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Example of stress evaluation for a pipe subjected to impeded thermal expansion according to ASME code

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Abstract. This material summarizes the results regarding the analysis of the mechanical stress states for a piping system subjected to impeded thermal expansion. It were considered different load cases corresponding to the primary loads (own weight + internal pressure) and the secondary loads (induced by thermal expansion, including the thermal displacements of the equipment connection points). The stresses values determined for each load cases were compared with the allowable limits evaluated according to ASME B31.3 code, resulting that the analyzed piping system is safe.
Keywords: *piping system, ASME code, stress, finite element analysis, load cases.*

1. Introduction

The pipeline systems are sets of elements and devices separating a closed tubular space from the environment, mounted on a precisely determined route, which serve to collect, transport and distribute (technological) working environments in different states of aggregation (fluid →liquid , gaseous, liquefied, fluidized, powdery, etc.).

The main components of a piping system are the pipes → the pipes or tubes that tightly separate/delimit the closed space through which the working environment is conveyed.

The strength calculation regarding the pipe systems has, as a rule, a verification character, it usually succeeding the dimensioning of the pipe elements and the establishment of the pipe route configuration.

Therefore, the strength calculation for a piping system usually takes into account its piping (including bends/curves associated with changes of direction, reductions related to section changes or possible tubular branches).

The article summarizes the results of the analysis of the mechanical stress states identified at the level of a piping system subjected to impeded thermal expansion.

The analysis objectives were:

• evaluation of the states of (thermo) mechanical stresses in the wall of the pipe tubular material, under the action of the applied loads and verification of the corresponding conditions of mechanical resistance;

• evaluation of loads on pipe supports;

• quantification of the reactions level in the equipment connections;

• validation of the maximum pipe displacements;

• checking the removable joints by flanges.

2. Analysis code and basic assumptions

The strength calculation of the tubular material of the pipes and the reactions evaluation in the equipment connections were performed according to the precepts of the North American Code ASME/ANSI B 31.3 [1] - "Process Pressure Piping Code" - Ed. 2006, for pressurized pipe systems used in the industries process (respectively oil refining, petrochemistry, chemistry, etc.).

The analysis of the mechanical stress states developed in the aforementioned pipe system was performed through the specialized calculation program Caesar II [2], Version 5.3.

The system installation temperature was considered t_{inst} = +21 ^{0}C.

The loads from thermal expansion correspond to the temperature variation of the pipes metallic wall from the installation temperature (t_{inst} = +21 ^{0}C) to the calculation temperature (respectively the maximum allowable working temperature, t_{calc}), on the one hand and, respectively, from the minimum temperature of the metallic wall (t_{min} = - 29 ^{0}C) up to the installation temperature (t_{inst} = +21 ^{0}C), on the other hand. In these circumstances, the calculations regarding the pipes structural integrity were performed according to the calculation temperature.

The internal pressure loading of the pipes tubular material corresponds to the action of the calculation manometric pressure (or maximum allowable, P_c).

The intensity of the seismic distributed load was evaluated according to P100 code [3]. Thus, the maximum calculation value of the horizontal seismic acceleration at the pipeline level is given by the formula:

$$a_s = (\gamma_{CNS} \cdot \beta_{CNS} / q_{CNS}) \cdot a_g \tag{1}$$

where:

γ_{CNS} = the structure importance factor; in case of the investigated pipes it was considered the covering value γ_{CNS} = 1.50;

β_{CNS} = the structure dynamic amplification coefficient; it was adopted the covering value β_{CNS} = 2.50;

q_{CNS} = the structure behaviour factor, depending on its deformation and energy absorbtion capacity; it was adopted the typical value q_{CNS} = 2.50;

a_g = the seismic calculation acceleration of land, established according to the seismic zoning map; for the area of Dobrogea and the Black Sea Coast, $a_g = 0.16 \cdot g$ (g = 9.81 m/s^2 is the gravitational acceleration).

Therefore:

$$a_s = (1.50 \times 2.50 / 2.50) \cdot (0.16 \cdot g) = 0.24 \cdot g \ \ (\text{m/s}^2) \tag{2}$$

The wind loads were evaluated according to NP-082-04 [4] – see table 1.

Table 1. Wind loads expression [4].

