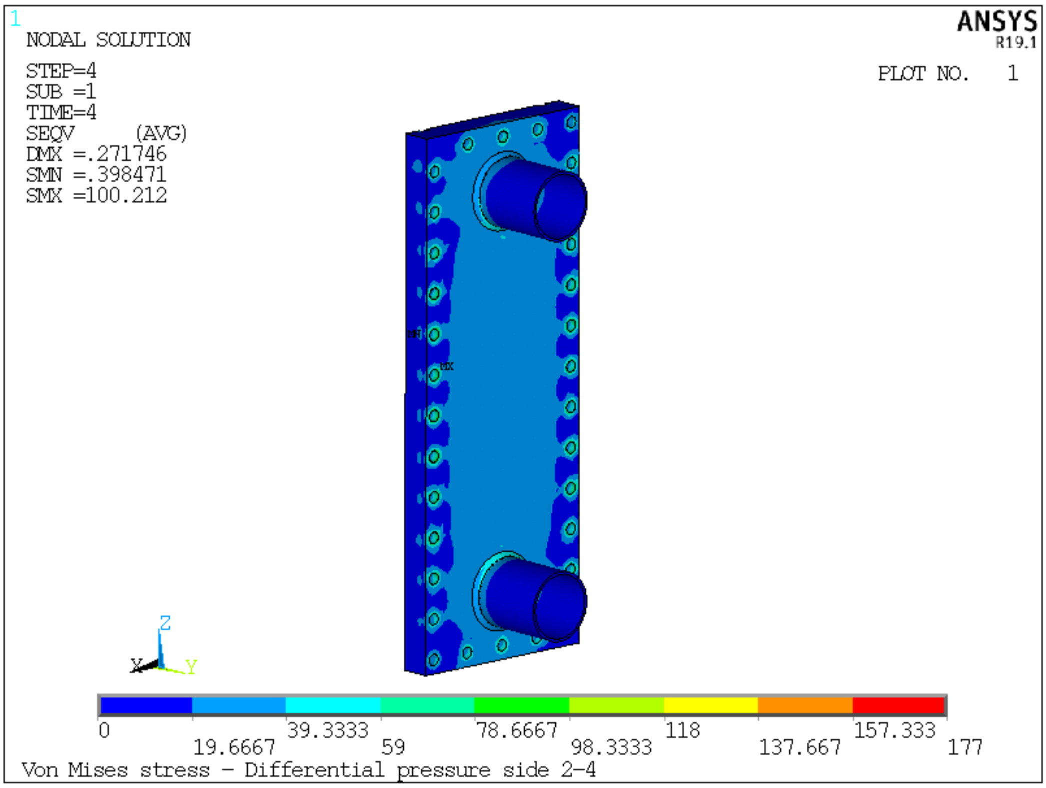

Figure 29: Von Mises stress - differential pressure side B

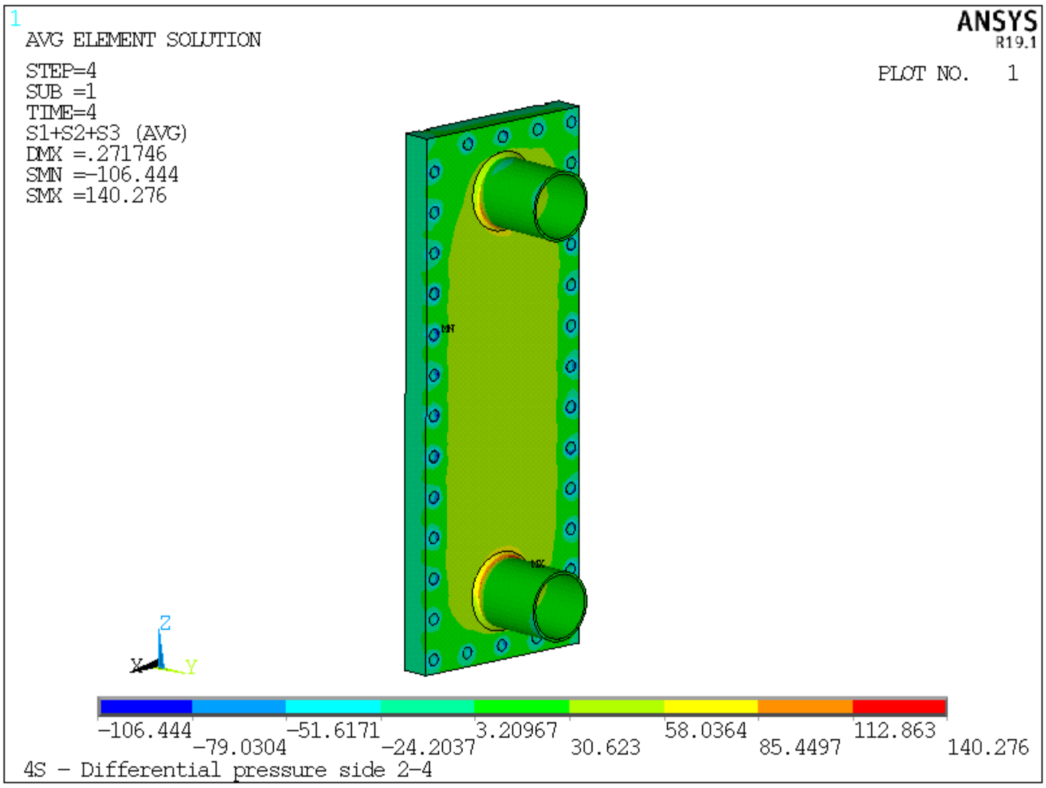

Figure 30: Sum of Principal stresses S1 + S 2 +S 3 - differential pressure side B

