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INTEGRITY ASSESSMENT OF REGULATION SYSTEM PIPELINE ELEMENTS IN HYDROELECTRIC GENERATING SET A6 OF HYDRO POWER PLANT 'DJERDAP 1'

OCENA INTEGRITETA ELEMENATA SISTEMA CEVOVODA ZA REGULACIJU NA HIDROELEKTRIČNOM GENERATORU A6 NA HIDROELEKTRANI 'DJERDAP 1'

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.1:621.224.35
Rad primljen / Paper received: 30.11.2016

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Keywords
- welded joint
- strength calculation
- pipeline integrity

Abstract

Vertical Kaplan turbines with nominal power of 176 MW manufactured in Russia are installed in 6 hydroelectric generating sets at hydro power plant 'Djerdap 1' (Kladovo, Serbia). Most of the components are made of materials in accordance to GOST and ASTM standards. During rehabilitation of hydroelectric generating set, the analysis of the current state and integrity assessment of turbine regulation system pipeline required non-destructive tests on parent material and welded joints between pipes and pipes-elbows.

The purpose of the regulation system, comprising of the pipeline for the turbine regulator oil supply, is to open and close vanes of the guide vane apparatus and to regulate the position of runner blades and their number of revolutions. Internal pressure in the regulation system is p = 4 MPa.

Structural integrity is a recent scientific and engineering discipline which in broader sense comprises state analysis and behaviour diagnostics, service life assessment and rehabilitation of structures, meaning that beside the usual situation where structural integrity assessment is required when flaws are detected by non-destructive testing, this discipline is also includes stress state analysis. This approach is especially important for welded structures, since crack-type flaws can originate from welding and from unfavourable service conditions.

In this paper, the results of non-destructive tests referring to the lack of penetration in roots of butt-welded joints between pipes and pipes-elbows, as well as tensile test results of technical specimens with reinforcements and in specimens with parallel machined sides and standard dimensions, are presented in order to carry out the integrity assessment of the turbine regulation system pipeline of hydroelectric generating set A6 at hydro power plant Djerdap 1. Results of analytical strength calculation of butt-welded joints between 2 pipes, and pipe-elbow with a lack of penetration in the root are also presented.

Ključne reči
- zavareni spoj
- proračun čvrstoće
- integritet cevovoda

Izvod

Vertikalne Kaplanove turbine, nominalne snage 176 MW proizvedene u Rusiji su instalirane u 6 hidroelektričnih generatora u okviru hidroelektrane "Djerdap 1" (Kladovo, Srbija). Većina komponenata je proizvedena od materijala u skladu sa standardima GOST i ASTM. Tokom obnavljanja hidroelektričnih generatora, izvršena je analiza trenutnog stanja i ocena integriteta sistema cevovoda za regulaciju turbina, kao i ispitivanje bez razaranja osnovnog materijala i zavarenih spojeva između cevi, kao i između cevi i lakta.

Uloga sistema za regulaciju, koji se sastoji od cevovoda za dovođenje ulja u regulator turbine, je da otvara i zatvara lopatice uređaja za navođenje i da reguliše položaj pokretnih lopatica i broj njihovih obrtaja. Unutrašnji pritisak u sistemu za regulaciju je p = 4 MPa.

Integritet konstrukcija je relativno nova naučna i inženjerska disciplina, koja u širem smislu obuhvata analizu stanja i dijagnostiku ponašanja, ocenu radnog veka i obnovu konstrukcija, što znači da, pored uobičajenih situacija u kojima je neophodno proceniti integritet konstrukcija, kada su greške utvrđene ispitivanjem bez razaranja, ova disciplina takođe obuhvata i analizu napona. Ovakav pristup je naročito bitan za zavarene konstrukcije, kod kojih greške tipa prslina mogu da se jave tokom zavarivanja i usled nepovoljnih radnih uslova.

U ovom radu su prikazani rezultati ispitivanja bez razaranja vezanih za nedostatak provara u korenu sučeonih zavarenih spojeva između cevi, kao i između cevi i lakta, zajedno sa rezultatima ispitivanja na zatezanje tehnički ojačanih epruveta i epruveta sa paralelno obrađenim stranama i standardnim dimenzijama, kako bi se izvršila ocena integriteta cevovoda sistema za regulaciju turbine hidroelektričnog generatora A6 u okviru hidroelektrane Djerdap 1. Rezultati analitičkog proračuna čvrstoće sučeonog zavarenog spoja između 2 cevi, kao i između cevi i lakta sa nedostatkom provara u korenu su takođe prikazani.

