STRESS AND STRAIN ANALYSIS OF CONNECTION OF PIPES WITH FLAT ENDS

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Abstract: *This paper investigates stress state in connection of pipes with flat ends used in pressurized pipelines and steam boiler connections. Flat ends are designed according standard EN 12952-3 and later numerically checked using linear elastic material model. These analyses showed areas with increased stress. Therefore, additional analyses were performed using linear elastic-ideally plastic material. The maximal pressure loads are obtained for series of pipes with flat ends and compared to calculated results according EN 12952-3 norm.*

Keywords: PIPES, FLAT END, CONNECTION, STRESS, STRAIN, NUMERICAL ANALYSIS, FINITE ELEMENT METHOD

1. Introduction

A large number of structures in the engineering industry are pressure vessels and pipelines used for different purposes, mainly for transport and storage of liquids, gases and grain matter. They are made of various materials who can operate from low temperatures and pressures to very high pressures and temperatures[1]. There are different perpendicular cross sections of pipes and pressure vessels from rectangular and other non-circular shape to cylindrical ones which are the most commonly used because cylindrical shape provides the maximum strength and can withstand the maximum applied internal pressure for the structure. This is due to the absence of bending stresses in the cylindrical shell wall[2]. Cylindrical cross-section pipes are commonly used in thermoenergetics, hydroenergetics and process technics but due to various thermotechological requirements it is necessary to disrupt the ideal continuity of the cylindrical shape, which can cause an increase in local stresses in that place. Such discontinuities in pipeline geometry are branching of pipeline, connecting pipes of different wall thicknesses, transition of cylindrical to conical shape, placing the connectors on pressure vessels, connecting cylindrical shapes with flat ends and in many other cases[3].

Nowadays, almost all parts of the metal structure are mainly produced partly or completely using welding process. Since pipes or pipe fittings are integral parts of most pressure boilers or boilers, their installation, shape and geometry are prescribed by standards. This paper investigates stress and strain state in connection of pipes with flat ends used in pressurized pipelines and steam boiler connections.

Flat end connection to pipes are commonly used in pressure test of pressure vessels where pressure connections are needed to be closed in order to apply internal pressure inside pressure vessel. Investigated flat ends are designed according standard EN 12952-3[4].

The calculation according to this standard can be divided into two parts: DBF (design by formula) – doing calculation using the formulas that are prescribed in the standard and DBA (design by analysis) – calculations based on analysis, experimental deformation methods or numerical calculation using finite element methods. After designing, flat ends are later numerically checked using linear elastic material model. These analyses showed areas with increased stress. Therefore, additional analyses were performed using linear elastic-ideally plastic material. The maximal pressure loads are obtained for series of connections of pipes with flat ends and compared to calculated results according EN 12952-3 standard. Therefore it was necessary to carry out calculations according to elastic-ideal plastic law referring to EN 13445-3 which describes that at maximum test conditions maximal principal deformation should not exceed 7%[5].

2. Analytical and numerical analysis, results and discussion

EN 12952-3 standard defines when numerical calculations can be used. Numerical calculations apply to components where there were no rules in their construction or where we cannot accurately determine the strength of components according to the equations prescribed by European standards. The methods used for the calculations are: the method of free bodies, the finite difference method and finite element method.

The assessment of the stresses of each component must be carried out in accordance with EN 13445-3. The stresses in this case are checked using strains occurring in the material. For each case of load or combination of loads, the verification must be carried out under the assumptions of linear elastic-ideally plastic material behavior and Tresca's flow condition. The maximum permissible strain value is 5% under normal operating conditions and 7% in test conditions[5].

Three main parameters are selected on multiple levels. The selected parameters are the outer diameter of the pressure vessel connection, the thickness of the pipe wall and the thickness of the flat wall end (cap).

Parameters are selected on multiple levels in order to obtain the wider range of allowable pressure for as many different cases in production. It was chosen that the outer diameter of the connection of the pressure vessel and the thickness of flat end the wall are analyzed on three different levels, and the thickness of the pipe wall on four levels. The selected parameter levels are shown in Tab. 1. According to EN 10029[6] the upper and lower tolerances on the end thickness for thicknesses ≥ 25 and <40, as all selected parameters are within this range, are -0.7 and +1.3. Considering the nominal thickness of the pipe wall in the calculation, tolerances with a negative sign are used in order to obtain less wall thickness and more secure calculations.