4.2.4. Panel 4

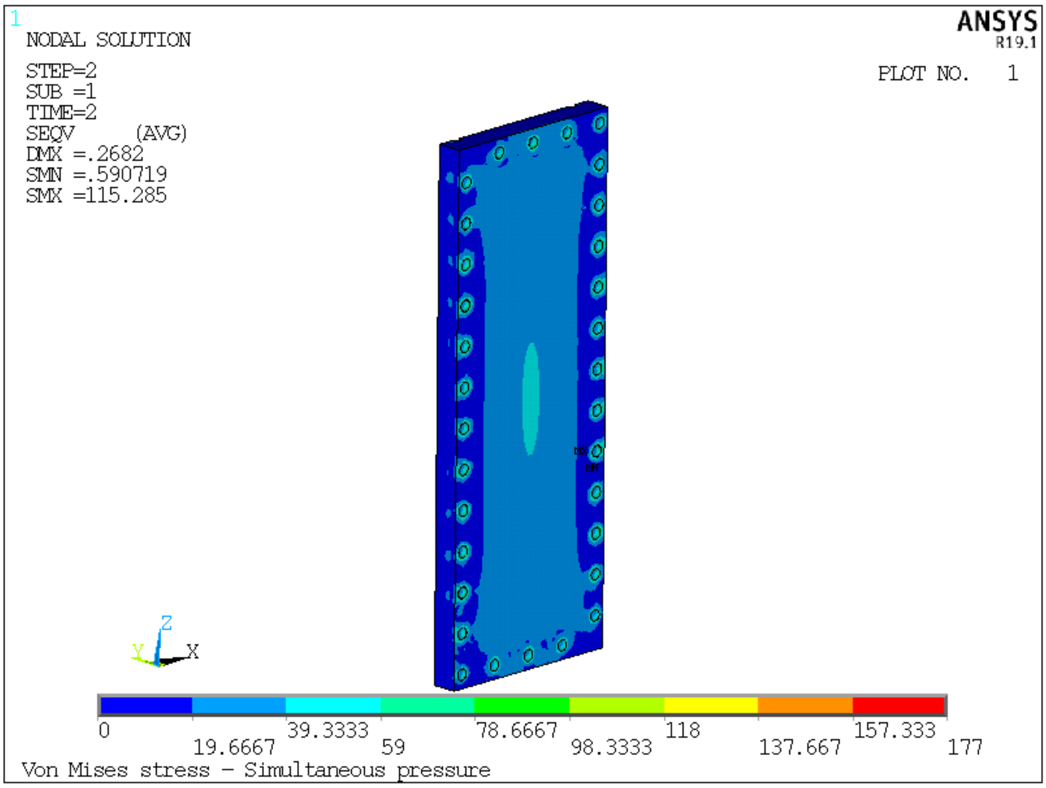

Figure 31: Von Mises stress - Simultaneous pressure

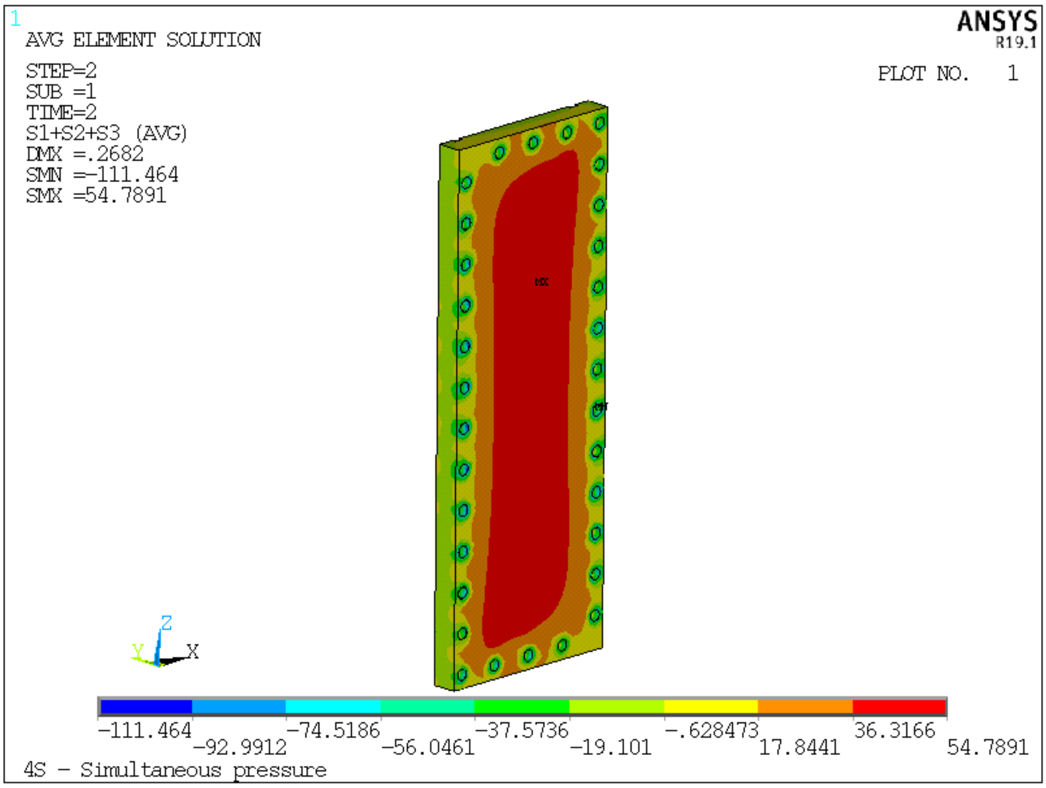

Figure 32: Sum of Principal stresses S1 + S 2 +S 3 - Simultaneous pressure

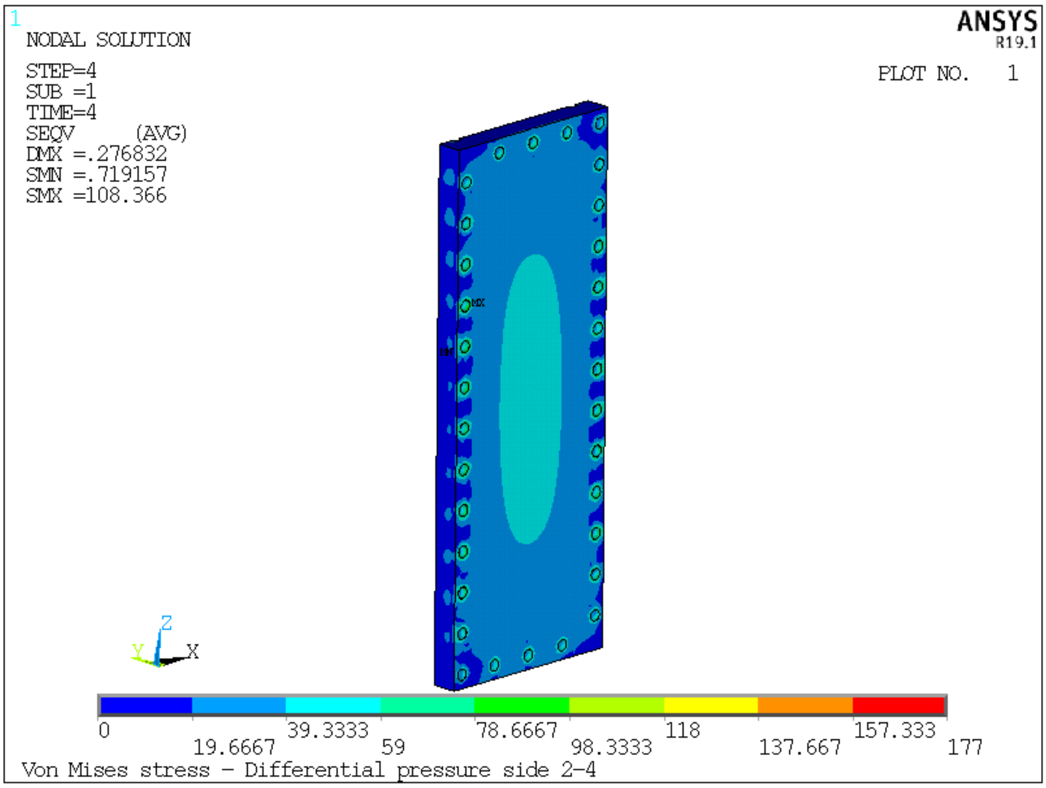

Figure 33: Von Mises stress - differential pressure side B

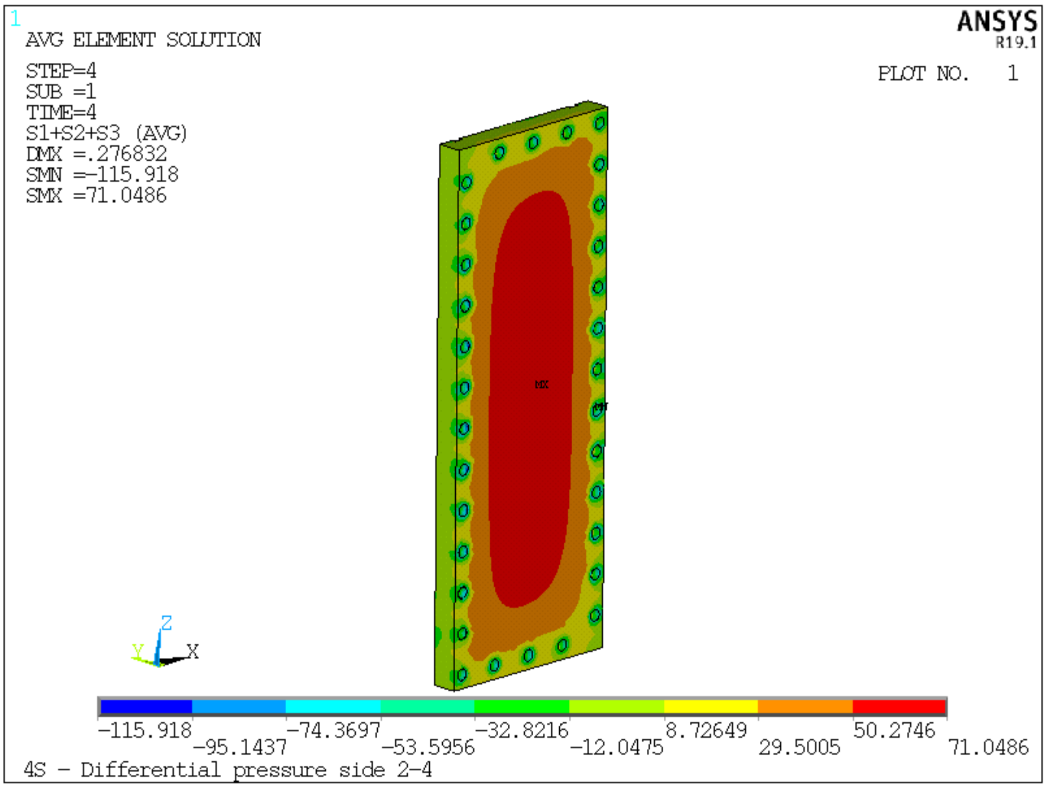

Figure 34: Sum of Principal stresses S1 + S 2 +S 3 - differential pressure side B