INTRODUCTION

Vertical Kaplan turbines of 176 MW nominal power manufactured in Russia, are installed in 6 hydroelectric generating sets at hydro power plant 'Djerdap 1', /1/. During the rehabilitation of the hydroelectric generating set, the analysis of current state and integrity assessment of the turbine regulation system pipeline (Fig. 1) had required non-destructive tests, that were carried out on parent material and welded joints between pipes, as well as between pipes and elbows.

Role of the regulation system, which comprises the pipeline for oil supply of the turbine regulator, is to open and close vanes of the guide vane apparatus and to regulate the position of runner blades and their number of revolutions. Internal pressure in the regulation system is p = 4 MPa.

Taking into account the fact that pipes and elbows of different diameters and wall thicknesses need to be designed in such a way to avoid failure regardless of loads they are subjected to, loads that can cause failure, or in other words the loss of integrity due to local plastic deformation /2, 3/ has to be adequately evaluated in order to ensure reliability of pipelines in exploitation.

Local thinning of pipe walls (due to the existence of cracks, grooves or volumetric defects) causes the decrease of pressure which can lead to failure and decrease of load carrying capacity, ability to deform and fatigue resistance. That is why it is important to adequately estimate the effect of local thinning, due to existing defects, on structural integrity of pipeline components /4, 5/, and to develop the procedure for pipeline integrity assessment. This is especially important for elbows, because the regulation system of the hydroelectric generating set A6 at hydro power plant 'Djerdap 1' consists of elbows made in several different ways, with various geometries and curve radii, Fig. 2.