***w(z)* - wind pressure at height *z* above the ground**
$w(z)=q_{ref} \cdot C_e(z) \cdot C_p$
C_p - the aerodynamic pressure coefficient
C_p =1, according to Chapter 12
q_{ref} - reference wind pressure
q_{ref} =0.5, according to figure A2 - Annex A
$C_e(z)$ - exposure factor at height z above the ground
$C_e(z) = C_g(z) \cdot C_r(z)$
$C_g(z)$ – burst factor
$C_g(z)=1+g \cdot [2 \cdot I(z)]$
g – peak factor
g =3.5, according to Chapter 10.2

I(z) - turbulence intensity for open field
$I(z)=1/[\ln(z/z_0)]$
z – construction height
z_0 - roughness length
It was taken $z_0=0.3$, according to Chapter 7.2 – Table 1
$C_r(z)$ - roughness factor, according to Chapter 8.4
$C_r(z) = k_r(z_0)\cdot[\ln(z/z_0)]$
$k_r(z_0)= 0.22$, according to Chapter 8.2 - Table 2

It resulted the calculation values presented in table 2.

Table 2. Calculation values for wind pressure.

***z* [m]**	***w(z)* [kPa]**
5	0.67
10	0.89
15	1.03
20	1.14
30	1.29

At the suppports level of the investigated pipes, the sliding friction between the components of the respective supports (slipper-base plate, slipper/profile-limiter, etc.) was taken into account. For the steel-steel contact, the slip friction coefficient was adopted at the standard value 0.30.

According to ASME B31.3 (see paragraph 302.3.6), the external wind and seismic loads were considered as occasional loads.

3. Initial calculation data and load cases

The initial calculation data are presented in table 3.

Table 3. Initial calculation data.

Line name	**PG-190-110-750-BX1M1-H**
From	190 S-1 / N2-750
to	190 S-2_S-3 / N1-750
Nominal diameter	DN750
Wall thickness [mm]	9.53
Material	API5L GR.B
Flanges	150#
Design pressure – p_1 [kPa]	400
Design temperature - t_1 [°C]	370
Minimum temperature in winter- t_2 [°C]	-29
Corrosion [mm]	1
Working fluid	Process gas
Fluid density [kg/cm^3]	0.0000009
Test pressure [kPa]	730
Test fluid	air
Insulation thickness [mm]	130
Insulation density [kg/cm^3]	0.00010

The isometric and the numerical model related to the analyzed system can be seen in figure 1, respectively figure 2.

