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A Methodology for Flexibility Analysis of Process Piping

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Design of piping system requires a systematic consideration of various factors as addressed by the codes and standards. This research paper aims to provide a method for flexibility analysis of selected area of process piping at an industrial plant. Analysis is done for the purpose of accommodating a spare heat exchanger in the process layout. The analysis follows a systematic procedure, with preparation of a tentative model of the system on CAESAR II software followed by insertion of different pipe supports. The selection and location of these supports is based on the results obtained from displacement, stress, reaction and equipment nozzle analysis of the piping system. The design is in accordance with ASME B31.3, which are the standard codes for process piping.

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Nomenclature

W Uniformly distributed weight of piping, N/m.
W_c Concentrated weight on piping, N.
L Span Length, m.
E Modulus of elasticity of pipe in, N/m^2.
I Moment of inertia of pipe, m^4.
d_o Outer diameter, m.
$\triangle T$ Change in temperature, °C.
a Linear expansion coefficient, m/m°C.
P Internal pressure inside the pipe, N/m^2.
d Inner diameter, m.
t Thickness of circular cross section, m.
E Modulus of elasticity of pipe in N/m^2
v Poisson ratio for the material.
S Allowable stress value for material from Table A-1 of ASME B31.3 code, Pa.
e Quality factor from Table A-1A9 or A-1B of ASME B31.3 code.

w Weld joint strength reduction factor per Para. 302.3.5 of ASME B31.3 code.

Y Coefficient from Table 304.1.1, valid for $t < D/6$ and for materials shown, of ASME B31.3code.

S_L Longitudinal stress due to sustained loads such as pressure and weight, Pa.

S_h Hot allowable stress for the material in the hot operating condition, which would be the design temperature for elevated temperature service or ambient for cold or cryogenic service, Pa. Table A-1 of ASME B31.3 Code.

S_E Displacement stress range, Pa.

S_A Allowable stress range, Pa

C Cold spring factor varying from zero for no cold spring to 1.0 for 100% cold spring.

E_a Reference modulus of elasticity at 21°C, Pa.

E_m Modulus of elasticity at maximum or minimum temperature, Pa.

R Range of reaction forces or moments (derived from flexibility analysis), N.

R_m Estimated instantaneous maximum reaction force or moment at maximum or minimum temperature, N.

1 Introduction

A piping system is crucial to any process plant hence it needs to be designed with precision and care. The efficiency of a plant highly depends on its ability to transport fluid through the pipes to equipments functioning collectively. A piping system, owing to its crucial role of fluid transport, requires a systematic analysis by various engineering methods prior to its construction [1]. Piping system is needed to be supported to prevent failure due to various loading conditions (self-weight, operating pressure and temperature) [2, 3].

The main concern for designing any process plant is safety of personnel involved. Design of piping systems complying the codes, standards or recommended practices ensures safety along with standardization of required items [4]. Flexibility analysis is concerned with the ability of pipe to change its length and deform elastically. Piping system must be flexible enough to cater for excessive thermal expansion or movement of support or pipe end points, thus preventing failure of pipe and support structure due to excessive stress [5]. The considerations deciding the minimum permissible flexibility on a piping system are as follows:

1. Displacements existing within the piping system.

2. Maximum allowable limit of stress range in the system.

3. Maximum allowable forces and moments that the piping system can impose on the connected equipment.

4. Maximum allowable load that can be applied on the supporting structure. In this paper, a systematic procedure is developed for determining and enhancing the flexibility of process piping. Flexibility analysis will be carried out under design operating conditions occurring in the system. For this purpose, CAESAR-II software will be used. It works by creating a piping system model, using simple beam elements, and defining the loading condition imposed on the system. With this input, CAESAR II produces results in the form of displacements, reactions, and stresses throughout the system. Most importantly, these results are compared with the limits specified by recognized codes and standards.

Deciding about the supports location is very important in flexibility analysis because any wrong location of support may lead to failure of a whole system [5, 6]. In this paper, the focus is mainly on the selection and placement of piping support. For this purpose, first the maximum span calculation is carried out by considering all loading conditions. Support locations and types are then inserted and adjusted until all flexibility (displacement, stress, reaction and nozzle) requirements are satisfied.

2 Material and Methods

Majority of the previous research is observed to be based wholly on either the software or analytical approach [7]. This may leads to either over conservative or under conservative results from the analysis [8]. For instance, in determining the displacements existing within the piping network, the span equation derived accounts only for the deadweight of the pipe [9]. There is a lack of systematic analysis accounting for both the theoretical and software approach [10–13]. This paper attempts to highlight a procedure of flexibility analysis which will lead to improved results and clear understanding of different constraints involved in the flexibility analysis of piping system. After modelling the whole system on CAESAR II software, displacement analysis was first done to determine the maximum support span and restraint locations. The maximum span calculation is carried out by considering all loading conditions. The stress analysis was done with the software, yielding two stress distribution diagrams for primary and secondary stresses respectively. After that, the system is checked for the reaction forces acting at the supports, and finally the connecting equipment nozzles are checked to ensure their integrity in the structure, thereby verifying the complete design of the system. Each of the four components of flexibility analysis has a crucial role in determining the consideration for a safe piping system design.