4.3. Paths on nozzles side 1 (differential pressure side A)

4.3.1. Panel 1

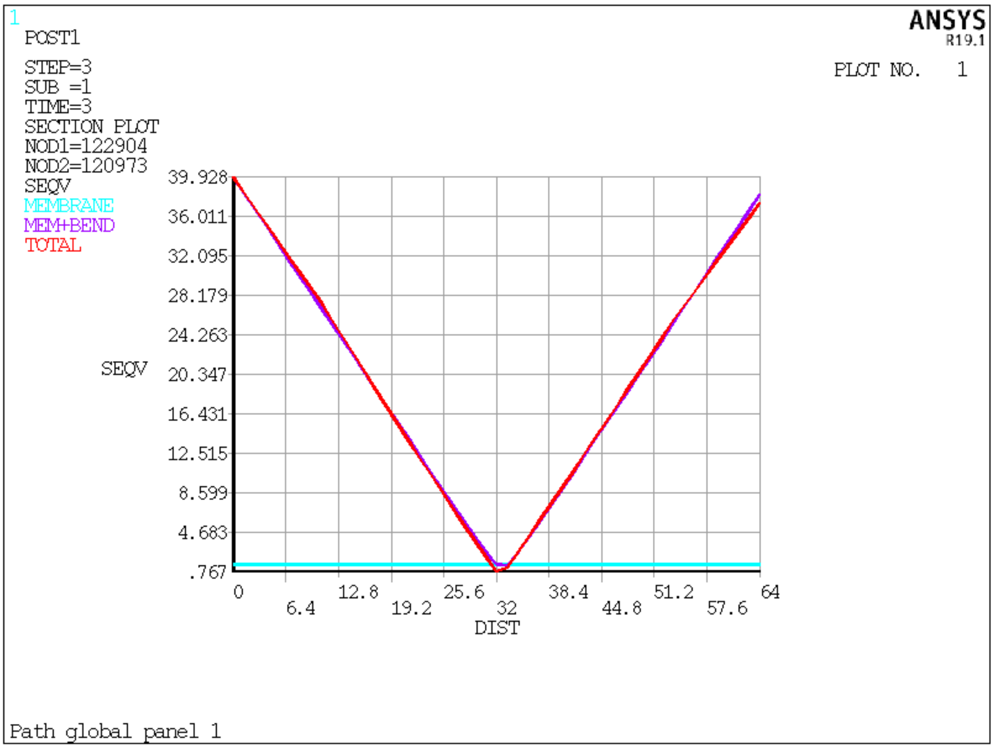

Figure 35: Maximal path of the global zone for the panel 1

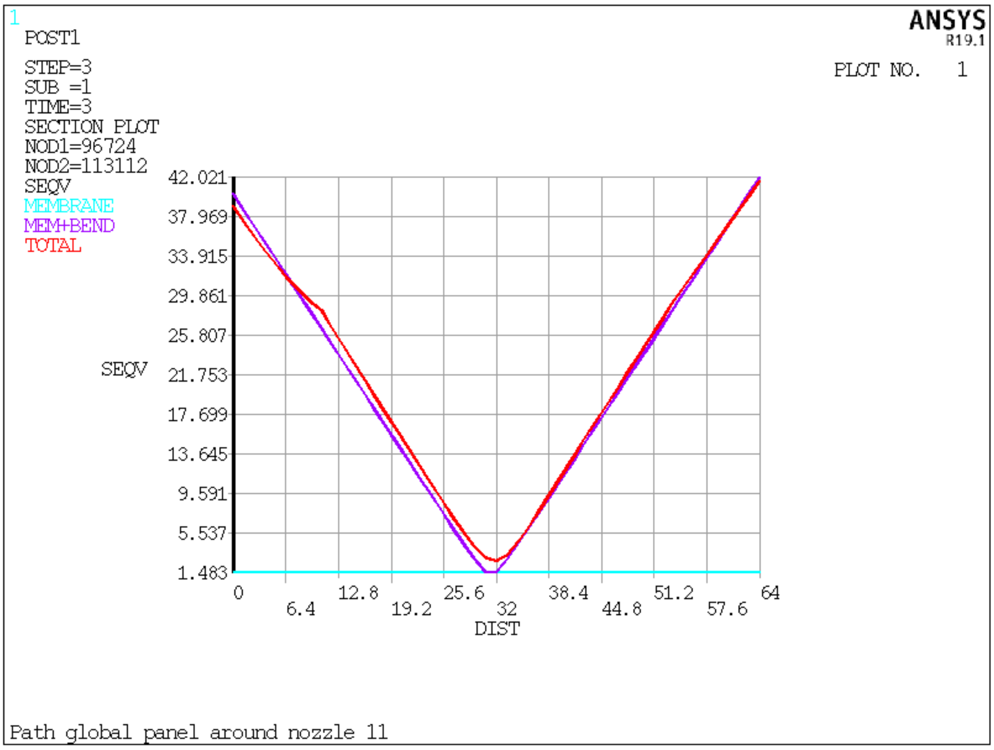

Figure 36: Maximal path of the panel 1 around the nozzle 1

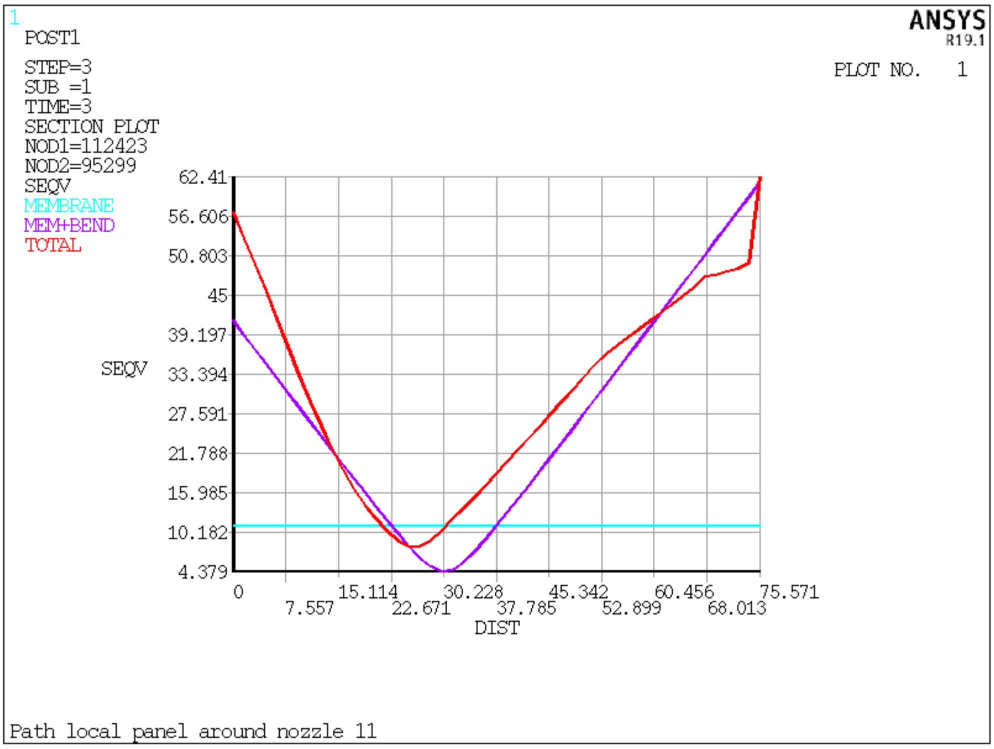

Figure 37: Maximal local path of the panel 1 around the nozzle 1

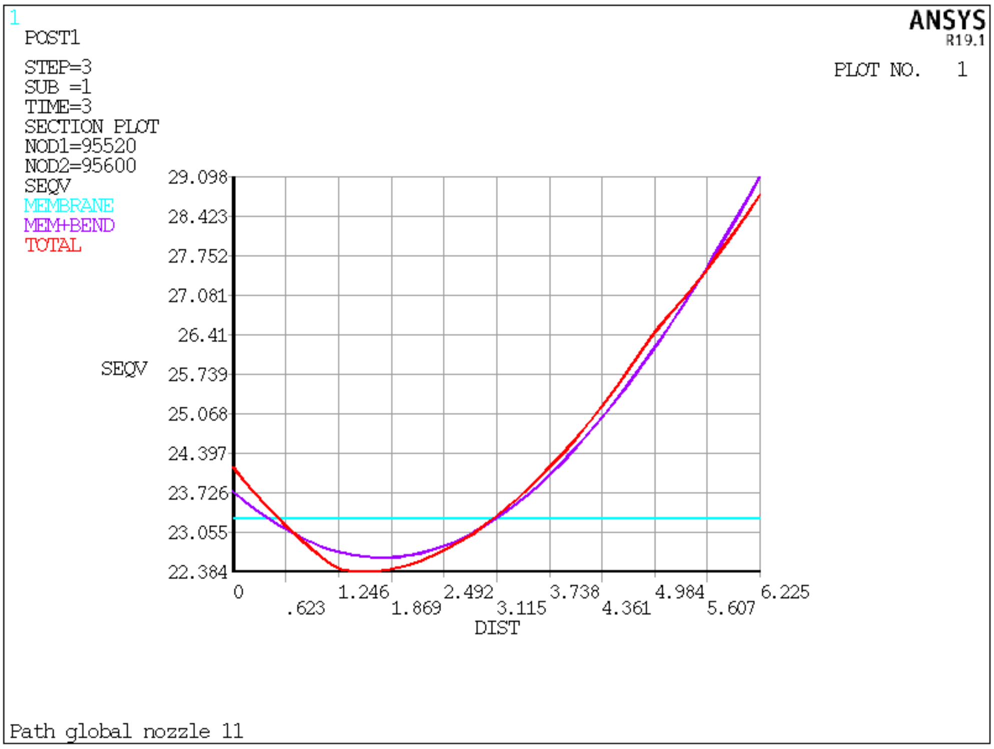

Figure 38: Maximal path of the global zone for the nozzle 1

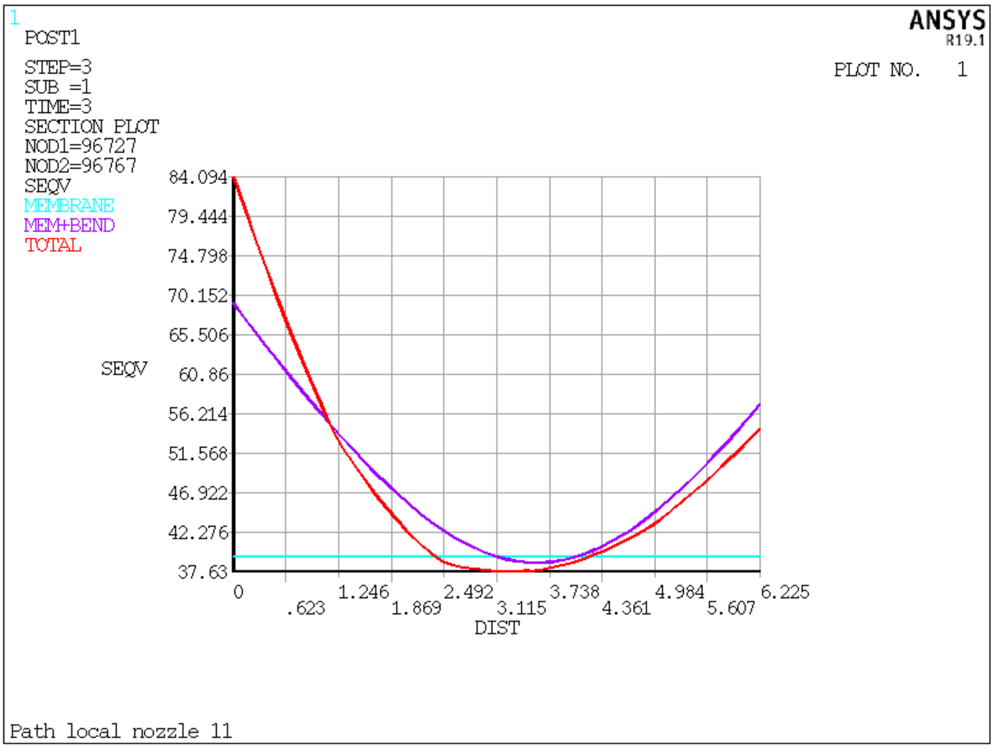

Figure 39: Maximal path of the local zone for the nozzle 1

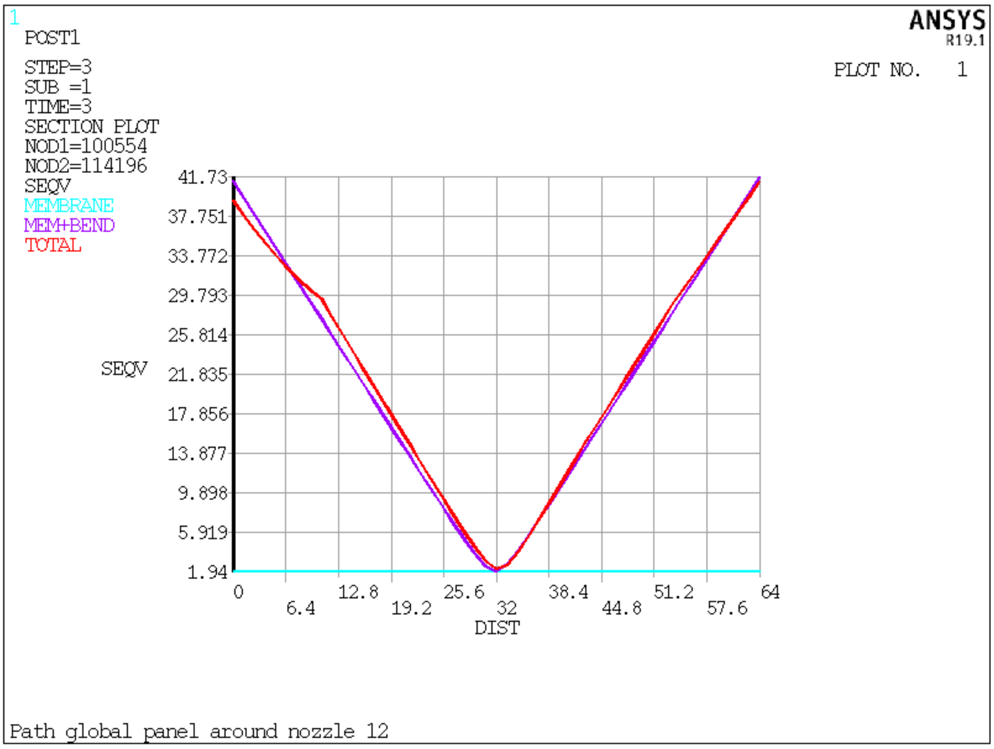

Figure 40: Maximal path of the panel 1 around the nozzle 2

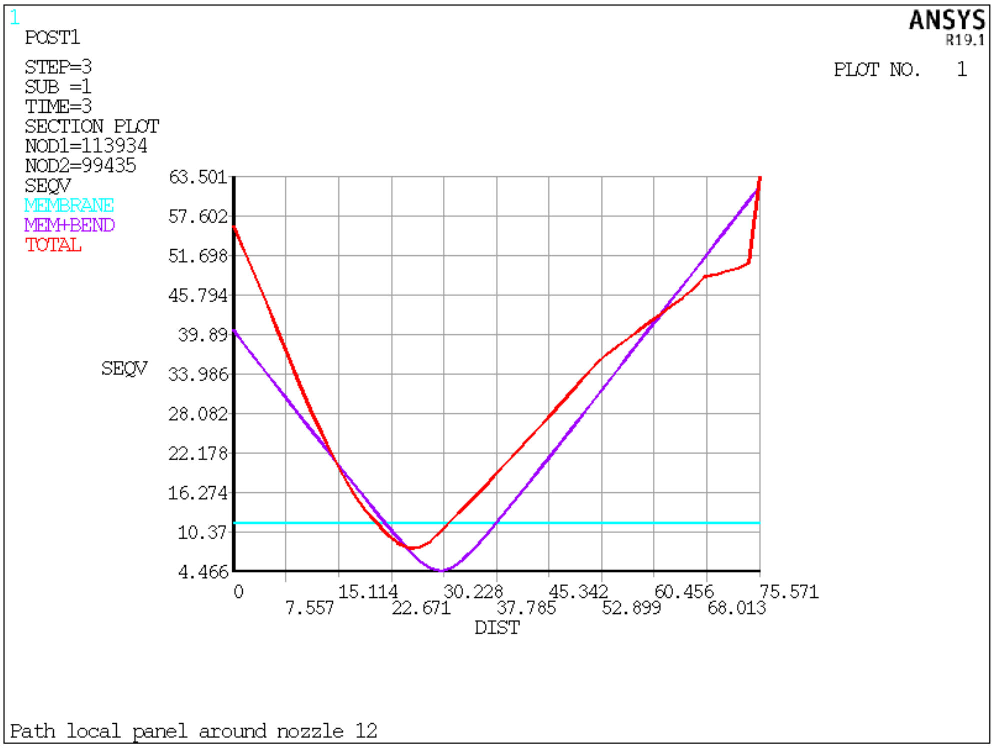

Figure 41: Maximal local path of the panel 1 around the nozzle 2

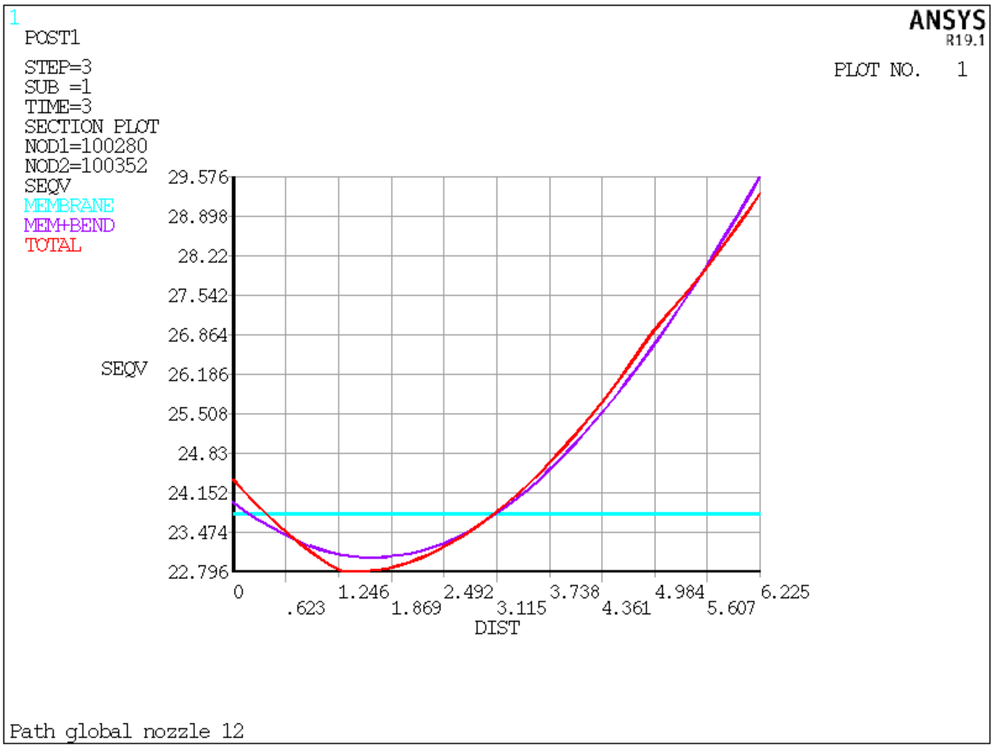

Figure 42: Maximal path of the global zone for the nozzle 2

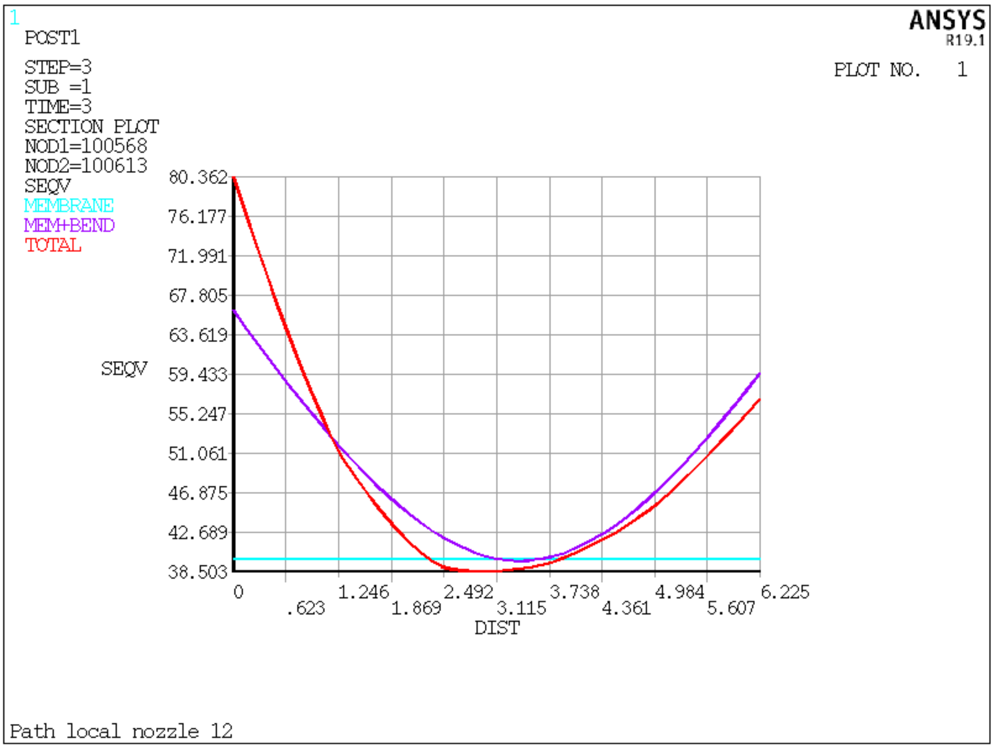

Figure 43: Maximal path of the local zone for the nozzle 2

4.3.2. Panel 3

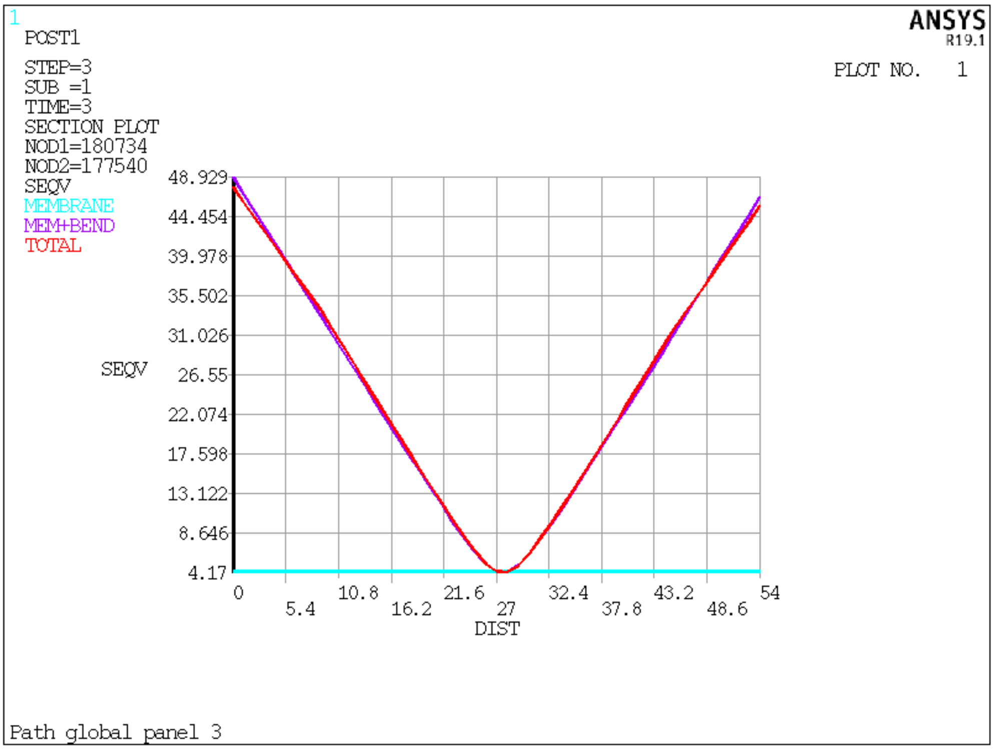

Figure 44: Maximal path of the global zone for the panel 3