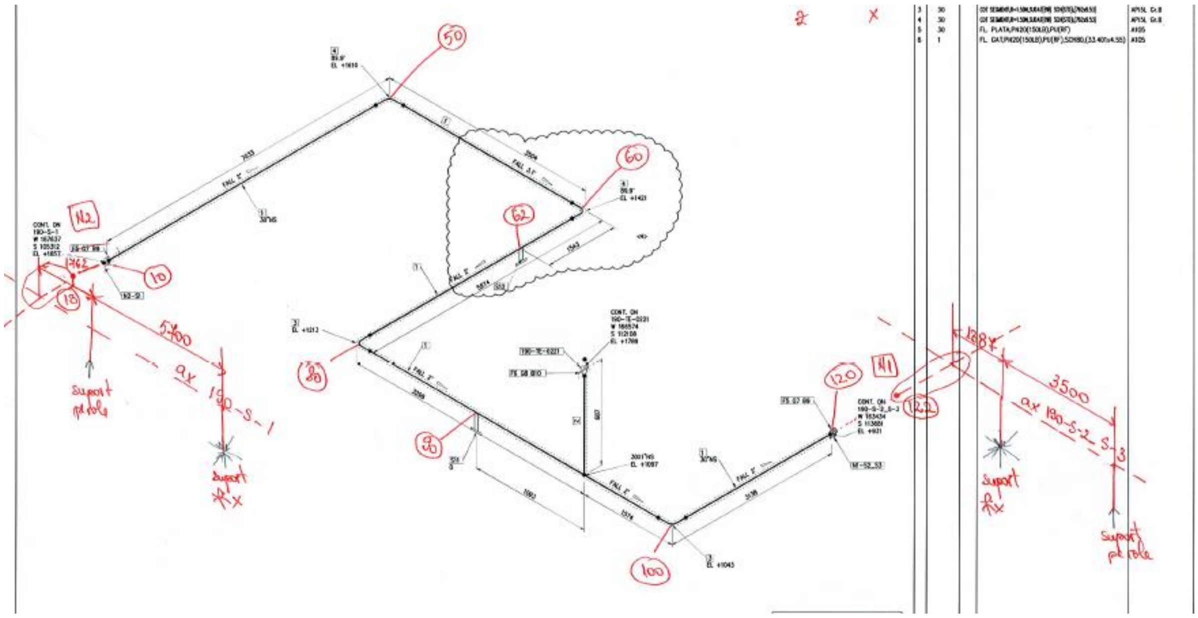

Figure 1. Isometric model related to the analyzed system.

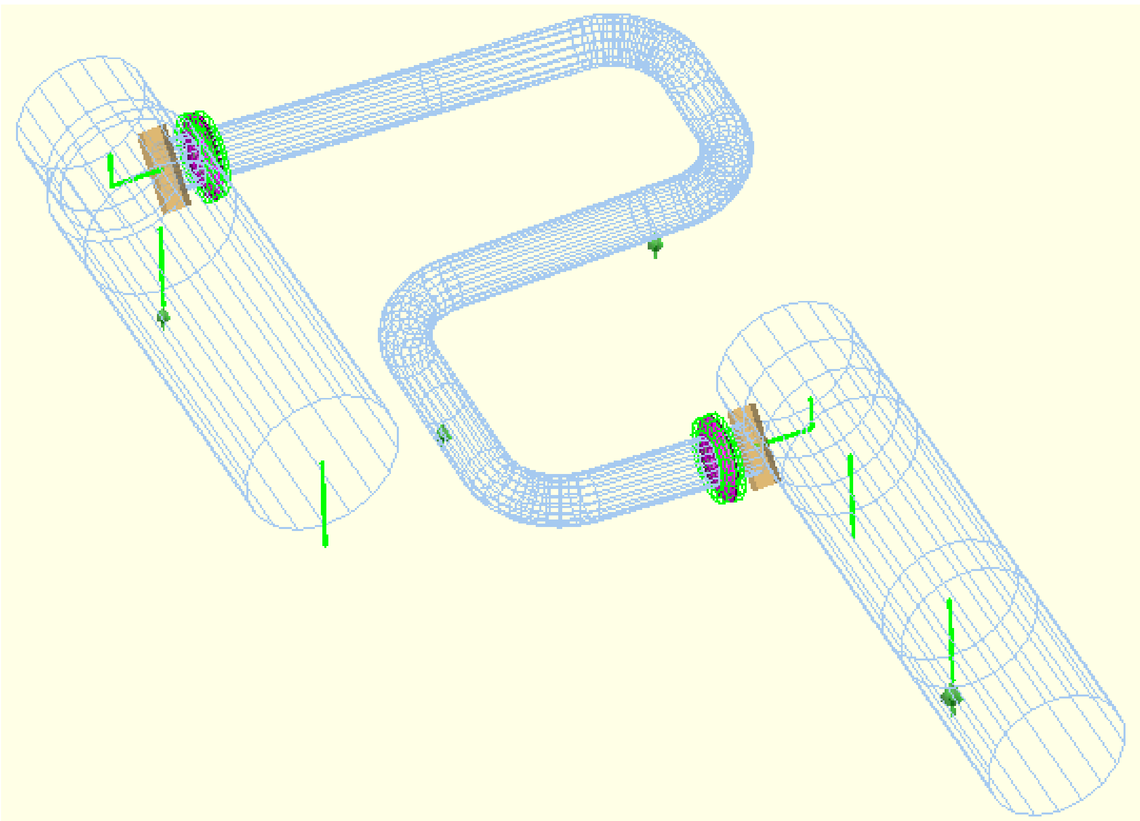

Figure 2. Numerical model related to the analyzed system.

Tables 4, 5 and 6 summarize the load cases considered in the analysis.

Table 4. Load cases details.