The analysis is done keeping in view the basic loading conditions existing in the piping system i.e., temperature, pressure and weight. The analysis covers the displacements, stresses, reaction loads and connected equipment loads existing in the system.

Few of the important results for a test model will be supported and validated by analytical solutions wherever possible. The design considerations associated with flexibility and stress analysis will be covered, keeping in view the piping layout, the recommended piping standards and the isometric drawings provided by the process industry.

3 Theory/Calculation

3.1 Design specifications of the model

The first step in carrying out the flexibility analysis is to model the entire heat exchanger layout in Caesar II software.

Table 1. Design operating conditions of the system.

No.	Pipe line	Design Temperature (°C)	Design Pressure (kPa)
1	Pump G1-604 B Inlet	170	420
2	Pump G1-604 A Inlet	170	420
3	Outlet Piping Extension	170	420
4	Inlet Piping Extension	170	420
5	Inlet Piping to the Heat Exchanger	170	420
6	Outlet Piping to the Heat Exchanger	170	420
7	Shell outlet piping	75	700
8	Shell inlet piping	250	4000
9	Heat exchanger Shell	224	2500

Table 2. Maximum allowable displacements as per industry requirement

Displacement	X-Dir.	Y-Dir	Z-Dir
Allowable Value	5mm - 8mm	0.5mm	5mm - 8mm

This was accomplished by using the isometrics and third angle projection drawings of different components of the heat exchanger layout. The heat exchanger in consideration is of shell and tube type. It is required to heat the Acetic Acid fluid in the tube side under normal operation. The heat exchanger uses high pressure steam on the shell inlet side as the heating medium. The shell outlet side pipe contains the condensed water resulting from this heat transfer process. Fig. 1 is the isometric drawing of heat exchanger obtained from the software. The drawing serves to divide the exchanger unit into nine distinct parts.

Table 1 summarizes the design operating conditions existing in various parts of heat exchanger unit.

3.2 Displacement analysis

The data for maximum allowable displacements in three directions was provided by the industry and summarized in Table 2.

It was decided to calculate the support span for inlet piping to heat exchanger. The value of span of support obtained was also implemented for other piping with considerations to design temperature and pressure. Deflection in –y direction for span support was divided into 3 parts, as shown in Eq. 1 and 2 [14, 15].

$$Y = Y_{weight} + Y_{pressure} + Y_{temperature} \quad (1)$$

$$Y = \frac{5WL^4 + 8W_cL^3}{384EI} + \frac{pd^2(2-v)}{4tE} + d_o\Delta T_a \quad (2)$$

Following data of inlet process piping was used:

Wc = 373.762 N (Weight of 2 flanges)
W = 3772.6N/12.355 m=305.35 N/m
Y = 0.0005 m
E = 1.8485 x 10^{11}Pa [16]
I = $(\pi d_i^4 - \pi d_o^4)/64$= 6.7658 X 10-6 m^4
$a\Delta T$ = 0.002550 m/m [16]
v = 0.292
d_i = 0.168275 m
d_o = 0.1750822 m
p = 420000 Pa (design Pressure)
t = 0.0034036 m

3.3 Stress Analysis

For most piping systems, two major types of stresses are encountered. These are classified as primary and secondary stresses. Primary stresses are generated by imposed loadings necessary to satisfy the equilibrium of internal and external forces and moments. The secondary stresses in a piping system are associated with cyclic conditions such as temperature increase or decrease, as the plant starts up or shut down.

3.3.1 Primary stress criteria

In ASME B31.3 code [17], there are two major criteria for primary stresses:

1. Stresses due to internal pressure shall be considered safe when the wall thickness of the piping component, including any reinforcement, shall not be less than that calculated in accordance with Eq. 3 [16].

$$t_m = \frac{PD}{2(Sew + PY)} \quad (3)$$

2. The sum of the longitudinal stresses due to pressure, weight and other sustained loadings S_L must be lesser than S_h, hot allowable stress for a hot operating system.

$$S_L \leq S_h \quad (4)$$

3.3.2 Secondary stress criteria

In ASME B31.3 code, one major criterion exists for secondary stresses [16, 18]:

$$S_E \leq S_A \quad (5)$$

$S_A$serves as a stress limit for stresses that are repetitive and cyclic. It is the allowable stress to be compared to the calculated displacement stress range, S_E. Both S_A and S_E are secondary stresses. S_E is the range of (secondary) stress a piping system will experience subjected to thermal expansion or contraction. The temperature range for this condition is the total expansion range from minimum to maximum for hot operating systems and from maximum to minimum for cryogenic or cold pipe [19].