Tab1e 1: *Parameter level and design thickness (with lower tolerance values in parenthesis)*

Level	Outside diameter of connection, mm	Wall thickness, mm	Flat end thickness, mm
1	219.1	20 (17.50)	30 (29.30)
2	168.3	22.2 (19.42)	28 (27.30)
3	139.7	25 (21.87)	25 (24.30)
4		28 (24.50)	

The materials used in the manufacturing of connections of pipes with the flat ends are construction steel for pressure equipment. The pipe material is 16Mo3 and the flat end material is P235GH (Tab. 2). For weld material, due to conservativism, a P235GH material with lower mechanical properties is chosen. Weld is predicted as homogeneous throughout the entire cross section. The following table (Tab. 2) show the main mechanical properties of the materials used at a test temperature of 20 °C.

Table 2: *Mechanical properties of materials P235GH and 16Mo3*

Material	$R_{p0.2}$, MPa	R_m, MPa	A,	ν	E,
	$16 < T \leq 40$ mm		%		GPa
P235GH	225	360-500	25	0,285	210
16Mo3	270	440-590	24	0,285	210

Numerical analyses are performed using the finite element method in ANSYS 14.5 software[7]. In this investigation, 108 different calculations were performed using three-dimensional models created in SolidWorks 2013[8] and only a quarter of the entire model is modeled in order to reduce the time of the analyses due to the symmetry of the problem. Maximum design pressure and weld dimensions are determined and calculated from EN 12952-3 for each geometry.

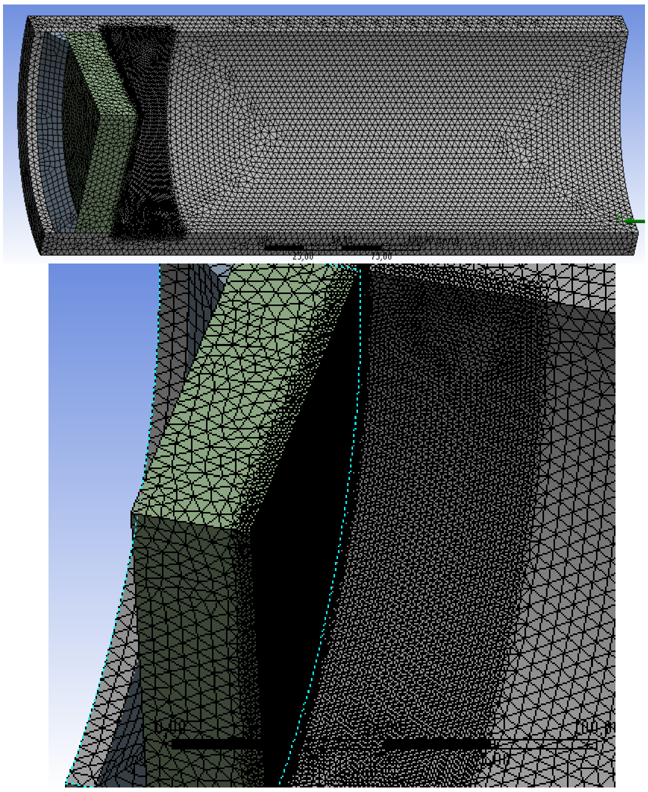

Fig. 1 *Meshed model with second order tetrahedral elements along with detail of finite element mesh refinement in one quarter of pipe with flat end connection*

The numerical analysis are done with second order tetrahedral elements. Because of the geometrical discontinuities around the connection of the pipe with flat end, where the stress concentration is expected, it was necessary to refine the finite element mesh to obtain more accurate stress and strain distribution.

The rest of the model is without discontinuity, so good results can be obtained with meshing with larger elements to reduce the time needed for analysis. The size of a single element in the part where meshing was coarse was 4 mm, while the size of the element on the finer part of the finite element mesh was 1.5 mm. Such level of mesh refinement was obtained using convergence of equivalent stress and strain solutions.

Because of the different dimensions of individual models, the number of elements and nodes varied from model to model. For largest model used in this investigation, the number of elements were 418195 and the number of nodes were 605250.

In finite element analysis the quickest and simplest way to perform analysis is to use linear elastic material behavior. It was the first step in this investigation too, but most of models showed significant stress concentrations i.e. areas where local stress values exceed allowable stress for materials P235GH and 16Mo3. Fig. 2 shows one finite element model where can be seen significant exceeding of allowable stress in the place of welded connection of the flat end with the pipe.