<table>
<tr><th colspan="4">The case of quasi-permanent static and occasional loads
- internal pressure, gravitational loads, thermal expansion,
wind and seismic loads</th></tr>
<tr><th colspan="2">Load case</th><th rowspan="2">Individual loads considered</th><th rowspan="2">Interpretation</th></tr>
<tr><th>Symbol</th><th>Name</th></tr>
<tr><td>L1</td><td>Gravitational load</td><td>Gravitational loads (W) – the weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid</td><td>L1 = W (HGR)</td></tr>
<tr><td>L2</td><td>Operation under the specified calculation conditions (“Design”)</td><td>Gravitational loads (W) – the weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid
Internal pressure corresponding to the calculation manometric pressure (P_1)
Thermal expansion from the installation temperature t_{inst} = +21 ^{0}C to the calculation temperature T_1</td><td>L2 = W+T1+P1 (HGR)</td></tr>
<tr><td>L3</td><td>Hydraulic Pressure Test</td><td>Gravitational loads (WW) – the weight of the pipe components and the water weight
The internal pressure corresponding to the test manometric pressure (HP)</td><td>L3 = WW + HP (HYD)</td></tr>
<tr><td>L4</td><td>Initial system state</td><td>Gravitational loads of pipes without working fluid (WNC) – weight of pipe components, together with the weight of the thermal insulation and/or the inner covering</td><td>L4 = WNC (OPE)</td></tr>
<tr><td>L5</td><td>Primary Static Load (so-called "Permanent")</td><td>Gravitational loads (W) – the weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid
Internal pressure corresponding to the calculation manometric pressure (P_1)</td><td>L5 = W + P1 (SUS)</td></tr>
<tr><td>L6</td><td>Operation under the specified calculation conditions (“Design”)</td><td>Gravitational loads (W) – The weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid
Internal pressure corresponding to the calculation manometric pressure (P_1)
Thermal expansion from the installation temperature t_{inst}=+21 ^{0}C to the calculation temperature T_1</td><td>L6 = W+T1+P1 (OPE)</td></tr>
</table>

The case of quasi-permanent static and occasional loads - internal pressure, gravitational loads, thermal expansion, wind and seismic loads			
Load case		**Individual loads considered**	**Interpretation**
Symbol	**Name**		
L7	Thermal contraction in the Stand-By situation during the winter ("Winter Stand-By")	Gravitational loads (*WNC*) – The weight of the pipe components and the weight of the thermal insulation Thermal contraction from from the installation temperature t_{inst}=+21 ^{0}C to minimum metallic wall temperature T_2 = -29^{0} C	L7 = WNC+T2 (OPE)
L8	Operation in winter conditions ("Operating")	Gravitational loads (*W*) – the weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid Internal pressure corresponding to the calculation manometric pressure (P_1) Thermal expansion from the installation temperature t_{inst} = +21 ^{0}C to the calculation temperature T_2	L8 = W+T2+P1 (OPE)
L9 L10 L11 L12	Wind action under the specified calculation conditions ("Design")	Gravitational loads (*W*) – the weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid Internal pressure corresponding to the calculation manometric pressure (P_1) Thermal expansion from the installation temperature t_{inst} = +21 ^{0}C to the calculation temperature T_1 The wind distributed load: ±WIN1 = the wind distributed load in directions ± X ; ±WIN2 =the wind distributed load in directions ± Z	L10, L9 = W+T1+P1±WIN1 (OPE) L12, L11 = W+T1+P1 ±WIN2 (OPE)
L13 L14 L15 L16	Seismic action under the specified calculation conditions ("Design")	Gravitational loads (*W*) – The weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid Internal pressure corresponding to the calculation manometric pressure (P_1) Thermal expansion from the installation temperature t_{inst} = +21 ^{0}C to the calculation temperature T_1 The seismic distributed load: ±U1 = seismic acceleration $a_s = 0.24 \times g$, in directions ± X ; ±U2 = seismic acceleration $a_s = 0.24 \times g$, in directions ± Z	L14, L13 = W+T1+P1±U1 (OPE) L16, L15 = W+T1+P1±U2 (OPE)

Table 5. Load cases details.