3.4 Reaction Analysis

ASME B31.3 code doesn't provide clear cut equations and conventions for evaluating maximum reactions for complex systems like multi anchor piping systems or two anchor systems with intermediate restraints. However, it provides an equation for calculating the estimated instantaneous maximum reaction force or moment, applicable only to a two anchor piping system without intermediate restraints. The equation is as follows

$$R_m = \frac{R[1-2c/3]E_m}{E_a} \tag{6}$$

C is the intentional deformation of piping during assembly to produce a desired initial displacement and stress.

This equation is not applicable for the considered system, because of two main reasons:

1. The piping system addressed by the code equation is a simple one. For multi anchor piping systems and for two-anchor systems with intermediate restraints, the above equation is not applicable. Each case must be studied to estimate location, nature, and extent of local overstrain, and its effect on stress distribution and reactions.

2. The reactions calculated only takes account of the temperature effect while the effect of pressure and weight forces is not considered.

Based on the above facts, it is reasonable to conclude that calculating reaction forces through theoretical analysis is a daunting and time consuming task. A much wiser approach would be to calculate reaction forces at normal operating conditions with the help of software analysis. For our case, the latter approach was adopted and the resulting discussion for reaction forces will be based on the software results.

ASME B31.3 code states that one of the main criterion for permissible reaction forces is based on the resulting stress distribution occurring on the system [16]. As long as primary and secondary stresses occurring in the system remain under the stated allowable stress limits, the flexibility analysis criterion set for reaction forces is passed.

3.5 Nozzle Analysis

Nozzles are one of the most sensitive and critical components of piping system, since they serve to connect the equipment with adjoining pipe network. In case of nozzle failure, entire design of piping system needs to be reconsidered [5]. In our heat exchanger system, there are total six nozzles- four located at the heat exchanger shell region and two at the pump side region. The exact location of these nozzles can be seen in Fig. 1. A set of allowable loads for nozzle in the form of forces and moments is usually provided by equipment designer in the isometrics or third angle projection drawings. Comparison of actual forces and moments imposed by the adjacent piping system on the nozzles with the allowable limits is done to check for nozzle integrity.

4 Result and Discussion

4.1 Displacement analysis

After substituting the input parameter values for inlet process piping in Eq. 2, the value of L for which the Eq. 2 equals zero is L = 1.68 m. For most parts of heat exchanger model, the support span was varied between 1m and 1.7m for keeping a symmetrical support configuration. For restricting the x and z displacements to the above mentioned allowable limits, Y supports were provided at proper locations in the software model, keeping in view the span length derived previously. The static analysis of model was done and displacements in x and z directions were observed at various locations. The model configuration and the values of some of the highest displacements obtained are shown in Fig. 2.

Fig. 3 shows the location and type of supports and restraints used for restricting the displacements in all three directions. The wire frame configuration is used here in order to show the hidden supports along the pipe length.

The results obtained from the displacement analysis in all three directions are summarized by the displacement bar charts shown in Figures 4, 5 and 6. From the figures, it can be observed that displacements are within the allowable range.

4.2 Stress Analysis

4.2.1 Code compliance results for wall thickness

The actual wall thickness t_{actual} (pipe schedule) is then compared with the respective minimum thickness value t_m calculated by the Eq. 3. The results are summarized in Table 3.

From Table 3, it can be observed that tactual is greater than tm. Therefore, the heat exchanger system passes the first criterion for primary stress.

4.2.2 Code compliance results for longitudinal stresses

The stress analysis was run on the heat exchanger software model so far constructed at the end of displacement analysis (Fig. 3). Stress percentage distribution diagram in Fig. 5 for longitudinal stress with respect to hot allowable stress was obtained. The highest stress percentage location is also highlighted. From Fig. 5, it can be seen that stresses are well under limits with highest stress percentage of 30.28%. High stress occurring region is the heat exchanger shell because it has the highest pressure and weight loads in the system.

Table 3. Comparison of calculated and minimum required thickness

No.	Component of Heat Exchanger	t_m (mm)	t_{actual} (mm)
1	Pump G1-604 B Inlet	0.34	7.11
2	Pump G1-604 A Inlet	0.34	7.11
3	Outlet Pipeline Extension	0.327	3.40
4	Inlet Pipeline Extension	0.327	3.40
5	Inlet Pipeline to the Heat Exchanger	0.327	3.40
6	Outlet Pipeline to the Heat Exchanger	0.327	3.40
7	Shell outlet pipeline	0.482	10.98
8	Shell inlet pipeline	1.024	5.54

4.2.3 Code compliance results for secondary stresses

From the software analysis, stress percentage distribution diagram in Fig. 6 for displacement stress range with respect to allowable stress range was obtained. The highest stress percentage location is also highlighted. From Figure 6, it can be seen that thermal stresses are well under limits with the highest stress percentage of 45.87%. The high stress occurring region is the shell inlet pipe because among the piping, it has the highest temperature in the system.