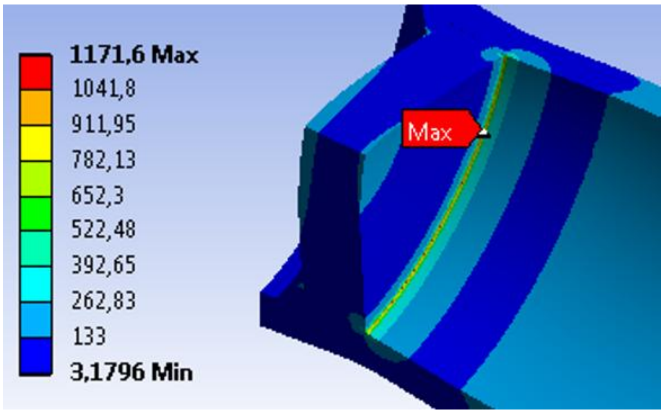

Fig. 2 *Equivalent von Mises stress distribution in finite element model with linear elastic material model, MPa*

In order to determine can this local increases in equivalent von Mises stress value be accepted and considered safe, an additional analyses had to be performed. That was done using different material models. Standard EN 13445-3 suggests using linear elastic-ideally plastic material models and checking principal strain limit. All models are analyzed with this material model and it is shown that models loaded with calculated design pressure give lower values of strain than the 7% permissible by EN 13445-3 standard. Part of these results are shown in Tab. 3 where table contains dimensions of pipe and flat end connection, design pressures according to EN 12952-3 and strains caused by design pressure.

Since all investigated models give lower values compared to allowable strain, another set of analyses are performed to obtain maximal pressure that produce maximal allowed values of principal stress of 7%. Every model had to gradually loaded with small pressure load step in order to precisely determine maximal pressure. Part of results of maximal pressure which gave maximal principal deformation of 7% with pipe diameter of 219.1 mm are also presented in the same Tab. 3.

Table 3: *Design pressure and principal strain for pipe to flat end connection with constant pipe diameter of 219.1 mm*

Connection of pipe with flat end dimensions, mm	Design pressure, MPa	Maximal principal strain for design pressure, %	Maximal pressure with maximal principal strain of 7%, MPa
219.1×17.5×29.3	32.29	1.60	53.42
219.1×17.5×27.3	28.03	0.89	42.42
219.1×17.5×24.3	22.21	0.87	41.59
219.1×19.42×29.3	33.68	1.35	51.21
219.1×19.42×27.3	29.24	0.75	47.67
219.1×19.42×24.3	23.17	0.75	42.83
219.1×21.87×29.3	35.59	1.20	59.43
219.1×21.87×27.3	30.89	0.98	55.09
219.1×21.87×24.3	24.48	0.53	48.79
219.1×24.5×29.3	37.82	0.70	65.28
219.1×24.5×27.3	32.83	0.47	64.13
219,1×24,5×24,3	26,02	0,5	36,98

Since presenting of all results of this investigation in form of tables or in form of diagrams would be impractical, only part of these results, where one geometric parameter (pipe outside diameter) is constant, showing dependence of design pressure and maximal pressure regarding wall and flat end thickness are presented in the following figures. Fig. 3, 4 and 5 show dependence of design pressure regarding end and wall thickness with constant pipe diameters of 219.1, 168.3 and 139.7 mm. It can be noted that thicker wall and thicker flat ends give higher values of design pressure. When comparing all three diagrams it is obvious that situation with same wall thickness but smaller pipe diameter also gives higher values of design pressure.

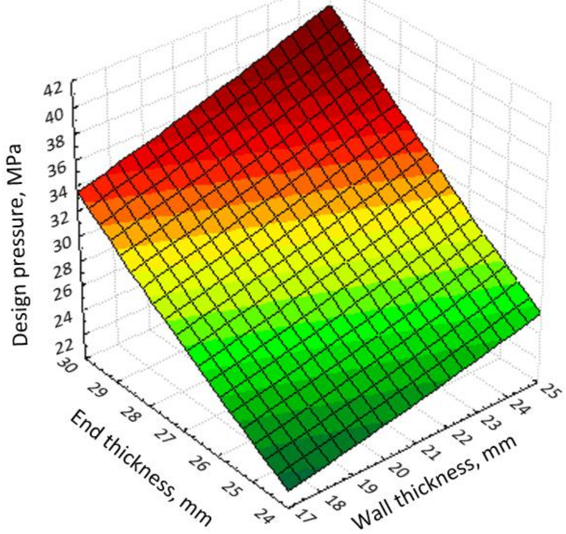

Fig. 3 *Dependence of design pressure on flat end and wall thickness with constant pipe diameter of 219.1 mm*