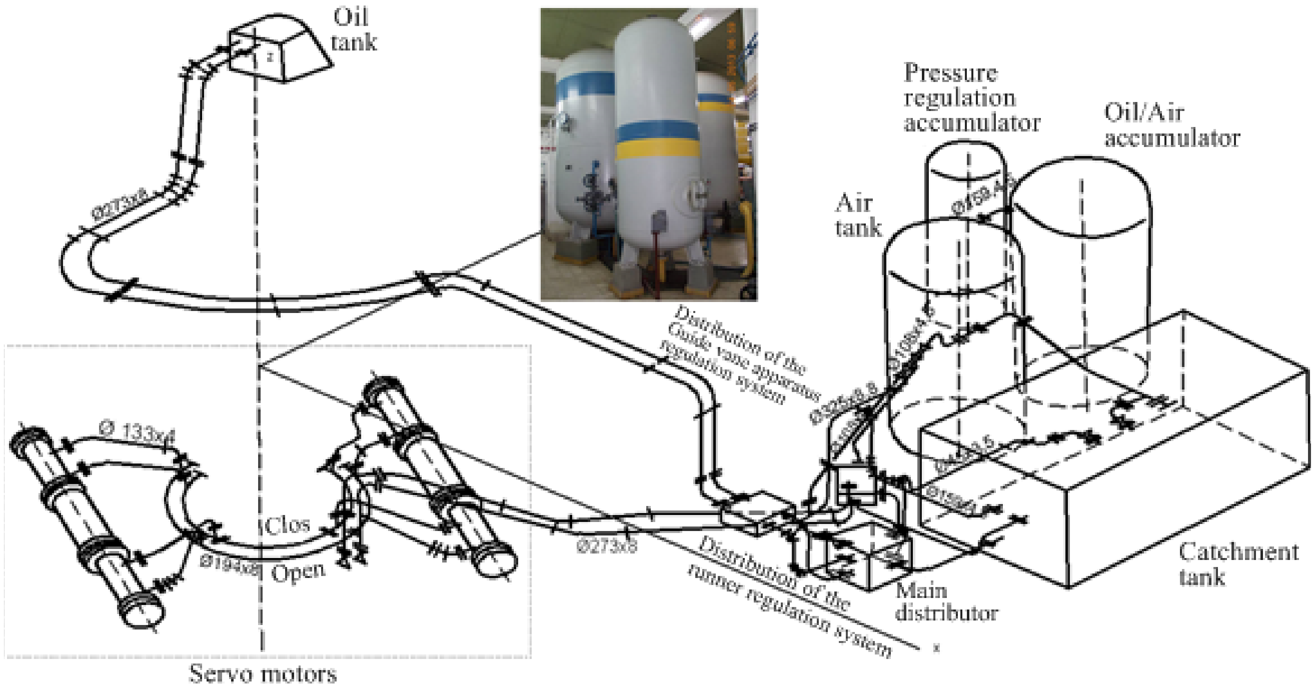


Figure 1. Schematic presentation of turbine system

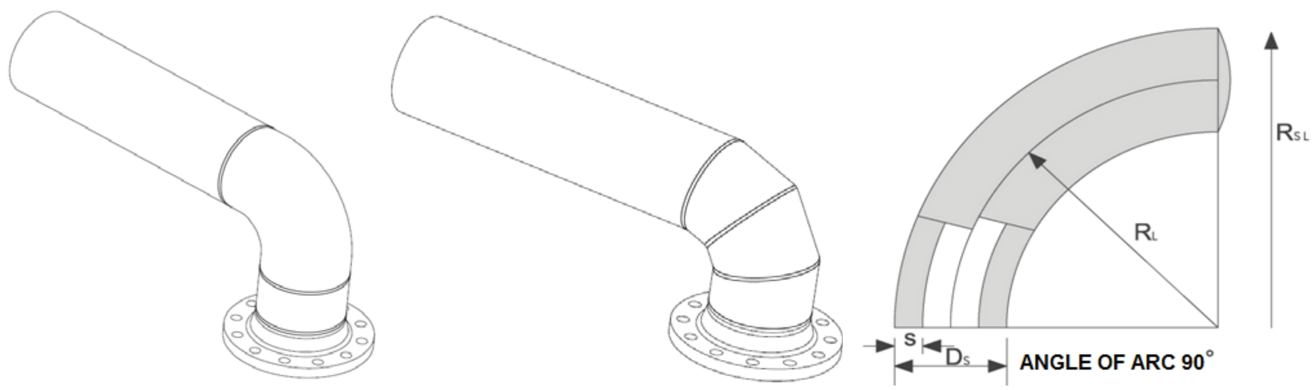


Figure 2. Geometrical characteristics of pipe elbows.

Pipes and elbows installed 35 years earlier were made of steel 20 (GOST standard, A53 according to ASTM). External diameters and nominal wall thicknesses are: Ø108 × 4 mm, Ø135 x 4 mm, Ø139 × 4 mm, Ø159 × 5 mm, Ø200 × 8 mm and Ø270 × 8 mm. Chemical composition and mechanical properties of steel 20 are presented in Tables 1 and 2. Figure 3 shows the true stress-true strain curve for this material.

Minimum wall thickness for pipes in the regulation system, without the correction for possible influence of corrosion (c_1) and thinning that occurs in pipe manufacture (c_2), is calculated using the standard for pressure equipment SRPS M.E2.260 /6/, while for the elbows, the theory of elasticity is used. Calculated thicknesses are presented in Table 3, with a remark that nominal thicknesses of pipes and elbows refer to thicknesses in the purchased condition.

Table 1. Chemical composition of steel 20 in mass %, according to GOST 1050.

Steel	mass %								
	C	Si	Mn	P	S	Cr	Ni	Cu	Al
				max.					
Steel 20	0.17-024	0.17-0.37	1.35-0.65	0.035	0.04	0. 25	0.25	0.25	0.08

Table 2. Mechanical properties of steel 20.

Steel	*YS* [MPa]	*TS* [MPa]	*A5* [%]	*Z* [%]
Steel 20	175-245	390-410	21-25	50-55

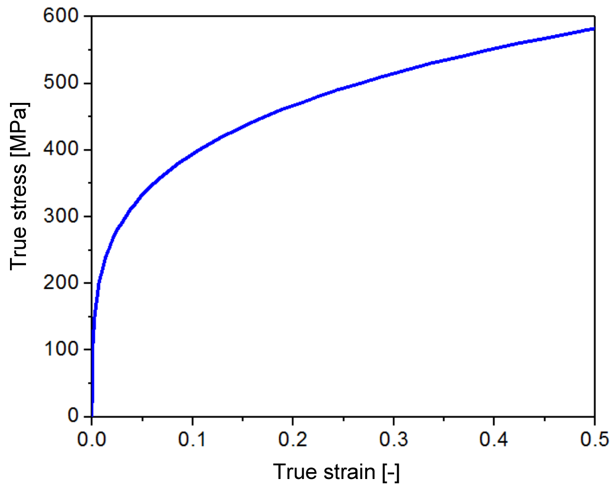


Figure 3. True stress-true strain curve for steel 20.