Based on the above results, it can be concluded that the heat exchanger system has passed the stress analysis check as directed by ASME B31.3 code.

4.3 Reaction Analysis

In our system, based on the results of stress analysis mentioned in the previous section, the reaction forces are within the allowable limit range. There is a possibility that magnitude of zero reaction forces may occur at some places, due to lifting up of pipe, rendering the rest supports use less. In that case, either those supports have to be removed for economic reasons or adjustments of nearby supports have to be done to account for efficient load distribution. Fig. 7 shows the support locations where magnitude of reaction force was coming out to be zero.

After removal and readjustment of some supports, all the zero reaction force supports were removed from the model. Fig. 8 configuration was obtained. The total number of supporting elements amount to around 50.

4.4 Nozzle Analysis

The results are obtained for the heat exchanger model constructed after the reaction analysis. They are based on design conditions provided for the system. The load limits are based on the local coordinate system ABC, [20] where:

• A - Pipe/nozzle axis

• B - Major equipment axis (the longitudinal direction of a vessel, or the pump shaft direction).

• C - Other perpendicular direction.

Table 4 summarizes the allowable and actual values of forces and moments occurring at the nozzle locations.

From the above table, it can be observed that the forces and moments on the nozzles are under the stated allowable limits. Therefore, all nozzles have passed the criteria of allowable loads set by the equipment designer.

5 Conclusion

In this paper, a systematic procedure is developed for determining and enhancing the flexibility of process piping. Apart from the contemporary principles in pipe engineering, the procedure also utilizes the extensive application of CAESAR II software. Using these tools, the design considerations relating to displacements, stresses, reactions and equipment nozzle loads present in the system are addressed, keeping in view the constraints of ASME B31.3 code for process piping. Each of the four components of flexibility analysis has distinct allowable limit criteria and is made to link systematically with each other. The future work includes modification in the routing of piping system to further reduce the thermal stress values. This will help in reducing the magnitude of the reaction forces and will overall enhance the flexibility of the system.

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Table 4. Summary of allowable and actual nozzle loads

Forces and Moments	Shell outlet pipe nozzle		Shell inlet pipe nozzle		Inlet process pipe nozzle		Outlet process pipe nozzle		Pump G1-604A inlet pipe nozzle		Pump G1-604B inlet pipe nozzle	
	Allowable	Actual	Allowable	Actual	Allowable	Actual	Allowable	Actual	Allowable	Actual	Allowable	Actual
F_a(N)	5000	-1827	1000	-280	20000	-1666	18000	-1587	4671	-158	4671	-21
F_b(N)	5000	121	1000	-235	20000	180	18000	-801	4671	-856	4671	116
F_c(N)	5000	-113	1000	531	20000	218	18000	-7227	-4671	0	-4671	0
M_a(Nm)	3000	53	200	-172	16000	992	14000	-409	1898	0	1898	0
M_b(Nm)	3000	-910	200	29	16000	353	14000	3440	1898	0	1898	0
M_c(Nm)	3000	30	200	-110	16000	521	14000	-777	-1898	-79	-1898	5