Load case		Individual loads considered	Interpretation
Symbol	Name		
L17	Thermal expansion under the specified calculation conditions ("Design")	Thermal expansion from the installation temperature t_{inst}=+21 ^{0}C to the calculation temperature T_1	L17 = L6 – L5 (EXP)
L18	Thermal contraction in the stand-by situation during the winter ("Winter Stand-By")	Thermal contraction from the installation temperature t_{inst}=+21 ^{0}C to minimum metallic wall temperature T_2 = -29^0 C	L18 = L7 – L5 (EXP)
L19	Total thermal expansion under the specified calculation conditions ("Design")	Thermal expansion from the minimum metallic wall temperature t_2 = -29^0 C to the calculation temperature t_1	L19 = L6 – L7 (EXP)
L20 L21 L22 L23	Occasional wind load	The wind distributed load: ±WIN1 = wind distributed load in the directions ± X ; ±WIN2 = = wind distributed load in the directions ± Z	L20 = L9 – L6 (OCC) L21 = L10 – L6 (OCC) L22 = L11 – L6 (OCC) L23 = L12 – L6 (OCC) Represents the exclusively wind loads applied to the pipeline system

Table 6. Load cases details.

Load case		Individual loads considered	Interpretation
Symbol	Name		
L24 L25 L26 L27	Occasional seismic load	The seismic distributed load: ±U1 = seismic acceleration $a_s = 0.24 \times g$, in directions ± X ; ±U2 = seismic acceleration $a_s = 0.24 \times g$, in directions ± Z	L24 = L13 – L6 (OCC) L25 = L14 – L6 (OCC) L26 = L15 – L6 (OCC) L27 = L16 – L6 (OCC) Represents the exclusively seismic loads applied to the pipeline system
L28 L29 L30 L31	Occasional wind resulting load	Gravitational loads (*W*) – The weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid Internal pressure corresponding to the calculation manometric pressure (P_1) The wind distributed load: ±WIN1 = the wind distributed load in directions ± X ; ±WIN2 =the wind distributed load in directions ± Z	L28 = L5 + L20 (OCC) L29 = L5 + L21 (OCC) L30 = L5 + L22 (OCC) L31 = L5 + L23 (OCC)

Load case		Individual loads considered	Interpretation
Symbol	**Name**		
L32 L33 L34 L35	Occasional seismic resulting load	Gravitational loads (W) – The weight of the pipe components, the weight of the thermal insulation and the weight of the working fluid Internal pressure corresponding to the calculation manometric pressure (P_1) The seismic distributed load: ±U1 = seismic acceleration $a_s = 0.24 \times g$, in directions ± X ; ±U2 = seismic acceleration $a_s = 0.24 \times g$, in directions ± Z	L32 = L5 + L24 (OCC) L33 = L5 + L25 (OCC) L34 = L5 + L26 (OCC) L35 = L5 + L27 (OCC)

4.Results

In table 7 are given the numerical results regarding the values of maximum displacements in pipes.

Table 7. The values of maximum displacements in pipes.

X-X direction	-34.8612 mm	Node 126 – Case L19
Y-Y direction	-1.5682 mm	Node 49 (from permanent loads) – Case no. L5
Y-Y direction	-1.5522 mm	Node 49 (from test loads) – Case no. L1
Y-Y direction	3.4821 mm	Node 150 – Case no. 6
Z-Z direction	-37.4107 mm	Node 49 – Case no. 6

The maximum stresses in pipes can be observed in figure 3.