Table 3. Minimum thickness of pipes and elbows of the regulation system pipeline.

Geometric characteristics of pipes and elbows		Minimum pipe wall thickness $e_{\min}$ [mm]	Minimum elbow thickness $e_{\min}$ [mm]
External pipe diameter D_e [mm]	Nominal pipe wall thickness e_n [mm]		
108	4	1.68	2.23
135	4	2.60	3.29
139	4	2.74	3.45
159	5	3.42	4.23
200	8	4.82	5.84
270	8	7.20	8.58

EXPERIMENTAL TESTS PERFORMED ON PIPES AND ELBOWS

Favourable structural solutions for pipes and elbows which would provide mechanical safety and pipeline integrity under exploitation conditions, can be achieved only by adequate selection of steel or, in other words, taking into account resistance to degradation and breakdown of parent material and welded joints due to the action of the internal pressure and influence of the environment, as well as by using adequate technology for pipeline fabrication. Basic tests performed on material of regulation system elements, as well as non-destructive tests, are presented in this paper, in accordance with /7/.

Ultrasonic measurement of wall thickness

Pipe and elbow wall thicknesses are measured on all pipeline components with a scope of testing that covered 10% of all elements. Measurements were carried out by KRAUTKRAMER DM4 ultrasonic device, in accordance with standard SRPS EN 14127, /8/.

From measurements it is determined that pipe and elbow wall thicknesses are 5-10% smaller than nominal (design) thicknesses. Smaller thicknesses, when it comes to pipes, are measured in the area of welded joints, while at elbows smaller thicknesses are measured in the tensioned and in the neutral area.

Radiographic testing of welded joints

By radiographic testing of pipe-pipe welded joints, as well as between pipes and elbows, unacceptable flaws such as gas pores (2011), linear slag inclusions (3011), isolated slag inclusions (30120) and lack of penetration in the root (402) are detected by taking into account the acceptance criteria defined by standard SRPS EN ISO 5817 /9/, quality level 'B'. Example of the lack of root penetration is presented in Fig. 4.

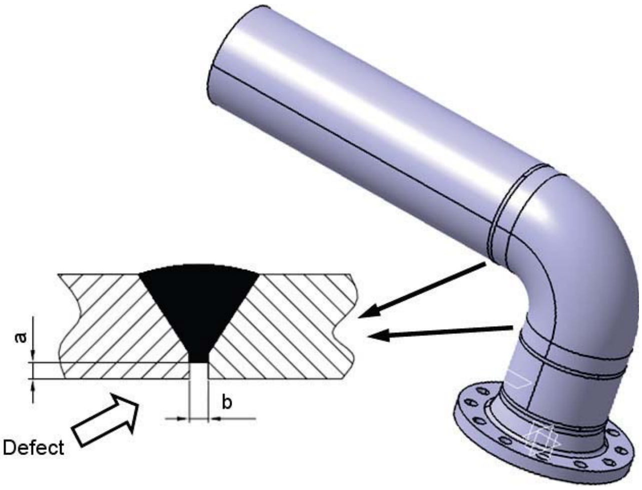
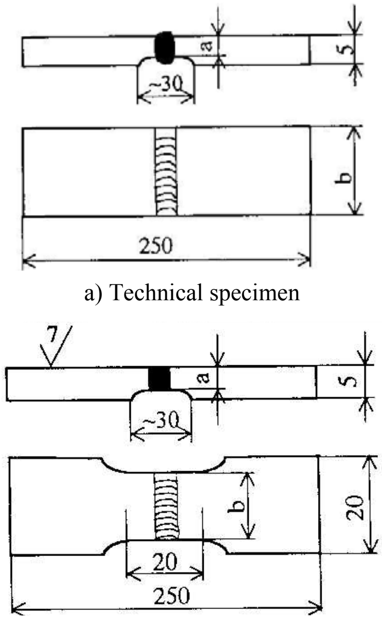


Figure 4. Elbow with a flange and a welded joint with an incompletely filled groove.