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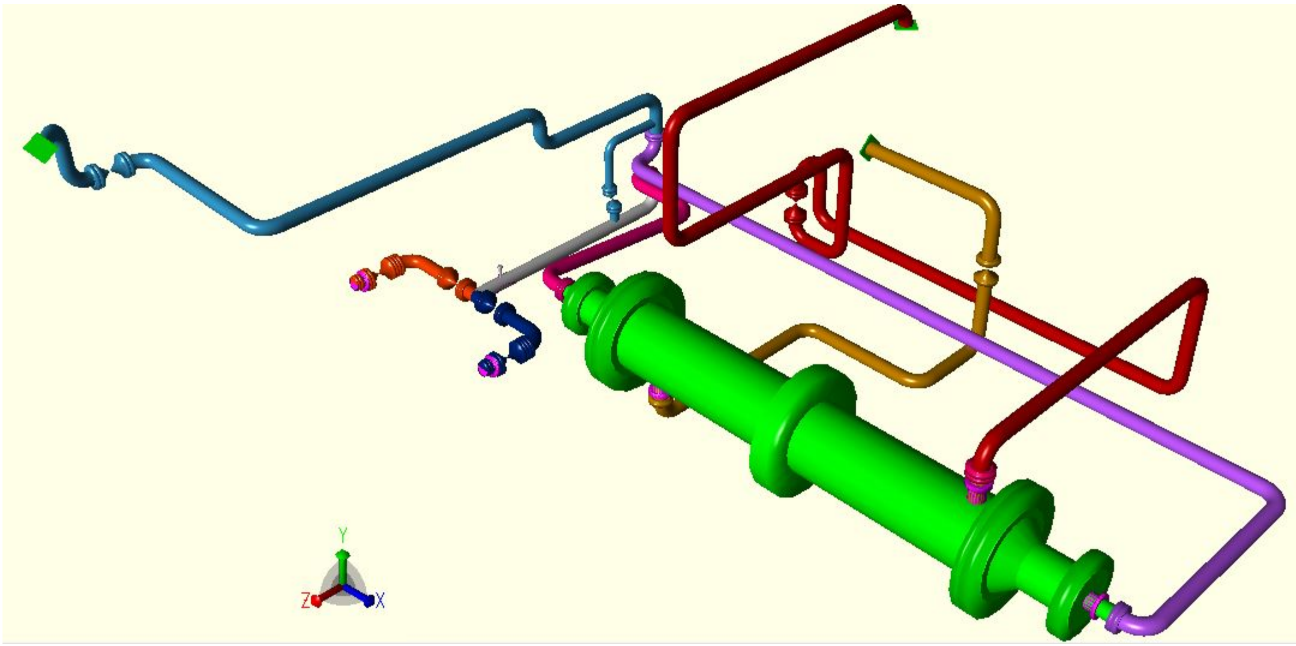

Parts Legend								
1.		Pump G1-604 B Inlet	4.		Inlet Piping Extension	7.		Shell outlet piping
2.		Pump G1-604 A Inlet	5.		Inlet Piping to the Heat Exchanger	8.		Shell inlet piping
3.		Outlet Piping Extension	6.		Outlet Piping to the Heat Exchanger	9.		Heat Exchanger Shell