4.4. Paths on nozzles side 2 (differential pressure side B)

4.4.1. Panel 2

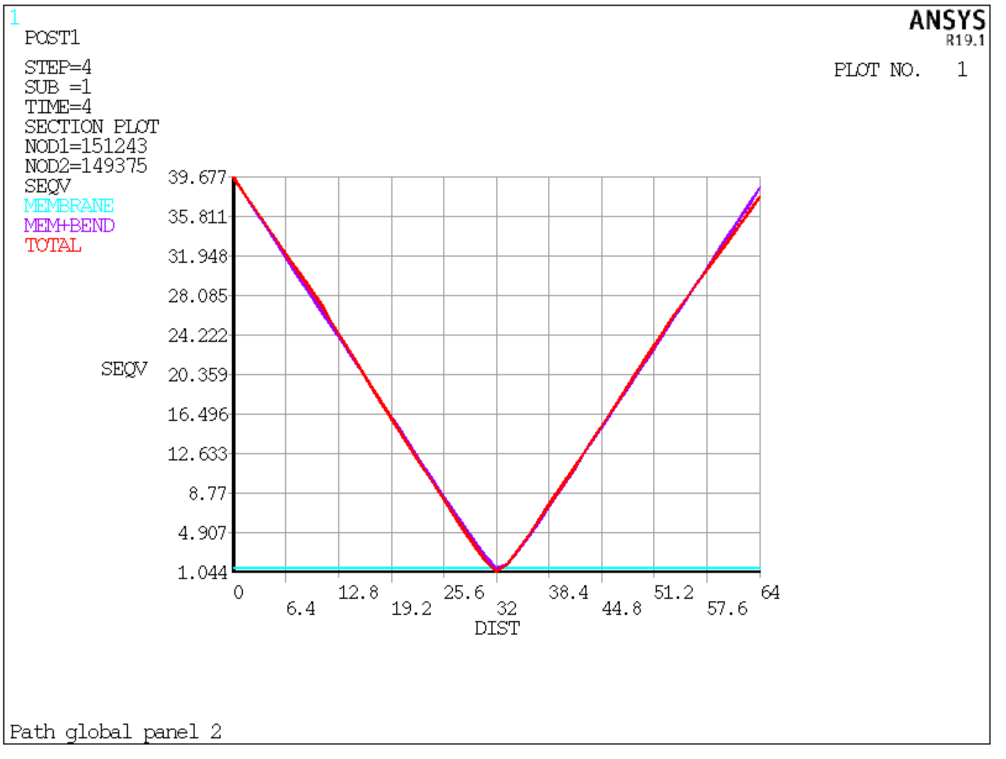

Figure 45: Maximal path of the global zone for the panel 2

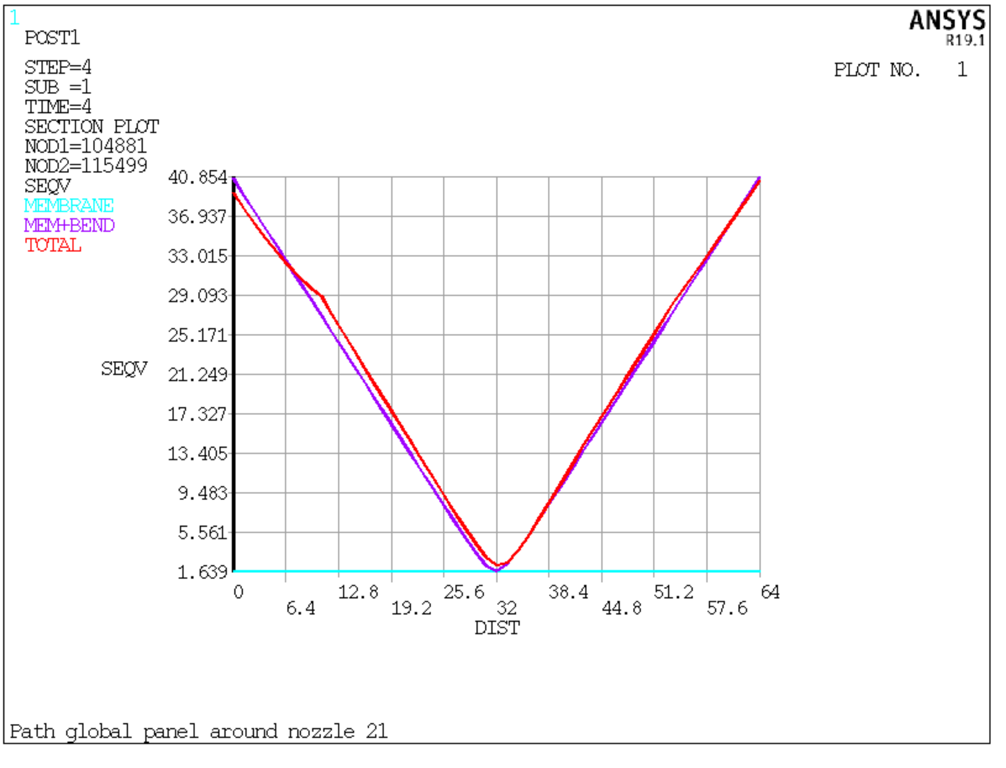

Figure 46: Maximal path of the panel 2 around the nozzle 1

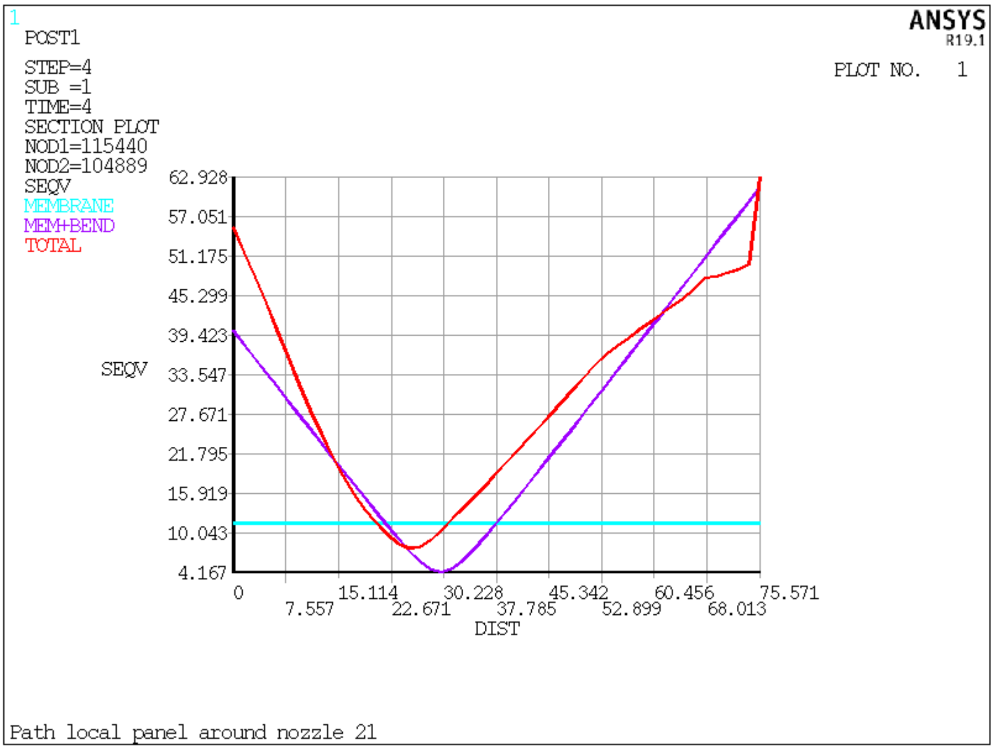

Figure 47: Maximal local path of the panel 2 around the nozzle 1

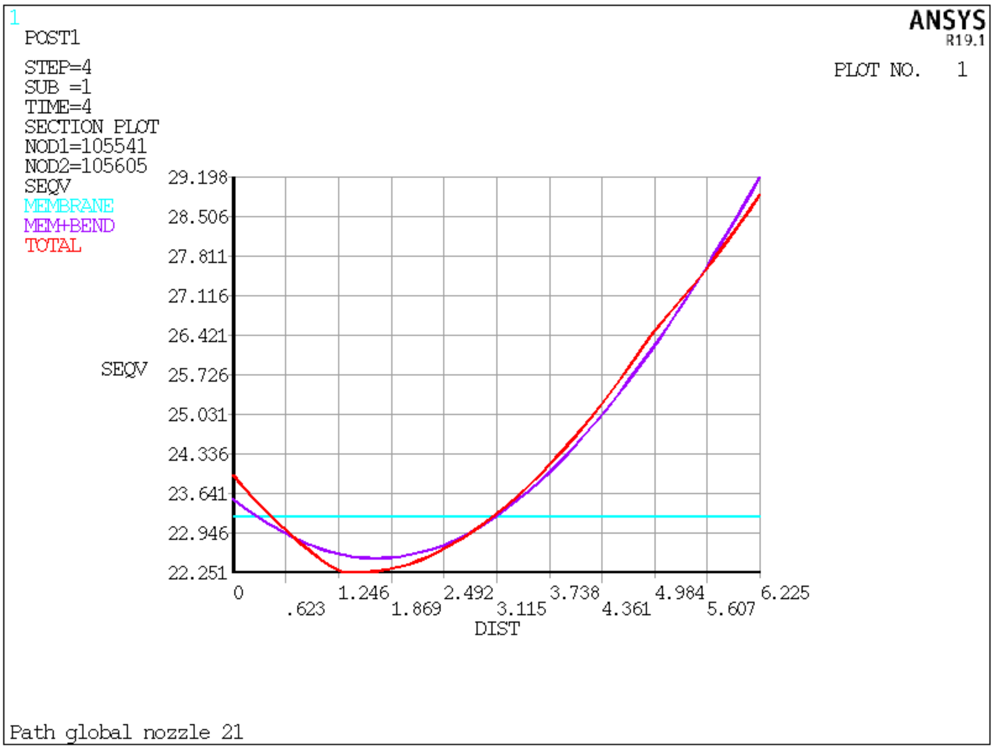

Figure 48: Maximal path of the global zone for the nozzle 1

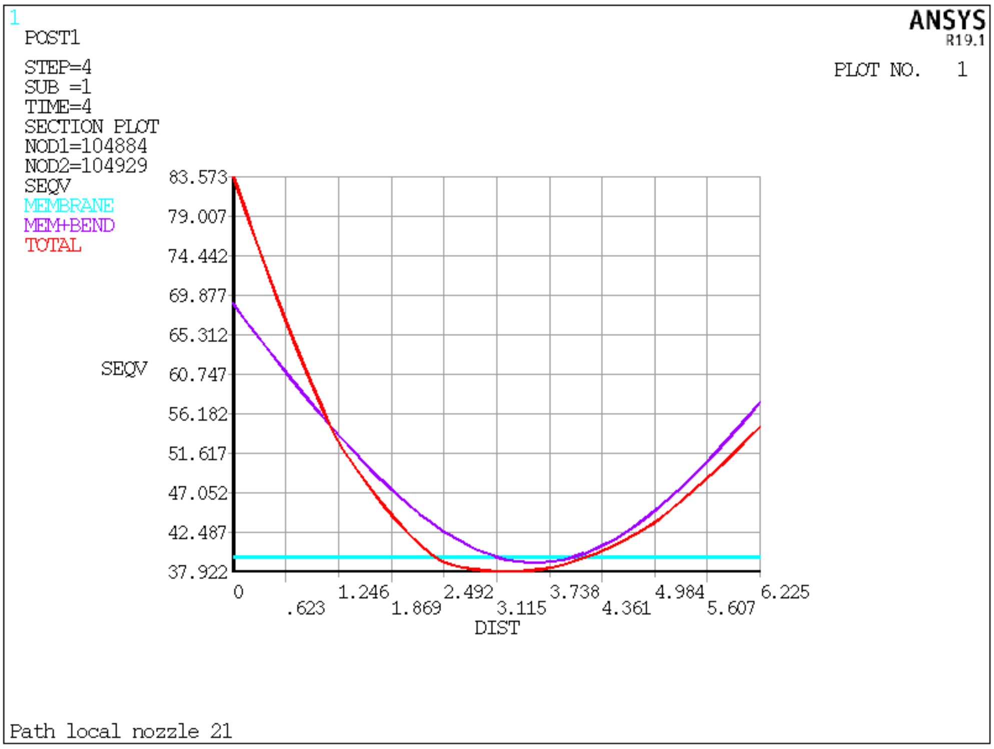

Figure 49: Maximal path of the local zone for the nozzle 1

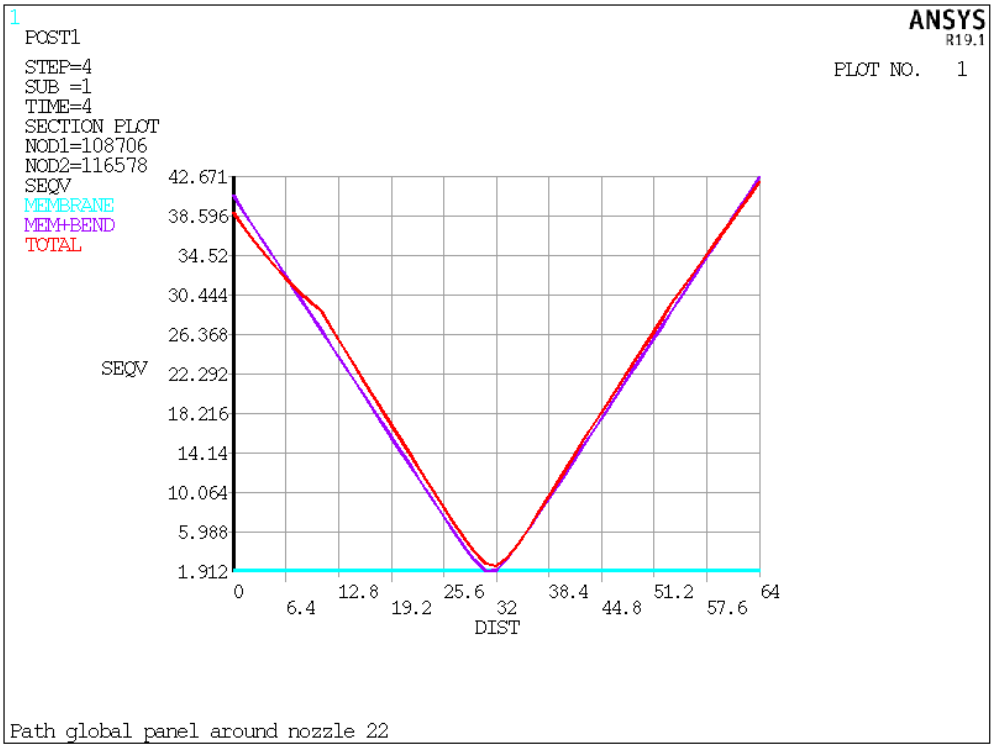

Figure 50: Maximal path of the panel 2 around the nozzle 2

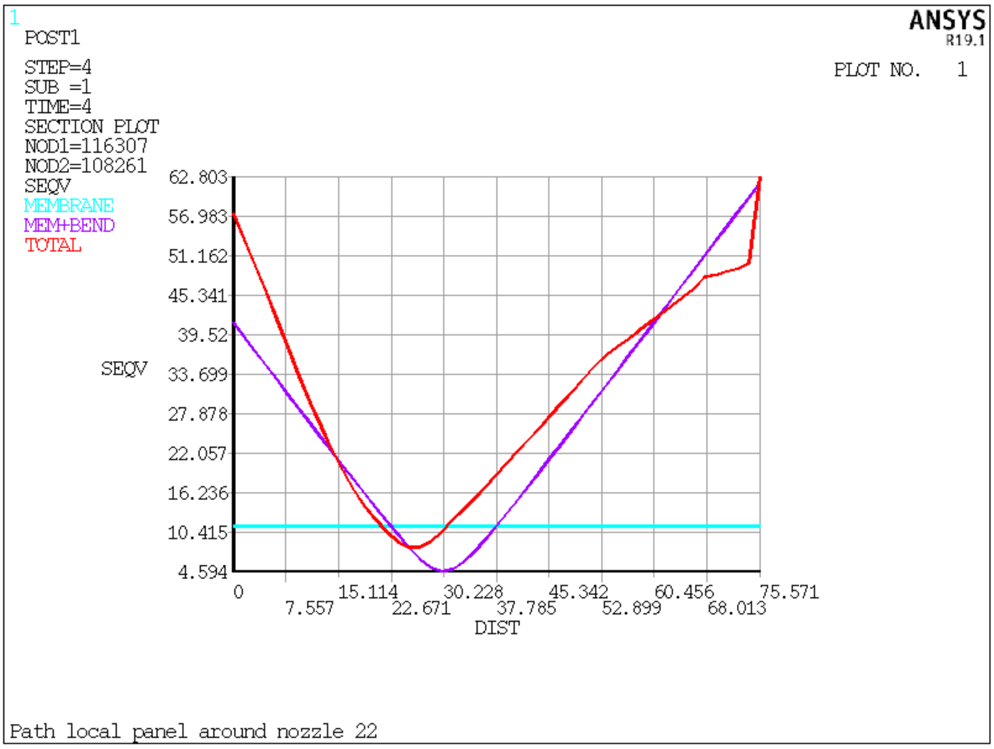

Figure 51: Maximal local path of the panel 2 around the nozzle 2

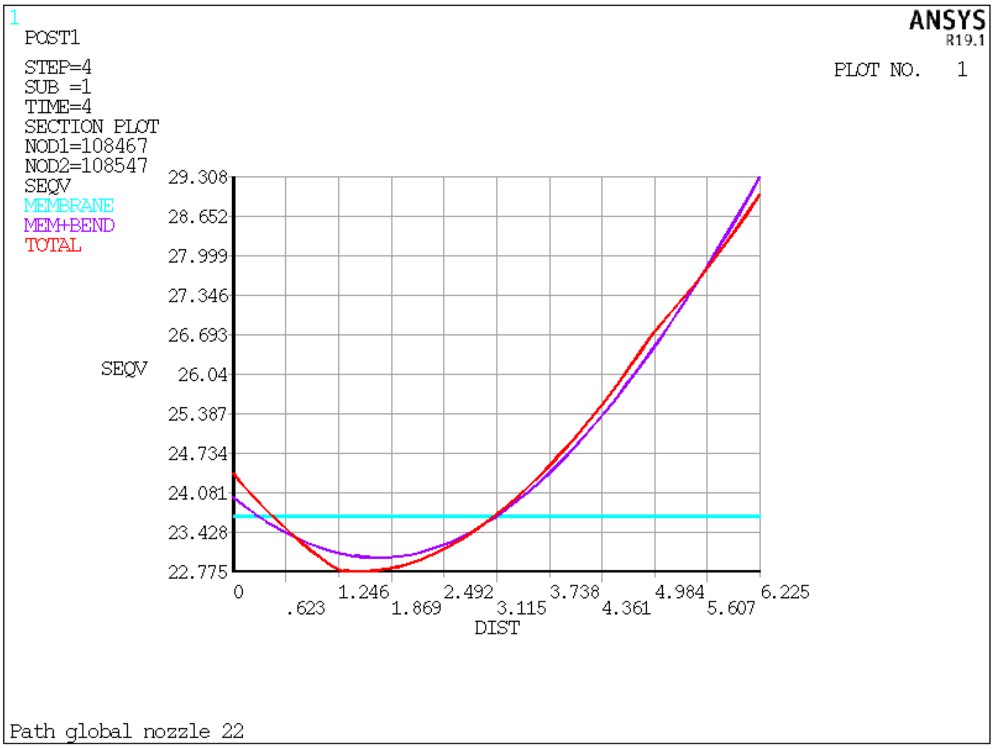

Figure 52: Maximal path of the global zone for the nozzle 2

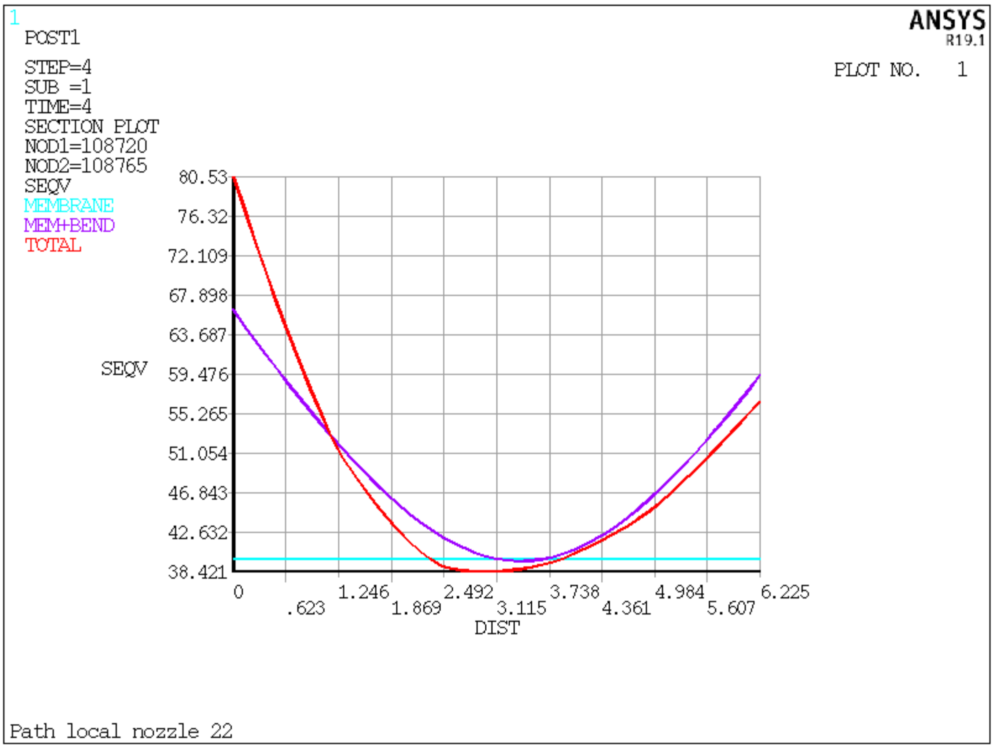

Figure 53: Maximal path of the local zone for the nozzle 2

4.4.2. Panel 4

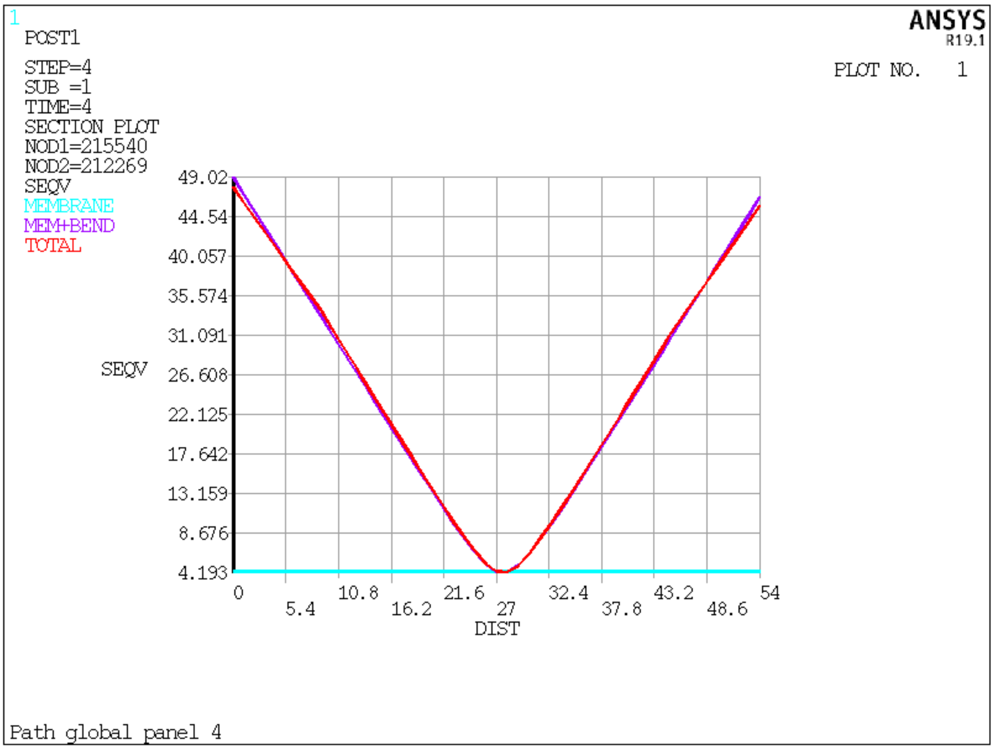

Figure 54: Maximal path of the global zone for the panel 4

4.5. Recapitulative results of paths