Tensile testing of welded joints

Taking into account the fact that lack of penetration in the root of welded joints is detected by non-destructive tests, tensile tests are carried out on technical specimens with reinforced welded joints, as well as on specimens with machined sides, in order to assess the integrity of the regulation system pipeline. Specimens are extracted from samples taken from Ø159 × 5 mm pipes, where additional machining is performed in the area of the welded joint in order to take into account the influence of width, and not just the height of the lack of root penetration. Drawings of specimens are presented in Fig. 5, while test results at room temperature (T = 20°C) are presented in Table 4 (basic tensile properties).



a) Technical specimen

b) Specimen with standard dimensions

Figure 5. Shape and dimensions of specimens.

No conclusion regarding the level of the degradation of welded joints, and pipes and elbows in the regulation system pipeline could be reached on the basis of results of tensile tests performed on specimens extracted from samples of in-service pipes, because no data regarding their true mechanical properties prior to assembly are available.

Impact energy tests were performed by Charpy pendulum 'Alfred Amsler', with range of 0-300 J, using the V2-notch specimens with dimensions 10 × 10 × 55 mm taken from 3 mutually perpendicular directions in the sample, in accordance with the standard /8/. Test results, presented in Table 5, are satisfactory.

Table 4. Mean values of tensile properties of welded joints with lack of root penetration at 0°C.

Specimens	Dimensions [mm]	YS [MPa]	TS [MPa]	A_5 [%]	Z [%]
Technical	a = 3.6, b = 17.54	178.4	396.5	21.3	52.3
Standard	a = 3.6, b = 15.4	162.7	354.8	18.6	49.6

Table 5. Impact energy test results, in accordance with SRPS EN 10045-1.

Sampling position	Specimen	Temperature T [°C]	Impact energy $KV_{2/300}$ [J]	Mean value [J/cm^2]
Direction of rolling	1	+20	120.66	104.97
	2		112.82	
	3		81.42	
Perpendicular to the direction of rolling	1	+20	139.30	126.55
	2		130.47	
	3		109.87	
z-direction	1	+20	31.39	25.50
	2		21.58	
	3		23.54	

CALCULATION OF PIPELINE ELEMENTS

In order to carry out the assessment of the regulation system pipeline of the hydroelectric generating set A6, analytical and numerical calculation regarding the strength of pipes and elbows is performed.

Allowable stresses for pressure equipment have to be limited taking into account predictable causes of degradation of parent material and welded joints in working conditions. Safety conditions which would eliminate the decrease of strength that occurs during production, due to working conditions, loads, calculation models, as well as due to properties and behaviour of material have to be applied.

The above mentioned demands can be fulfilled by applying one of the following methods or their combination, as well as by performing necessary experimental tests:

– check of strength by application of empirical formulas and/or national standards,
– check of strength by application of analytical calculation,
– check of strength by application of numerical calculation,
– check of strength by application of fracture mechanics (in case of existing damage in the structure).

Calculation of wall thickness of straight pipes subjected to internal pressure

Calculation of strength for pipeline of steel 20 is performed taking into account the pipes with diameters: 108 mm, 135 mm, 139 mm, 159 mm, 200 mm and 270 mm. Minimum required wall thicknesses of pipes are calculated by using the currently valid standard SRPS EN 13480-3, /10/.

Working temperature is t = 20°C, which was taken into account while determining material properties. Working pressure for the pipeline is 4 bar, while the pipeline consists of seamless pipes. Calculation (for test conditions) is carried out in accordance with the standard /10/. Used data are presented in Table 6.

In accordance with the currently valid Book of technical regulations for design, manufacture and compliance assessment of pressure equipment /11/, the category of pipeline for considered diameters and pressure is defined. It is determined that pipes with diameters ranging from 108 to 270 mm belong to the area of 'good engineering practice', Fig. 6.

Table 6. Data used for the calculation of wall thickness.