Fig. 1. Schematic of Heat Exchanger divided in 9 parts

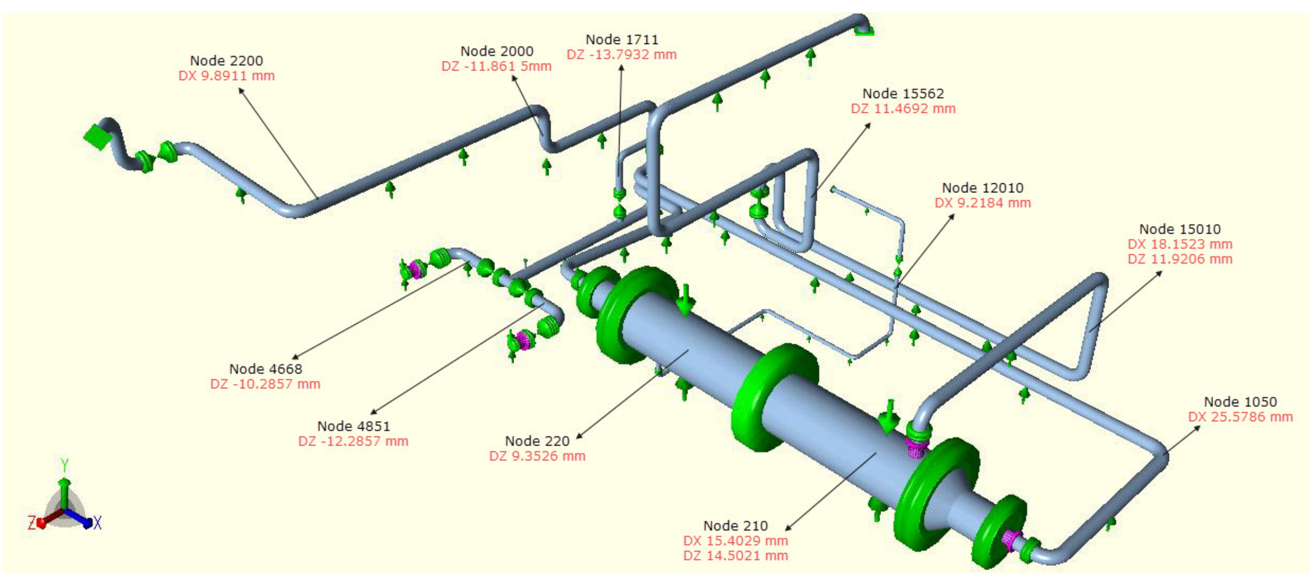

Fig. 2. Model configuration and the values of some of the highest displacements

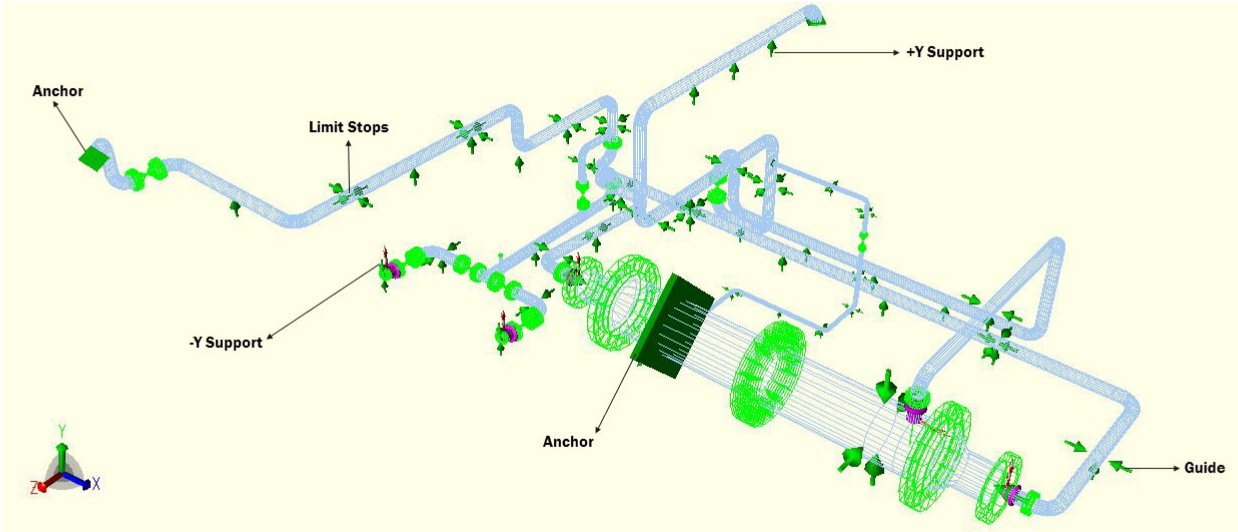

Fig. 3. Location and type of supports and restraints

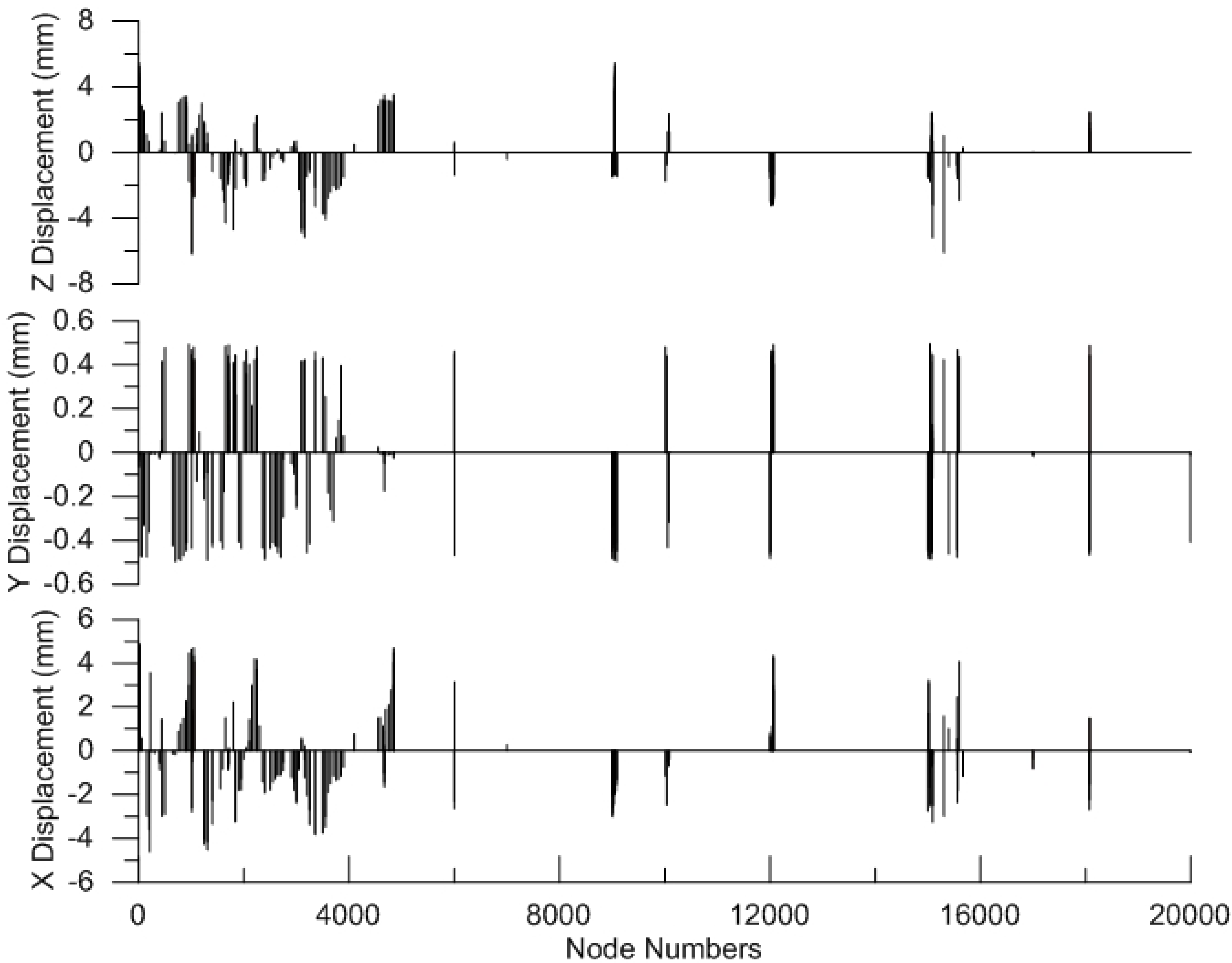