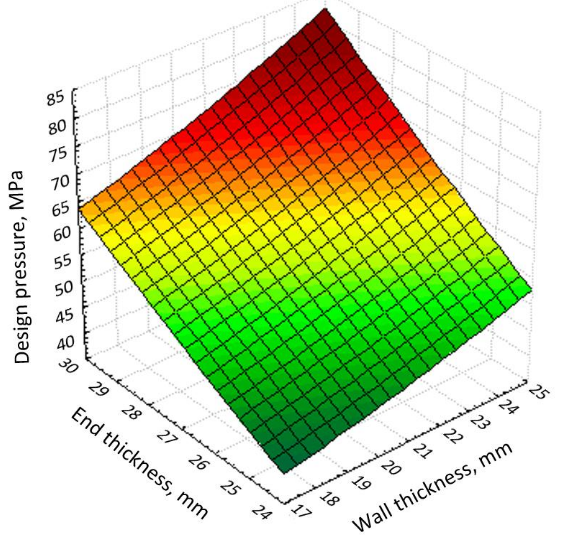

Fig. 4 *Dependence of design pressure on flat end and wall thickness with constant pipe diameter of 168.3 mm*

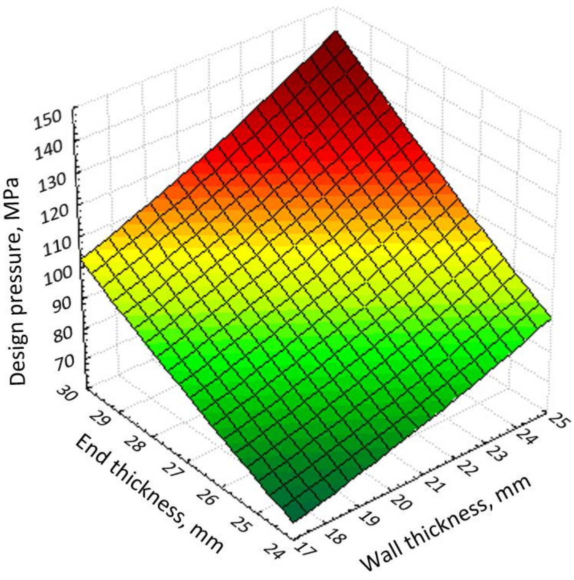

Fig. 5 *Dependence of design pressure on flat end and wall thickness with constant pipe diameter of 139.7 mm*

Fig. 6, 7 and 8 show dependence of maximal pressure causing strain of 7% on flat end and wall thickness with constant pipe diameter of 219.1, 168.3 and 139.7 mm from which it can be concluded that generally and similarly to design pressure, a maximal pressure which gives maximal principal strain of 7% is also increased regarding higher values of wall thickness and thicker flat ends.

When wall thickness and flat ends are kept constant, higher values of pipe diameter give higher values of maximal allowed pressure. All values of maximal pressure causing maximal strain are higher than calculated design pressure. From that it can be concluded that analytical calculation give more conservative values of design pressure compared to maximal allowable pressure obtained considering maximal strains.

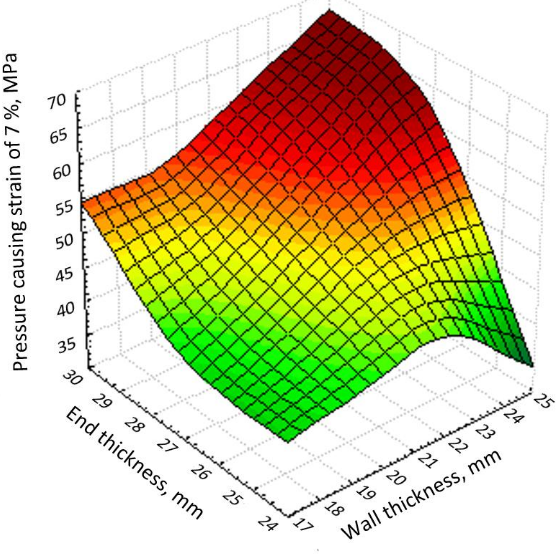

Fig. 6 *Dependence of pressure causing strain of 7% on flat end and wall thickness with constant pipe diameter of 219.1 mm*