Working pressure	P = 4 MPa (40 bar)
Working temperature	t = 20 °C
Coefficient of the WJ	z = 1 (for test conditions, according to SRPS EN 13480-3)
External diameter of the pipe	D_e = 270 mm – calculation is shown (Ø108, Ø135, Ø139, Ø159, Ø200 mm)
Yield strength	YS = 175 MPa (t = 0 °C)
Tensile strength	TS = 390 MPa (t = 0 °C)

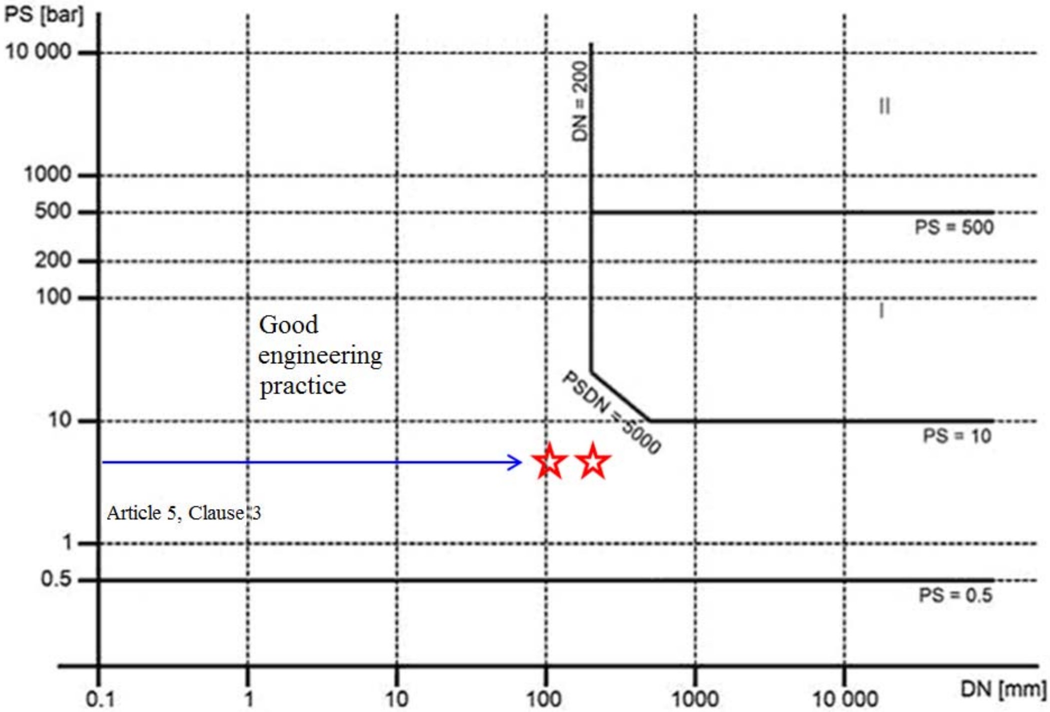


Figure 6. Determining the category of pipeline comprised of pipes subjected to internal pressure, diameters ranging from 108 to 270 mm.

First of all, pipe wall thickness needs to be checked taking into account the fluid pressure. Wall thickness of the straight pipe is calculated in accordance with standard SRPS EN 13480 /12/:

$$e = \frac{p \cdot D_e}{2 \cdot \sigma_{all} \cdot z + p} \quad (1)$$

for the ratio of external and internal diameter $D_e/Di \leq 1.7$, and Eq.(2)

$$e=\frac{d}{2}\cdot\left(\sqrt{\frac{\sigma_{all}\cdot z+p}{\sigma_{all}\cdot z-p}}-1\right) \tag{2}$$

for the ratio of external and internal diameter $D_e/D_i > 1.7$.

For pipes made of non-austenitic steels, allowable stress, taking into account the working conditions, is:

$$\sigma_{all}=\min\left\{\frac{YS_{t^\circ}}{1.5} ili \frac{YS_{p0.2t^\circ}}{1.5}; \frac{TS}{2.4}\right\} \tag{3}$$

When applying the test pressure on the pipe, the following condition has to be met:

$$(\sigma_{all})_{test}\le 0.95\cdot YS_{test} \tag{4}$$

$$\sigma_{all}=\min\left\{\frac{170}{1.5};\frac{390}{2.4}\right\}=\{113.33;162.5\}=133.3 \text{ MPa} \tag{5}$$

After the application of test pressure, pipe wall thickness has to be checked again:

$$e=\frac{p_{test}\cdot D_e}{2\cdot\sigma_{all}\cdot z+p_{test}} \tag{6}$$

for the ratio of external and internal diameter $D_e/D_i \le 1.7$.