Fig. 4. Displacement bar chart for x, y and z directions

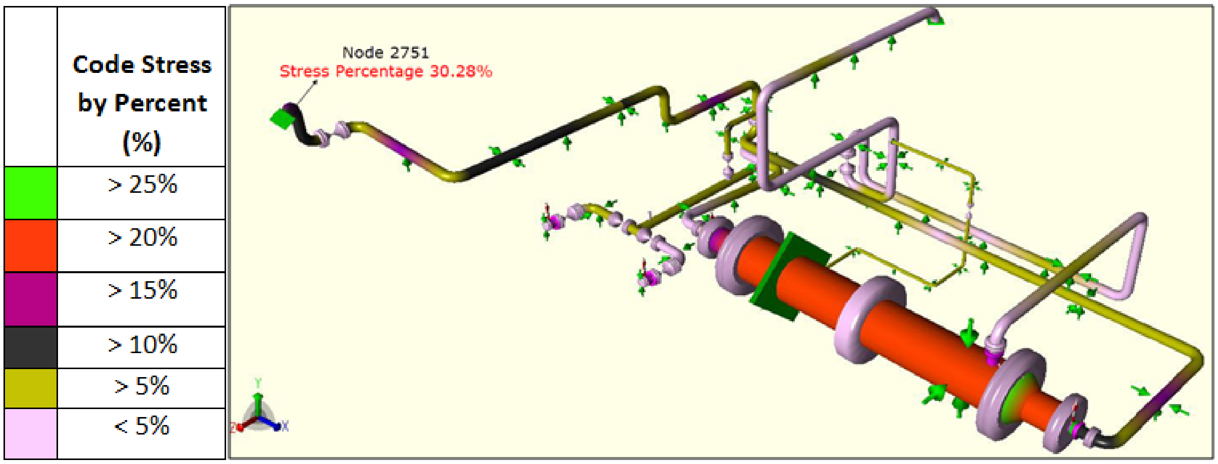

Fig. 5. Stress percentage distribution diagram for longitudinal stress

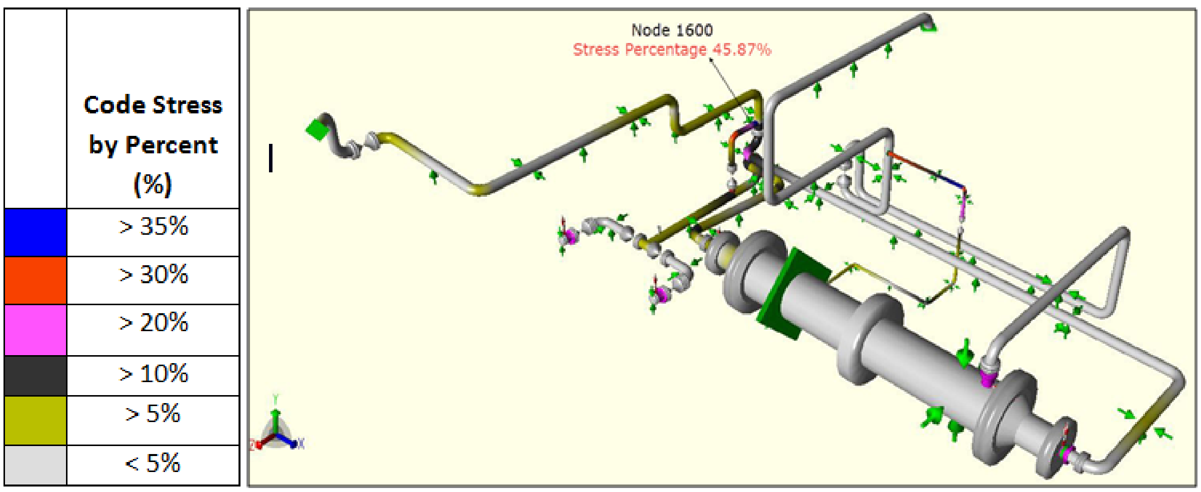

Fig. 6. Stress percentage distribution diagram for displacement stress range.