Sp: allowable stress of panel from § 2.2

Sn: allowable stress of nozzle from § 2.2

Panel 1		Von Mises stress (MPa)	Criteria	Criteria value (MPa)	Validated criteria
Path global panel	Membrane	1	Sp	118	TRUE
	Membrane + bending	40	1.5 × Sp	177	TRUE
Path global panel around the nozzle 1	Membrane	2	Sp	118	TRUE
	Membrane + bending	42	1.5 × Sp	177	TRUE
Path local panel around the nozzle 1	Membrane	11	1.5 × min(Sp,Sn)	173	TRUE
	Membrane + bending	62	3 × min(Sp,Sn)	345	TRUE
Path global nozzle 1	Membrane	23	Sn	115	TRUE
	Membrane + bending	29	1.5 × Sn	173	TRUE
Path local nozzle 1	Membrane	39	1.5 × Sn	173	TRUE
	Membrane + bending+secondary	69	3 × Sn	345	TRUE
	$\sigma_1 + \sigma_2 + \sigma_3$	144	4 × Sn	460	TRUE
Path global panel around the nozzle 2	Membrane	2	Sp	118	TRUE
	Membrane + bending	42	1.5 × Sp	177	TRUE
Path local panel around the nozzle 2	Membrane	12	1.5 × min(Sp,Sn)	173	TRUE
	Membrane + bending	62	3 × min(Sp,Sn)	345	TRUE
Path global nozzle 2	Membrane	24	Sn	115	TRUE
	Membrane + bending	30	1.5 × Sn	173	TRUE
Path local nozzle 2	Membrane	40	1.5 × Sn	173	TRUE
	Membrane + bending+secondary	66	3 × Sn	345	TRUE
	$\sigma_1 + \sigma_2 + \sigma_3$	142	4 × Sn	460	TRUE