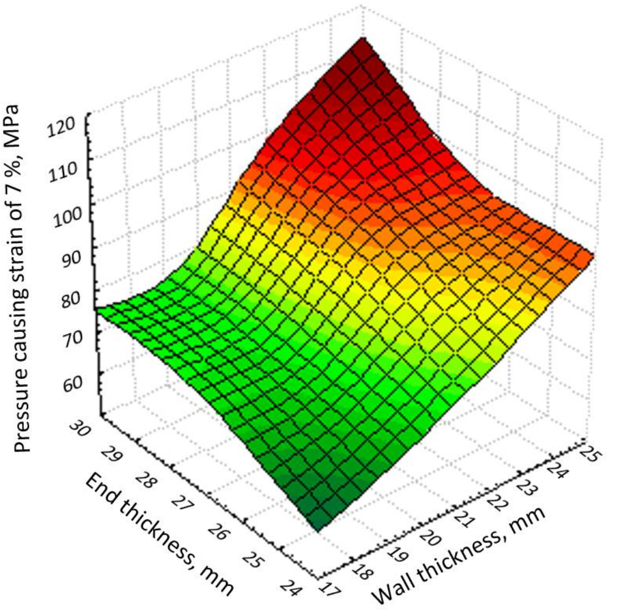

Fig. 7 *Dependence of pressure causing strain of 7% on flat end and wall thickness with constant pipe diameter of 168.3 mm*

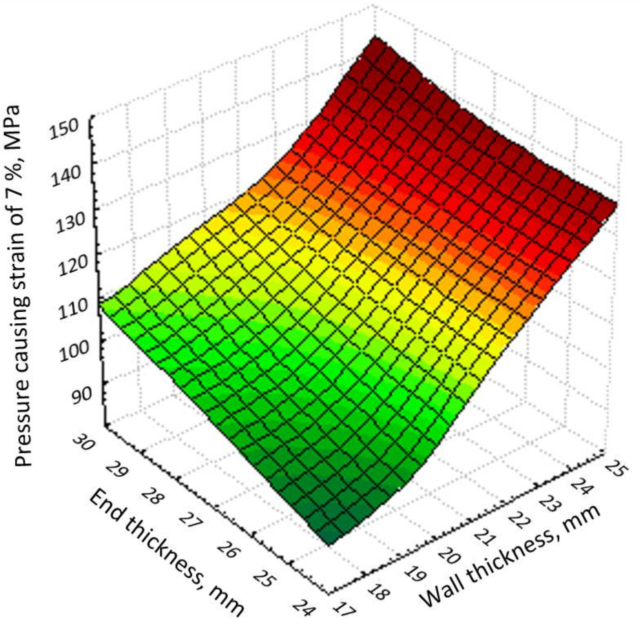

Fig. 8 *Dependence of pressure causing strain of 7% on flat end and wall thickness with constant pipe diameter of 139.7 mm*

3. Conclusion

Flat end connection to pipes are commonly used in pressure test of pressure vessels where pressure connections are needed to be closed in order to apply internal pressure inside pressure vessel. In this investigation flat ends are designed according standard EN 12952-3, and 36 different geometries are modelled regarding different pipe diameter, wall thickness and flat end thickness.

According to the linear-elastic material behavior, a total of 36 analysis were made, while with elastic-ideally plastic material model 72 analyses were performed, giving total of 108 numerical analyses. Linear elastic behavior of materials yielded to occurrence of very large local stresses. The main problem with these calculations was that it was not easy to determine limit of acceptable local stress. Therefore it was necessary to carry out analyses according to elastic-ideally plastic law referring to EN 13445-3 which describes that at the test maximum pressure cannot lead to exceeding maximal principal stress of 7%.

These analyses with linear elastic-ideally plastic material behavior gave lower values of principal strain compared to allowable strain. That can lead to conclusion that analytical calculation gives more conservative values of design pressure compared to maximal allowable pressure obtained considering maximal strains.

Another set of analyses are performed to obtain maximal pressure that produce maximal allowed values of principal stress of 7%, there results also showed conservatism in calculation of design pressure. The results obtained through the numerical calculations should not be taken as final but certainly confirm that the results obtained by the analytical calculations using standard are conservative and what is certainly appropriate because it strives for a more conservative but safer solution.

To estimate how conservative calculations using standard can be, these numerically obtained results, as a further investigation, are also planned to be checked and verified by experiment.

4. References

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