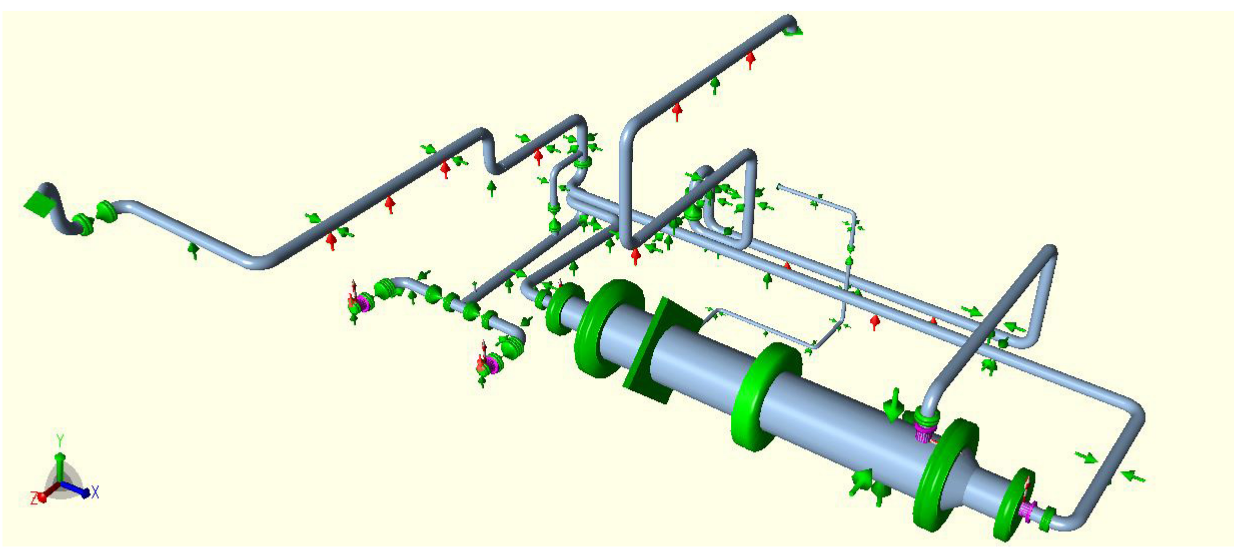

Fig. 7. Support locations where magnitude of reaction force is zero

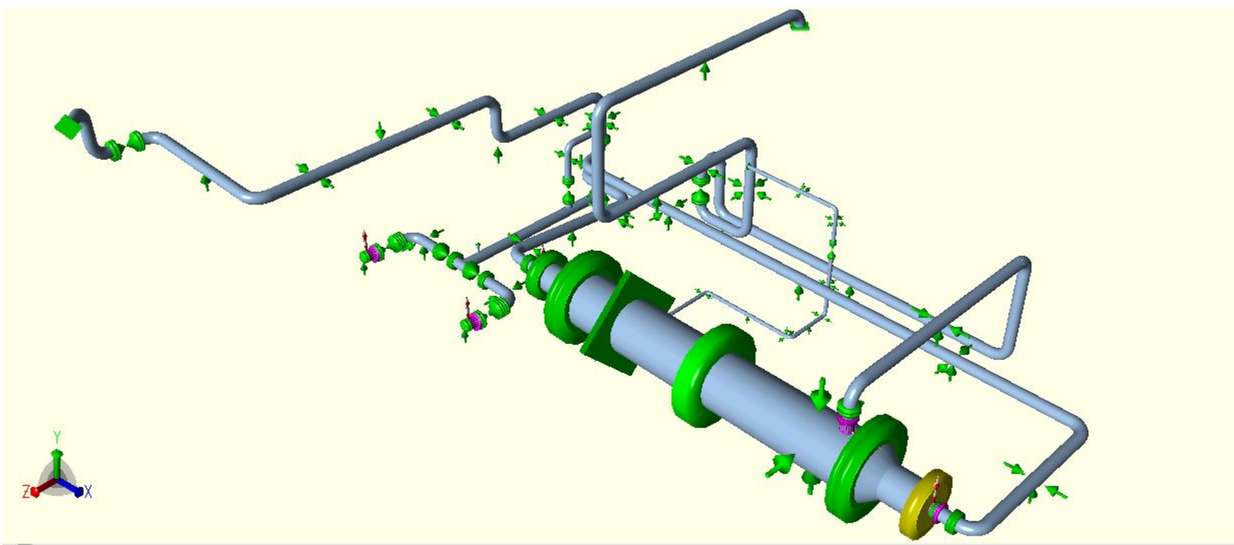

Fig. 8.   Final configuration

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