Table 6: Path result of panel 1

Panel 2		Von Mises stress (MPa)	Criteria	Criteria value (MPa)	Validated criteria
Path global panel	Membrane	1	Sp	118	TRUE
	Membrane + bending	40	1.5 × Sp	177	TRUE
Path global panel around the nozzle 1	Membrane	2	Sp	118	TRUE
	Membrane + bending	41	1.5 × Sp	177	TRUE
Path local panel around the nozzle 1	Membrane	12	1.5 × min(Sp,Sn)	173	TRUE
	Membrane + bending	61	3 × min(Sp,Sn)	345	TRUE
Path global nozzle 1	Membrane	23	Sn	115	TRUE
	Membrane + bending	29	1.5 × Sn	173	TRUE
Path local nozzle 1	Membrane	40	1.5 × Sn	173	TRUE
	Membrane + bending+secondary	69	3 × Sn	345	TRUE
	$\sigma_1 + \sigma_2 + \sigma_3$	143	4 × Sn	460	TRUE
Path global panel around the nozzle 2	Membrane	2	Sp	118	TRUE
	Membrane + bending	43	1.5 × Sp	177	TRUE
Path local panel around the nozzle 2	Membrane	11	1.5 × min(Sp,Sn)	173	TRUE
	Membrane + bending	62	3 × min(Sp,Sn)	345	TRUE
Path global nozzle 2	Membrane	24	Sn	115	TRUE
	Membrane + bending	29	1.5 × Sn	173	TRUE
Path local nozzle 2	Membrane	40	1.5 × Sn	173	TRUE
	Membrane + bending+secondary	66	3 × Sn	345	TRUE
	$\sigma_1 + \sigma_2 + \sigma_3$	142	4 × Sn	460	TRUE

Table 7: Path result of panel 2

Panel 3		Von Mises stress (MPa)	Criteria	Criteria value (MPa)	Validated criteria
Path global panel	Membrane	4	Sp	118	TRUE
	Membrane + bending	49	1.5 × Sp	177	TRUE

Table 8: Path result of panel 3

Panel 4		Von Mises stress (MPa)	Criteria	Criteria value (MPa)	Validated criteria
Path global panel	Membrane	4	Sp	118	TRUE
	Membrane + bending	49	1.5 × Sp	177	TRUE

Table 9: Path result of panel 4

4.6. Results on heads

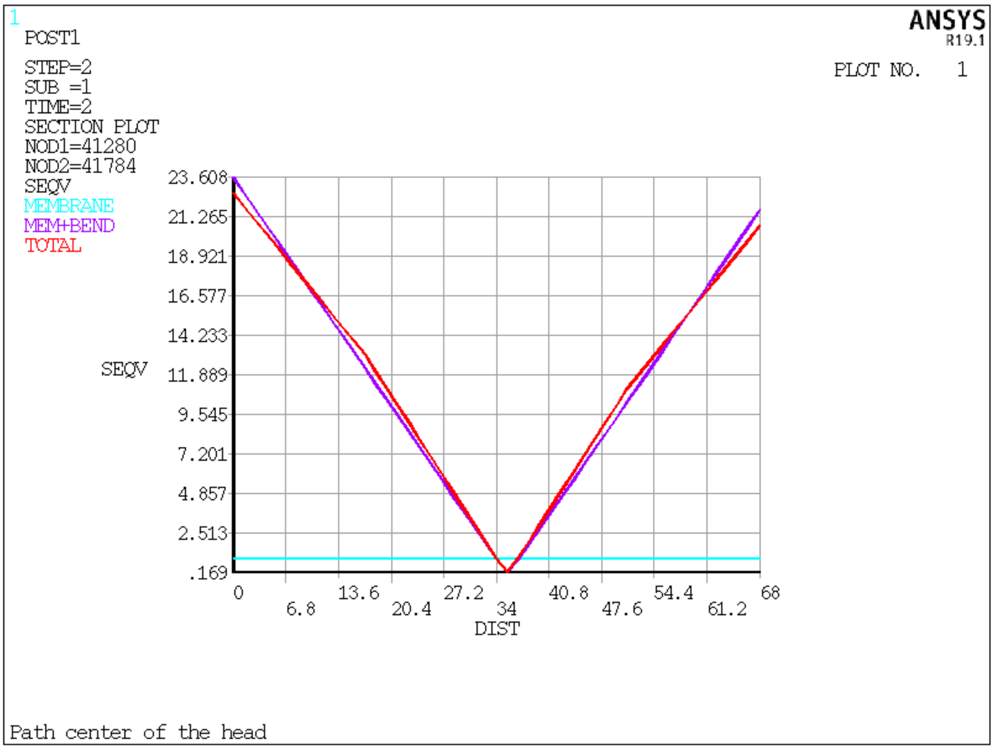

Figure 55: Maximal path on the centre of head

Path on head		Von Mises stress (MPa)	Criteria	Criteria value (MPa)	Validated criteria
Panel on head centre	Membrane	1	Sp	118	TRUE
	Membrane + bending	24	1.5 × Sp	177	TRUE

Table 10: Path result of head

4.7. Analytical calculation for nozzle

4.7.1. Nozzle thickness checking

The minimal thickness of the nozzle is checked according to the chapters UG-16 (b), UG-45 and UG-27.

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Nozzle material			SA-312 TP316L	SA-312 TP316L	SA-312 TP316L	SA-312 TP316L
DN			150	150	150	150
Internal calculation pressure	MPa	P	1.06	1.06	1.06	1.06
External diameter	mm	De	168.3	168.3	168.3	168.3
Max Internal diameter	mm	Di	155.85	155.85	155.85	155.85
Minimal J position	mm	J	100.5	100.5	100.5	100.5
External corrosion	mm	ce	0	0	0	0
Internal corrosion	mm	ci	0	0	0	0
Machining depth if weld pipe/flange with step	mm	pw	0	0	0	0
Maximal Internal Radius in corroded condition	mm	R = Di/2 + ci + pw	77.925	77.925	77.925	77.925
Internal diameter in corroded condition	mm	d = 2R	155.85	155.85	155.85	155.85
Minimal thickness UG-16(b)	mm	ta	1.5	1.5	1.5	1.5
Mininal thickness Table UG-45	mm	tb	6.22	6.22	6.22	6.22
Allowable stress at design T	MPa	Sn	115	115	115	115
Longitudinal join factor		El	0.85	0.85	0.85	0.85
Circonferential join factor		Ec	0.7	0.7	0.7	0.7
Minimal pipe thickness UG-27 (c) eq.1	mm	tc = P x R /(Sn x El - 0.6P)	0.85	0.85	0.85	0.85
Minimal pipe thickness UG-27 (c) eq.2	mm	tl = P x R /(2Sn x Ec + 0.4P)	0.51	0.51	0.51	0.51
Minimal required thickness for pipe	mm	trn = max(tc,tl,ta,tb)	6.22	6.22	6.22	6.22
Actual pipe thickness in corroded condition	mm	tn = (De - Di)/2 - ce - ci	6.225	6.225	6.225	6.225
Pipe criterion at the minimal thickness		tn - pw >= trn	OK	OK	OK	OK

Table 11: Nozzle thickness checking

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Nozzle material			SA-312 TP316L	SA-312 TP316L	SA-312 TP316L	SA-312 TP316L
DN			150	150	150	150
Internal calculation pressure	PSI	P	154	154	154	154
External diameter	in	De	6.63	6.63	6.63	6.63
Max Internal diameter	in	Di	6.14	6.14	6.14	6.14
Minimal J position	in	J	3.96	3.96	3.96	3.96
External corrosion	in	ce	0.000	0.000	0.000	0.000
Internal corrosion	in	ci	0.000	0.000	0.000	0.000
Machining depth if weld pipe/flange with step	in	pw	0.000	0.000	0.000	0.000
Maximal Internal Radius in corroded condition	in	R = Di/2 + ci + pw	3.068	3.068	3.068	3.068
Internal diameter in corroded condition	in	d = 2R	6.136	6.136	6.136	6.136
Minimal thickness UG-16(b)	in	ta	0.0625	0.0625	0.0625	0.0625
Mininal thickness Table UG-45	in	tb	0.245	0.245	0.245	0.245
Allowable stress at design T	PSI	Sn	16700	16700	16700	16700
Longitudinal join factor		El	0.85	0.85	0.85	0.85
Circonferential join factor		Ec	0.7	0.7	0.7	0.7
Minimal pipe thickness UG-27 (c) eq.1	in	tc = P x R /(Sn x El - 0.6P)	0.034	0.034	0.034	0.034
Minimal pipe thickness UG-27 (c) eq.2	in	tl = P x R /(2Sn x Ec + 0.4P)	0.020	0.020	0.020	0.020
Minimal required thickness for pipe	in	trn = max(tc,tl,ta,tb)	0.245	0.245	0.245	0.24500
Actual pipe thickness in corroded condition	in	tn = (De - Di)/2 - ce - ci	0.245	0.245	0.245	0.245
Pipe criterion at the minimal thickness		tn - pw >= trn	OK	OK	OK	OK

Table 12: Nozzle thickness checking (Customary units)

4.7.2. Attachment welds at opening

The design is done according to figure UW-16.1

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Fillet apothem (in corroded condition)	mm	t1	8	8	8	8
Groove apothem in case of set-in (in corroded condition)	mm	t2	7	7	7	7
Check of the fillet external weld Figures UW-16.1 (a) or UW-16.1 (j)		t1 >= min(6mm,0.7tn)	OK	OK	OK	OK
Check of the groove internal weld (set-in) Figure UW-16.1 (j)		t2 >= min(6mm,0.7tn)	OK	OK	OK	OK
Check of the sum of apothem (set-in) Figure UW-16.1 (j)		t1 + t2 >= 1.25 min(tn ; 19 mm)	OK	OK	OK	OK

Table 13: Weld sizes

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Fillet apothem	in	t1	0.315	0.315	0.315	0.315
Groove apothem in case of set-in	in	t2	0.276	0.276	0.276	0.276
Check of the fillet external weld Figures UW-16.1 (a) or UW-16.1 (j)		t1 >= min(1/4in,0.7tn)	OK	OK	OK	OK
Check of the groove internal weld (set-in) Figure UW-16.1 (j)		t2 >= min(1/4in,0.7tn)	OK	OK	OK	OK
Check of the sum of apothem (set-in) Figure UW-16.1 (j)		t1 + t2 >= 1.25 min(tn ; 3/4 in)	OK	OK	OK	OK

Table 14: Weld sizes (Customary units)

4.7.3. Specific check for set in nozzle

To find the minimal panel thickness from the FEA calculation the following equation (classic mechanical strength evaluation of a bending beam) is used at the critical position around each nozzle:

$$t_{min.FEA} = t_{min.cal} \times \sqrt{(\sigma_{m+b} / 1.5S)}$$

- $t_{min.FEA}$: minimal panel thickness from FEA
- $t_{min.cal}$: minimal panel thickness used in the FEA calculation for the corresponding nozzle
- σ_{m+b}: maximum membrane+ bending for panel around the nozzle stress from each previous table
- 1.5S: corresponding membrane + bending criterion

And, in conservative way, these minimal panel thicknesses around the nozzles are taken into account like the minimal blind panel thickness at the same locations.

	Minimum thickness from FEA (mm)
Panel 1 Nozzle 1	31.18
Panel 1 Nozzle 2	31.06
Panel 2 Nozzle 1	30.76
Panel 2 Nozzle 2	31.43

Table 15: Set in FEA checking

4.7.4. Strength of nozzle attachment checking

According to the chapter UW-15 and the figure UW-16.1 (j), the following table check the analytical design of nozzle weld with the UG-41 chapter of [1]. According to UW-15 (b) (2) the openings defined in UG-36 (c) (3) (DN < 60 mm) are exempted from the strength calculation attachment weld.