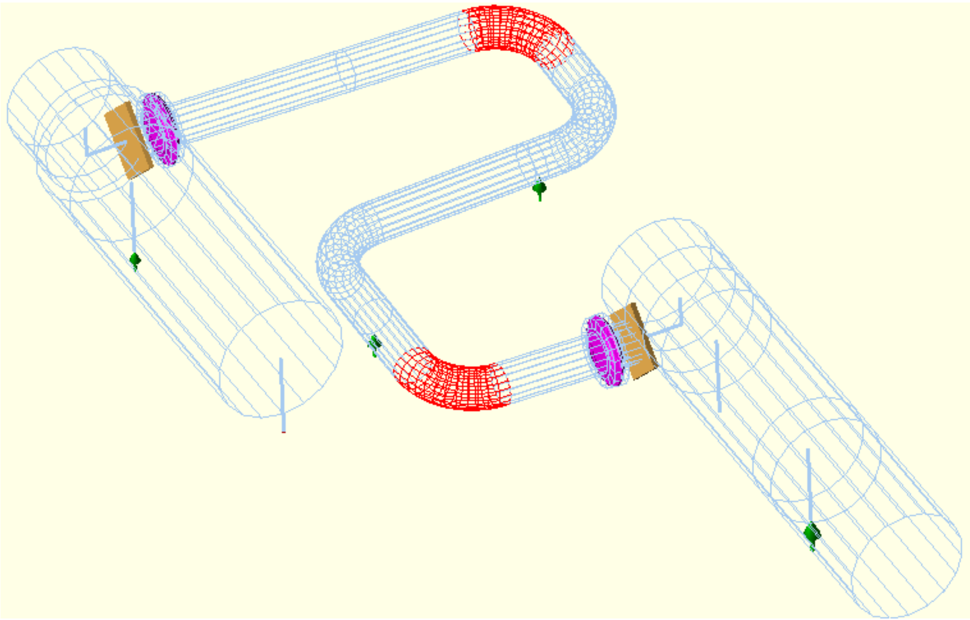

Figure 3. The maximum stress value in case of impeded thermal expansions.

In table 8 are presented the calculated and the allowable stresses for the analyzed pipe.

Table 8. Comparison between the calculated and allowable stress values for the analyzed pipe.

Case	Calculated stress kPa	Allowable stress kPa	Percent
Test conditions (hydraulic or pneumatic)	24705.7	217179.0	11.4
Permanent loads Case 5	54644	116484.3	46.9
Thermal expansion (maximum from expansion L17…L19) Case no. L19	80262.2	200839.2	40.0
Ocassional wind loads (maximum from L28…L31) Case no. L29	54761.0	154923.4	35.3
Ocassional seismic loads (maximum from L32…L35) Case no. L34	55341.2	154923.4	35.7

Loads in equipment connections

In tables 9 and 10 are presented the loads for the pipe sockets.

Table 9. Loads for 190-S-1; Socket N2

Load case	Node number	Forces - N			Moments - N·m		
		x	y	z	x	y	z
1(HYD) WNC+P1 Note 1	13	-442	-14935	-16	-35587	2924	9311
4(OPE) WNC	13	-241	-14993	-253	-36059	2184	9278
5(SUS) W+P1	13	1322	**-15284**	-209	**-37214**	-8673	9936
6(OPE) W+T1+P1	13	3350	-13120	17495	-29892	-80572	16383
7(OPE) WNC+T2	13	-2883	-13898	-3492	-29046	29113	9182
8(OPE) W+T2+P1	13	-2103	-14171	-3385	-30088	23910	9636
9(OPE) W+T1+P1+WIN1	13	7618	-13126	16917	-29775	-97966	16840
10(OPE) W+T1+P1-WIN1	13	-925	-13115	18074	-30010	-63138	15925

Load case	Node number	Forces - N			Moments - N·m		
		x	y	z	x	y	z
11(OPE) W+T1+P1+WIN2	13	3799	-13311	19394	-31451	-85490	16345
12(OPE) W+T1+P1-WIN2	13	2900	-12930	15589	-28333	-75646	16421
13(OPE) W+T1+P1+U1	13	**8828**	-13134	16833	-29821	**-101695**	16949
14(OPE) W+T1+P1-U1	13	-2139	-13107	18159	-29963	-59379	15815
15(OPE) W+T1+P1+U2	13	5174	-13914	**23992**	-36414	-95101	15523
16(OPE) W+T1+P1-U2	13	1465	-12328	10937	-23355	-65496	**17226**
Allowable		**-**	**-**	**45000**	**67500**	**87750**	**-**