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Panel thickness with opening minimal value	mm	tp	64	64	64	64
Minimal blind panel thickness from FEA	mm	tr	31.18	31.06	30.76	31.43
factors		fr1 = fr2 = Sn / Sp	0.97	0.97	0.97	0.97
Required reinforcement area UG-39 (b)	mm²	A= R x tr + tr x tn x (1 -fr1)	2435	2425	2402	2454
First area in panel A11	mm²	A11 = min(d,J)x(E1 x tp -F x tr)-2tn(E1 x tp - F x tr) (1 - fr1)	3288	3300	3330	3263
Second area in panel A12	mm²	A12 = 2(tp+tn)(E1 x tp -F x tr)-2tn(E1 x tp -F x tr)(1-fr1)	4599	4616	4658	4564
Area available in panel	mm²	A1 = max(A11,A12)	4599	4616	4658	4564
Total weld load Fig. UG-41.1	N	W = (A - A1 + 2tn x fr1 (E1 x tp-F x tr)) Sp	-208426	-211344	-218640	-202347
First area in nozzle A21	mm²	A21 = 5(tn-trn)fr2 x tp	2	2	2	2
Second area in nozzle A22	mm²	A22 = 5(tn-trn)fr2 x tn	0	0	0	0
Area available in nozzle	mm²	A2 = min(A21,A22)	0	0	0	0
Fillet apothem	mm	t1	8	8	8	8
Groove apothem	mm	t2	7	7	7	7
weld leg	mm	leg = t1 x √2	11	11	11	11
Area available in weld	mm²	A41 = leg² x fr2	125	125	125	125
Weld load path 1-1 Fig. UG-41.1	N	W11 = (A2 + A41)Sp	14738	14738	14738	14738
Weld load path 2-2 Fig. UG-41.1	N	W22= (A2 + A41+2tn x tp x fr1)Sp	106370	106370	106370	106370
Fillet weld shear UW-15 (c) and UG-45	MPa	Fws = 0.49 Sn	56.35	56.35	56.35	56.35
Nozzle wall shear UW-15 (c) and UG-45	MPa	Nws = 0.7 Sn	80.5	80.5	80.5	80.5
Groove weld tension UW-15 (c) and UG-45	MPa	Gwt = 0.74 Sn	85.1	85.1	85.1	85.1
Mean diameter of pipe	mm	Dm = d + tn	162.08	162.08	162.08	162.08
Strenght of connection element weld shear	N	Afws = π/2 x De x t1 x Fws	119176	119176	119176	119176
Strenght of connection element weld tension	N	Bgwt = π/2 x De x t2 x Gwt	157482	157482	157482	157482
Strenght of connection element wall shear	N	Cnws = π/2 x Dm x tn x Nws	127577	127577	127577	127577
Criteria path 1-1		Afws + Cnws > min(W,W11)	OK	OK	OK	OK
Criteria path 2-2		Afws + Bgwt > min(W,W22)	OK	OK	OK	OK

Table 16: Set in analytical checking

	Unit	Symbol / equation	Panel1 nozzle 1	Panel1 nozzle 2	Panel2 nozzle 1	Panel2 nozzle 2
Panel thickness with opening minimal value	in	tp	2.520	2.520	2.520	2.520
Minimal blind panel thickness from FEA	in	tr	1.228	1.223	1.211	1.237
factors		fr1 = fr2 = Sn / Sp	0.98	0.98	0.98	0.98
Required reinforcement area UG-39 (b)	in^2	A= R x tr + tr x tn x (1 -fr1)	3.77	3.76	3.72	3.80
First area in panel A11	in^2	A11 = min(d,J)x(E1 x tp -F x tr)-2tn(E1 x tp - F x tr) (1 - fr1)	5.10	5.12	5.16	5.06
Second area in panel A12	in^2	A12 = 2(tp+tn)(E1 x tp -F x tr)-2tn(E1 x tp -F x tr)(1-fr1)	7.13	7.16	7.22	7.08
Area available in panel	in^2	A1 = max(A11,A12)	7.13	7.16	7.22	7.08
Total weld load Fig. UG-41.1	lbf	W = (A - A1 + 2tn x fr1 (E1 x tp-F x tr)) Sp	-46867	-47523	-49162	-45500
First area in nozzle A21	in^2	A21 = 5(tn-trn)fr2 x tp	0.00	0.00	0.00	0.00
Second area in nozzle A22	in^2	A22 = 5(tn-trn)fr2 x tn	0.00	0.00	0.00	0.00
Area available in nozzle	in^2	A2 = min(A21,A22)	0.000	0.000	0.000	0.000
Fillet apothem	in	t1	0.315	0.315	0.315	0.315
Groove apothem	in	t2	0.276	0.276	0.276	0.276
weld leg	in	leg = t1 x $\sqrt{2}$	0.445	0.445	0.445	0.445
Area available in weld	in^2	A41 = leg^2 x fr2	0.19	0.19	0.19	0.19
Weld load path 1-1 Fig. UG-41.1	lbf	W11 = (A2 + A41)Sp	3318	3318	3318	3318
Weld load path 2-2 Fig. UG-41.1	lbf	W22= (A2 + A41+2tn x tp x fr1)Sp	23960	23960	23960	23960
Fillet weld shear UW-15 (c) and UG-45	PSI	Fws = 0.49 Sn	8183	8183	8183	8183
Nozzle wall shear UW-15 (c) and UG-45	PSI	Nws = 0.7 Sn	11690	11690	11690	11690
Groove weld tension UW-15 (c) and UG-45	PSI	Gwt = 0.74 Sn	12358	12358	12358	12358
Mean diameter of pipe	in	Dm = d + tn	6.38	6.38	6.38	6.38
Strenght of connection element weld shear	lbf	Afws = π/2 x De x t1 x Fws	26825	26825	26825	26825
Strenght of connection element weld tension	lbf	Bgwt = π/2 x De x t2 x Gwt	35447	35447	35447	35447
Strenght of connection element wall shear	lbf	Cnws = π/2 x Dm x tn x Nws	28716	28716	28716	28716
Criteria path 1-1		Afws + Cnws > min(W,W11)	OK	OK	OK	OK
Criteria path 2-2		Afws + Bgwt > min(W,W22)	OK	OK	OK	OK

Table 17: Set in analytical checking (Customary units)

4.8. Bolts

The requirements for bolts are roughly described in ASME VIII div. 2 chapter 5.7, which does not consider practical aspects, such as tightening torque uncertainty, friction factor variations, gasket relaxation, retightening, etc. which can overall affect design results. For this reason, bolts design is made using equations described in [7], from Appendix 2.5 of the ASME VIII div. 1. Moreover, ASME VIII div1 also provides guidelines on bolts stress, considering practical aspects (Appendix S).

As compared to a regular bolted assembly, Compabloc is specific in 2 ways: bolts can be subject to an additional moment due to the panel bending, and/or subject to additional load to column rotation:

- the bending effect in bolt is neglected, the rotation of panel is low compared to the gap in the screw.
- the supplementary traction force due to an addition moment with the rotation of the girder in case of differential pressure is not depending on the panel thickness.

4.9. Global equilibrium check

The following table shows the results of the global equilibrium for each load case. Only the sum of nozzles appears, indeed the sum of the pressure need to be 0 for an enclose box.

The vertical reaction for the first load corresponds to the exchanger weight without the plate pack (calculation with the steel density of the model parts). The real weight not influence the mechanical stresses on panels and nozzles.

	Rx (N)	Ry (N)	Rz (N)
Setting	0	0	-15040
Simultaneous pressure	3309	3309	-15040
Pressure side A	1755	1552	-15030
Pressure side B	1553	1758	-15030

Table 18: Global equilibrium

Data forces	Rx (N)	Ry (N)	Rz (N)
Simultaneous pressure	3104	3104	-15040
Pressure side A	1552	1552	-15040
Pressure side B	1552	1552	-15040

Table 19: Data of sum of nozzle loads plus the weight

The values between the two last tables need to be compare. The low differences are due to the mesh of circle with small linear parts.

The direction of nozzle loads in the global coordinate system are chosen in the following conservative way:

- For the axial loads always in the same direction than the end caps effect
- For the vertical direction (axe Z in the model), positive for the nozzle with a high or centre position and negative for a low position
- For the lateral direction, always positive (axe Y for side A and axe X for side B)

5. CONCLUSION

The static analysis shows that the dimensions of panels of the Studied Compabloc subjected to design pressures at design temperature of [6], fulfils the requirements of the division 1 section VIII ASME Code.

6. ANNEXE – PARAMETERS FILE

The following text corresponds to the parameters file with all the data use by ANSYS.

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!!! full CP with nozzle
!!! Parameters.mac
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!!!! units : mm, N, MPa

fini
/clear
ori =           'V'

! corrosion (external and internal)
ce =                    0       !   mm
ci1 =                   0
ci2 =                   0
ci3 =                   0
ci4 =                   0

!!! allowable stresses
sp=                   118       !    MPa  for panel

!!!!!!!!! head parameters !!!!!!!!!
```

l_h=	490	! head lenght (mm)
tht_h=	8	! tongue/hang high
ht_h=	15	! tongue/hang width
c_h=	60	! lenght of girder part adjusted compare to 171 mm
th_h=	68 -ce	! head thickness

!!!!!!!!! Girder parameters !!!!!!!!!!

C_g=	60	! girder width
tht_g=	8	! tongue/hang high
ht_g=	15	! tongue/hang width

!!!!!!!!! Panel parameters !!!!!!!!!

tn_1=	80	! nominal panel thickness side 1
tn_2=	80	! nominal panel thickness side 2
tn_3=	70	! nominal panel thickness side 3
tn_4=	70	! nominal panel thickness side 4
usi=	2	! external machining
tol1=	5	! tolerance
tol2=	5	
tol3=	5	
tol4=	5	

l_p=	1297	! total panel height
w_p=	482	! total panel width
li_p=	1191.7	! height of internal part
wi_p=	400.5	! width of internal part
X1=	9 +ci1	! panel depth
X2=	9 +ci2	
X3=	9 +ci3	
X4=	9 +ci4	

```
*do,ii,1,4
          th_p%ii%=tn_%ii%-usi-tol%ii%-ce    ! thickness of external part side ii
*enddo

*do,ii,1,4
          thd_p%ii%=th_p%ii%-X%ii%         ! thickness of internal part side ii
*enddo

pt_p=                  25          ! tongue space

!!!!!gasket
th_g=                  4.8         ! gasket thickness    corresponding to the lining thickness +gasket
w_g=                   14          ! gasket width


!!!bolts
l_b=                   1229        !position of bolt in the panel lenght direction
w_b=                   432         !position of bolt in the panel width  direction

dnom=                  24
pas=                   3.00

dib=dnom-0.9743*pas                ! diametre correspondant à la section résistante
dir=2*dib                          ! diamètre de la rondelle
dih=                   28          ! hole diameter

nbh=                   3           ! nombre de vis dans la largeur
sph=                   110         ! espacement vis dans la largeur
nbv=                   13          ! nombre de vis dans la hauteur
spv=                   98.32       ! espacement vis dans la hauteur
dec_bh=                0           ! For CP15 and CP20 for the shift o bolt due to a non symmetry
dec_b=                 0           ! Not use for the moment: decalage de la 1ier vis cote droit si pas aligne au vis fond
```

```
nb=2*(nbh+ nbv)                         ! nombre total de vis pour 1 panel

!!!!!!! number of openings for panel1
n_n1=                         2

!nozzle 1
seton11=                       0          ! if 0 nozzle set-in
Mat11=                         0          ! if 1 CS
de11=                     168.3 -2*ce*mat11  ! external diameter
di11=                    155.85 +2*ci1*mat11 ! internal diameter
do11=                       170           !  opening diameter
epn11=(de11-di11)/2
ln11=                       266           ! lenght of nozzle (with panel's thickness)
f11=                        8 -ce*mat11    ! apothem fillet
g11=                         7            ! groove fillet
dloc11=((di11+de11)/4*epn11)**0.5                ! Edge local / global nozzle

J11=                      100.5
fn11=                        1
Nv11=(li_p/2-J11)*fn11                         ! nozzle position between center of panel
Nl11=                        0
F_x11=                      776           ! N
F_y11=                      776           ! N
F_z11=                      776           ! N
M_x11=                       750e3          !Nmm
M_y11=                       750e3          !Nmm
M_z11=                       750e3          !Nmm

!nozzle 2
seton12=                       0          ! if 0 nozzle set-in
Mat12=                         0          ! if 1 CS
de12=                     168.3 -2*ce*mat12  ! external diameter
di12=                    155.85 +2*ci1*mat12 ! internal diameter
do12=                       170           !  opening diameter
```

```
epn12=(de12-di12)/2
ln12=                    266          ! lenght of nozzle (with panel's thickness)
f12=                     8 -ce*mat12  ! apothem fillet
g12=                     7            ! groove fillet
dloc12=((di12+de12)/4*epn12)**0.5                ! Edge local / global nozzle

J12=                     100.5
fn12=                    -1
Nv12=(li_p/2-J12)*fn12                  ! nozzle position between center of panel
Nl12=0                   0
F_x12=                   776          ! N
F_y12=                   776          ! N
F_z12=                   776          ! N
M_x12=                   750e3        !Nmm
M_y12=                   750e3        !Nmm
M_z12=                   750e3        !Nmm

!nozzle 3
seton13=                 0            ! if 0 nozzle set-in
Mat13=                   1            ! if 1 CS
de13=                    457 -2*ce*mat13  ! external diameter
di13=                    0.25 +2*ci1*mat13 ! internal diameter
do13=                    462          !  opening diameter
epn13=(de13-di13)/2
ln13=                    12           ! lenght of nozzle (with panel's thickness)
f13=                     12 -ce*mat13 ! apothem fillet
g13=                     7            ! groove fillet
dloc13=((di13+de13)/4*epn13)**0.5                ! Edge local / global nozzle

J13=                     0
fn13=                    1
Nv13=(li_p/2-J13)*fn13                  ! nozzle position between center of panel
Nl13=                    250
F_x13=                   3818         ! N
```

```
F_y13=                    3818          ! N
F_z13=                    3818          ! N
M_x13=                     6742e3         !Nmm
M_y13=                     6742e3         !Nmm
M_z13=                     6742e3         !Nmm

!nozzle 4
seton14=                     0           ! if 0 nozzle set-in
Mat14=                       1           ! if 1 CS
de14=                    406.4 -2*ce*mat14  ! external diameter
di14=                    0.25 +2*ci1*mat14 ! internal diameter
do14=                     411           !  opening diameter
epn14=(de14-di14)/2
ln14=                     12           ! lenght of nozzle (with panel's thickness)
f14=                     10 -ce*mat14    ! apothem fillet
g14=                       7           ! groove fillet
dloc14=((di14+de14)/4*epn14)**0.5                  ! Edge local / global nozzle

J14=                      0
fn14=                     -1
Nv14=(li_p/2-J14)*fn14                       ! nozzle position between center of panel
Nl14=                    -250
F_x14=                    3314          ! N
F_y14=                    3314          ! N
F_z14=                    3314          ! N
M_x14=                     5333e3         !Nmm
M_y14=                     5333e3         !Nmm
M_z14=                     5333e3         !Nmm


!!!!! number of openings for panel2
n_n2=                       2

!nozzle 1
```

```
seton21=                    0         ! if 0 nozzle set-in
Mat21=                      0         ! if 1 CS
de21=                  168.3 -2*ce*mat21  ! external diameter
di21=                 155.85 +2*ci2*mat21 ! internal diameter
do21=                    170          !  opening diameter
epn21=(de21-di21)/2
ln21=                    266          ! lenght of nozzle (with panel's thickness)
f21=                     8 -ce*mat21    ! apothem fillet
g21=                      7           ! groove fillet
dloc21=((di21+de21)/4*epn21)**0.5                 ! Edge local / global nozzle

J21=                   100.5
fn21=                     -1
Nv21=(li_p/2-J21)*fn21                        ! nozzle position between center of panel
Nl21=                      0
F_x21=                    776         ! N
F_y21=                    776         ! N
F_z21=                    776         ! N
M_x21=                    750e3         !Nmm
M_y21=                    750e3         !Nmm
M_z21=                    750e3         !Nmm

!nozzle 2

seton22=                    0         ! if 0 nozzle set-in
Mat22=                      0         ! if 1 CS
de22=                  168.3 -2*ce*mat22  ! external diameter
di22=                 155.85 +2*ci2*mat22 ! internal diameter
do22=                    170          !  opening diameter
epn22=(de22-di22)/2
ln22=                    266          ! lenght of nozzle (with panel's thickness)
f22=                     8 -ce*mat22    ! apothem fillet
g22=                      7           ! groove fillet
dloc22=((di22+de22)/4*epn22)**0.5                 ! Edge local / global nozzle
```

```
J22=                  100.5
fn22=                   1
Nv22=(li_p/2-J22)*fn22                 ! nozzle position between center of panel
Nl22=                   0
F_x22=                  776        ! N
F_y22=                  776        ! N
F_z22=                  776        ! N
M_x22=                  750e3       !Nmm
M_y22=                  750e3       !Nmm
M_z22=                  750e3       !Nmm

!nozzle 3
seton23=                0          ! if 0 nozzle set-in
Mat23=                  1          ! if 1 CS
de23=                   273 -2*ce*mat23  ! external diameter
di23=                   0.25 +2*ci2*mat23 ! internal diameter
do23=                   276        !  opening diameter
epn23=(de23-di23)/2
ln23=                   12         ! lenght of nozzle (with panel's thickness)
f23=                    10 -ce*mat23    ! apothem fillet
g23=                    7          ! groove fillet
dloc23=((di23+de23)/4*epn23)**0.5            ! Edge local / global nozzle

J23=                    153
fn23=                   -1
Nv23=(li_p/2-J23)*fn23                 ! nozzle position between center of panel
Nl23=                   250
F_x23=                  1886       ! N
F_y23=                  1886       ! N
F_z23=                  1886       ! N
M_x23=                  2167e3      !Nmm
M_y23=                  2167e3      !Nmm
M_z23=                  2167e3      !Nmm
```

```
!nozzle 4
seton14=                 0          ! if 0 nozzle set-in
Mat24=                   0          ! if 1 CS
de24=                219.1 -2*ce*mat24  ! external diameter
di24=                27.38 +2*ci2*mat24 ! internal diameter
do24=                  222          !  opening diameter
epn24=(de24-di24)/2
ln24=                   12          ! lenght of nozzle (with panel's thickness)
f24=                 10 -ce*mat24   ! apothem fillet
g24=                     7          ! groove fillet
dloc24=((di24+de24)/4*epn24)**0.5            ! Edge local / global nozzle

J24=                   126
fn24=                    1
Nv24=(li_p/2-J24)*fn24                       ! nozzle position between center of panel
Nl24=                 -250
F_x24=                1443          ! N
F_y24=                1443          ! N
F_z24=                1443          ! N
M_x24=              1431e3          !Nmm
M_y24=              1431e3          !Nmm
M_z24=              1431e3          !Nmm



!!!!!!!!!!!! number of openings for panel3
n_n3=                    0

!nozzle 1
seton31=                 0          ! if 0 nozzle set-in
Mat31=                   1          ! if 1 CS
de31=                168.3 -2*ce*mat31  ! external diameter
```

```
di31=                    0.25 +2*ci3*mat31 ! internal diameter
do31=                     170          !  opening diameter
epn31=(de31-di31)/2
ln31=                     12          ! lenght of nozzle (with panel's thickness)
f31=                      8 -ce*mat31   ! apothem fillet
g31=                      7           ! groove fillet
dloc31=((di31+de31)/4*epn31)**0.5               ! Edge local / global nozzle

J31=                     101
fn31=                     1
Nv31=(li_p/2-J31)*fn31                  ! nozzle position between center of panel
Nl31=                     0
F_x31=                    776          ! N
F_y31=                    776          ! N
F_z31=                    776          ! N
M_x31=                    750e3         !Nmm
M_y31=                    750e3         !Nmm
M_z31=                    750e3         !Nmm

!nozzle 2

seton32=                   0           ! if 0 nozzle set-in
Mat32=                     1           ! if 1 CS
de32=                    114.3 -2*ce*mat32  ! external diameter
di32=                    0.25 +2*ci3*mat32 ! internal diameter
do32=                     116          !  opening diameter
epn32=(de32-di32)/2
ln32=                     12          ! lenght of nozzle (with panel's thickness)
f32=                      6 -ce*mat32   ! apothem fillet
g32=                      6           ! groove fillet
dloc32=((di32+de32)/4*epn32)**0.5               ! Edge local / global nozzle

J32=                      74
fn32=                     -1
```

```
Nv32=(li_p/2-J32)*fn32                 ! nozzle position between center of panel
Nl32=              0
F_x32=             628        ! N
F_y32=             628        ! N
F_z32=             628        ! N
M_x32=             388e3       !Nmm
M_y32=             388e3       !Nmm
M_z32=             388e3       !Nmm

!nozzle 3
seton33=           0          ! if 0 nozzle set-in
Mat33=             0          ! if 1 CS
de33=              88.9 -2*ce*mat33  ! external diameter
di33=              11.11 +2*ci3*mat33 ! internal diameter
do33=              90         !  opening diameter
epn33=(de33-di33)/2
ln33=              12         ! lenght of nozzle (with panel's thickness)
f33=               6 -ce*mat33    ! apothem fillet
g33=               6          ! groove fillet
dloc33=((di33+de33)/4*epn33)**0.5              ! Edge local / global nozzle

J33=               61
fn33=              1
Nv33=(li_p/2-J33)*fn33                 ! nozzle position between center of panel
Nl33=              250
F_x33=             480        ! N
F_y33=             480        ! N
F_z33=             480        ! N
M_x33=             246e3       !Nmm
M_y33=             246e3       !Nmm
M_z33=             246e3       !Nmm

!nozzle 4
seton34=           0          ! if 0 nozzle set-in
```

```
Mat34=                 0          ! if 1 CS
de34=               60.3 -2*ce*mat34  ! external diameter
di34=               7.53 +2*ci3*mat34 ! internal diameter
do34=                61          !  opening diameter
epn34=(de34-di34)/2
ln34=                12          ! lenght of nozzle (with panel's thickness)
f34=                 5 -ce*mat34    ! apothem fillet
g34=                 5           ! groove fillet
dloc34=((di34+de34)/4*epn34)**0.5             ! Edge local / global nozzle

J34=                47
fn34=               -1
Nv34=(li_p/2-J34)*fn34                   ! nozzle position between center of panel
Nl34=               -560
F_x34=               273          ! N
F_y34=               273          ! N
F_z34=               273          ! N
M_x34=                80e3         !Nmm
M_y34=                80e3         !Nmm
M_z34=                80e3         !Nmm

!!!!!!!!!!!!!!!!!! number of openings for panel4
n_n4=                 0

!nozzle 1
seton41=               0          ! if 0 nozzle set-in
Mat41=                 1          ! if 1 CS
de41=               48.3 -2*ce*mat41  ! external diameter
di41=               0.25 +2*ci4*mat41 ! internal diameter
do41=                49          !  opening diameter
epn41=(de41-di41)/2
ln41=                12          ! lenght of nozzle (with panel's thickness)
f41=                 4 -ce*mat41    ! apothem fillet
g41=                 4           ! groove fillet
```

```
dloc41=((di41+de41)/4*epn41)**0.5                ! Edge local / global nozzle

J41=                            41
fn41=                           1
Nv41=(li_p/2-J41)*fn41                           ! nozzle position between center of panel
Nl41=                           28.5
F_x41=                          159         ! N
F_y41=                          159         ! N
F_z41=                          159         ! N
M_x41=                          37e3        !Nmm
M_y41=                          37e3        !Nmm
M_z41=                          37e3        !Nmm

!nozzle 2

seton42=                        0           ! if 0 nozzle set-in
Mat42=                          1           ! if 1 CS
de42=                           33.4 -2*ce*mat42  ! external diameter
di42=                           0.25 +2*ci4*mat42 ! internal diameter
do42=                           35          !  opening diameter
epn42=(de42-di42)/2
ln42=                           12          ! lenght of nozzle (with panel's thickness)
f42=                            4 -ce*mat42    ! apothem fillet
g42=                            4           ! groove fillet
dloc42=((di42+de42)/4*epn42)**0.5                ! Edge local / global nozzle

J42=                            0
fn42=                           -1
Nv42=(li_p/2-J42)*fn42                           ! nozzle position between center of panel
Nl42=                           0
F_x42=                          119         ! N
F_y42=                          119         ! N
F_z42=                          119         ! N
M_x42=                          1e3         !Nmm
```

```
M_y42=                         1e3          !Nmm
M_z42=                         1e3          !Nmm

!nozzle 3
seton43=                       0            ! if 0 nozzle set-in
Mat43=                         0            ! if 1 CS
de43=                      48.3 -2*ce*mat43  ! external diameter
di43=                      6.03 +2*ci4*mat43 ! internal diameter
do43=                        49             !  opening diameter
epn43=(de43-di43)/2
ln43=                        12             ! lenght of nozzle (with panel's thickness)
f43=                         4 -ce*mat43    ! apothem fillet
g43=                         4              ! groove fillet
dloc43=((di43+de43)/4*epn43)**0.5                      ! Edge local / global nozzle

J43=                         41
fn43=                         1
Nv43=(li_p/2-J43)*fn43                            ! nozzle position between center of panel
Nl43=                        250
F_x43=                       209            ! N
F_y43=                       209            ! N
F_z43=                       209            ! N
M_x43=                        40e3          !Nmm
M_y43=                        40e3          !Nmm
M_z43=                        40e3          !Nmm

!nozzle 4
seton44=                       0            ! if 0 nozzle set-in
Mat44=                         0            ! if 1 CS
de44=                      48.3 -2*ce*mat44  ! external diameter
di44=                    6.0375 +2*ci4*mat44 ! internal diameter
do44=                        49             !  opening diameter
epn44=(de44-di44)/2
ln44=                        12             ! lenght of nozzle (with panel's thickness)
```

```
f44=            4 -ce*mat44   ! apothem fillet
g44=            4             ! groove fillet
dloc44=((di44+de44)/4*epn44)**0.5        ! Edge local / global nozzle

J44=            41
fn44=           -1
Nv44=(li_p/2-J44)*fn44                   ! nozzle position between center of panel
Nl44=           -250
F_x44=          209           ! N
F_y44=          209           ! N
F_z44=          209           ! N
M_x44=          40e3          !Nmm
M_y44=          40e3          !Nmm
M_z44=          40e3          !Nmm


Pre13 =         1.06
Pre24=          1.06          ! pressure differential(MPa)
Fb=             36300         ! Tightening load of panels  (N) by bolt


Ecs=            197000        !MPa
Ess=            188000
Ebcs=           199000

pcs=            0.30
pss=            0.31

dcs=            7850e-12
dss=            7950e-12

acs=            0.00001222
ass=            0.00001636
```