Table 10. Loads for 190-S-2_S-3; Socket N1

Load case	Node number	Forces - N			Moments - N·m		
		x	y	z	x	y	z
1(HYD) WNC+P1 Note 1	122	1397	-5960	-1336	3176	3814	-2659
4(OPE) WNC	122	-24	-5880	96	3105	-159	-2651
5(SUS) W+P1	122	1890	-5972	-1478	3092	5249	-2861
6(OPE) W+T1+P1	122	2254	-7719	-12956	6373	-52916	1723
7(OPE) WNC+T2	122	-3733	-2473	2241	-7199	-6664	**-8642**
8(OPE) W+T2+P1	122	-4048	-2528	1978	**-7234**	-8156	-8606
9(OPE) W+T1+P1+WIN1	122	6220	-7798	-12317	6778	-42090	1364
10(OPE) W+T1+P1-WIN1	122	-1716	-7641	-13599	5967	-63762	2082
11(OPE) W+T1+P1+WIN2	122	-1976	-7776	-11027	6697	-50712	1813
12(OPE) W+T1+P1-WIN2	122	-2532	-7663	-14890	6049	-55130	1632
13(OPE) W+T1+P1+U1	122	**8408**	-7843	-12217	6969	-36482	1195
14(OPE) W+T1+P1-U1	122	-3909	-7596	-13701	5776	**-69385**	2252

Load case	Node number	Forces - N			Moments - N·m		
		x	y	z	x	y	z
15(OPE) W+T1+P1+U2	122	1090	**-7972**	-8549	7104	-48973	2345
16(OPE) W+T1+P1-U2	122	3369	-7469	**-17433**	5634	-57160	1109
Allowable		-	-	**45000**	**67500**	**87750**	-

Flange analysis - equivalent pressure method

The flange loads were calculated under operating-design conditions as well as under test conditions.

Under operating-design conditions, the calculations were performed taking into account the loss of thickness by corrosion, for the flanges.

They were checked with the equivalent pressure method and for those that do not fall within the allowed ones, the checks were performed according to ASME Section VIII Div.1. The checks were made considering the same type of flange (material, rating) for the flange with the higher loads according to the equivalent pressure method.

The tables 11 and 12 show the results of the verification calculations with the equivalent pressure method (in the operating-design conditions, respectively test). Flanges that do not fall within the permitted ones are shown with "*" .

Table 11. The verification calculation in the operating-design conditions - Flange Peq : 6 (OPE) W+T1+P1

NODE	Axial Force, N	Bending Moment, N·m	G/C mm.	*P* Equivalent kPa	Rating Temperature ºC	Allowable Pressure /Stress	Ratio %	
10	17170	82187	787.40	1292.68	370.03	762.54	169.52	*
20								
110								
120	13114	54293	787.40	993.34	370.03	762.54	130.27	*

Table 12. The verification calculation in the test conditions - Flange Peq : 1 (HYD) WNC+P1

NODE	Axial Force, N	Bending Moment, N·m	G/C mm.	P Equivalent kPa	Rating Temperature ºC	Allowable Pressure /Stress	Ratio %	
10	395	27383	787.40	1016.47	20.00	2613.40	38.89	
20								
110								
120	1440	3138	787.40	765.68	20.00	2613.40	29.30	

P_1 represents the pneumatic test pressure and has the value of 730 kPa.

5. Conclusions

The calculation resulted in the stresses values for each finite element of pipe, given by the primary loads (own weight + internal pressure) and the secondary loads (induced by thermal expansion, including the thermal displacements of the equipment connection points). These stresses are below the maximum allowable limits (determined according to ASME code B31.3) which leads to the conclusion that the analyzed piping system satisfies the requirements of the mechanical strength calculation.

The stresses resulting from the pneumatic pressure test are below the maximum allowable limits (determined according to ASME Code B31.3).

The loads (forces and moments) coming from the pipe were compared with the allowable loads for the equipment connections. From this comparison it results that these loads are below the allowable ones. Where the loads resulting from the calculation exceeded the allowable loads on the equipment connections, they were verified using finite element analysis (FEA), there being no overstress in the related connections. The connection meets the ASME requirements in terms of existing stresses.

The flange loads were calculated under the operating-design and test conditions and were verified with the equivalent pressure method (respectively ASME Section VIII Div.1), obtaining admissible values.

In conclusion, it can be said that the piping system is safe and does not endanger the installation safety. This conclusion is valid with the condition that the manufacturer respects all the data provided by the designer (material, wall thickness, geometric dimensions and supports location, etc.).

6. References

[1] ASME B31.3. Process Pressure Piping Code, 2006
[2] Caesar II Software
[3] P100-1, Cod de proiectare seismică, 2013
[4] NP-082-04, Cod de proiectare. Bazele proiectării și acțiuni asupra construcțiilor. Acțiunea vântului, 2004