$$p_{test}=\max\left\{1.25\cdot p\cdot\frac{(\sigma_{all})_{test}}{\sigma_{all}};\ 1.43\cdot p\right\} \tag{7}$$

Taking into account the fact that test temperature is equal to working temperature, the following stands: $(\sigma_{all})_{test} = \sigma_{all}$,

$$p_{test}=\max\{1.25\cdot 4\cdot 1;\ 1.43\cdot 4\}=\{5;\ 5.72\}=5.72 \text{ bar} \tag{8}$$

$$e=\frac{5.72\cdot 270}{2\cdot 113.33\cdot 1+5.72}=6.7 \text{ mm} \tag{9}$$

Addition of material due to allowable deviation from nominal dimensions (c_0), addition of material due to sheet metal thinning because of corrosion (c_1) and addition of material due to wall thinning during the production (c_2) were not taken into account.

Required thicknesses for regulation system pipes of all considered diameters are obtained in the same way as for pipes of 270 mm by calculation taking into account their current condition determined by ultrasonic tests, and are presented in Table 7. Considering that minimal thicknesses obtained by ultrasonic tests are 5-10% smaller than nominal values (but larger than the minimal required thicknesses obtained by calculation) it can be concluded that the integrity of existing pipes is not threatened.

Table 7. Minimum required values of wall thicknesses obtained by calculation.

Basic pipe characteristics		Minimum required pipe wall thickness e_{min} [mm]
External pipe diameter D_e [mm]	Nominal pipe wall thickness e_n [mm]	
108	4	2.7
135	4	3.4
139	4	3.5
159	5	4.0
200	8	5.0
270	8	6.7

Calculation of wall thickness for elbows subjected to internal pressure

Calculation of welded pipes is carried out for the radius of the elbow which is equal to the external diameter of the pipe ($R = D_e$).

The entire calculation for the fragment of the pipeline which consists of 270 mm pipes is presented in this section, while results for other diameters are shown at the end of the section. Data used for calculating elbow wall thickness are presented in Table 8.

Table 8. Data used for calculating elbow wall thickness.

External diameter of the pipe	D_e = 270 mm 108, 135, 139, 159, 200 mm
Radius of the elbow used for the calculation	$R = D_e$
Mean radius of the pipe	r (mm)
Required pipe wall thickness without additions	e = 6.7 mm, D_e = 270 mm
Required wall thickness at the internal side of the elbow without additions	e_i (mm)
Required wall thickness at the external side of the elbow without additions	e_e (mm)

Wall thickness at the internal side of the elbow is obtained from the following equation:

$$e_i=e\cdot\frac{\frac{R}{D_e}-0.25}{\frac{R}{D_e}-0.5} \tag{10}$$

For the pipe with external diameter D_e = 270 mm and elbow radius R = 270 mm:

$$e_i=6.7\cdot\frac{\frac{270}{270}-0.25}{\frac{270}{270}-0.5}=10.04 \text{ mm} \tag{11}$$

Wall thickness at the external side of the elbow is obtained by the following equation:

$$e_e = e \cdot \frac{\frac{R}{D_e} - 0.25}{\frac{R}{D_e} + 0.5} \tag{12}$$

For the pipe with external diameter D_e = 270 mm and elbow radius R = 270 mm:

$$e_e = 6.7 \cdot \frac{\frac{270}{270} + 0.25}{\frac{270}{270} + 0.5} = 5.58 \text{ mm} \tag{13}$$

Required elbow wall thicknesses obtained from calculation are presented in Table 9. It is obvious that the required thickness at the internal side of the elbow, obtained by calculation, is larger than nominal thickness, which is quite usual because elbows, due from manufacture, have the largest thickness in that area.

Table 9. Minimum required elbow wall thicknesses, as calculated.

Geometric characteristics of pipes and elbows		Minimum required elbow wall thicknesses	
External diameters of pipes and elbows D_e [mm]	Nominal pipe wall thickness e_n [mm]	Internal side of arc $e_{\text{min-}i}$ [mm]	External side of arc $e_{\text{min-}e}$ [mm]
108	4	4.1	2.3
135	4	5.1	2.8
139	4	5.2	2.9
159	5	6.0	3.3
200	8	7.5	4.2
270	8	10.1	5.6

Taking into account the fact that smallest thicknesses, determined by ultrasonic testing, are 5-10 % smaller than nominal thicknesses (but larger than minimal required thicknesses obtained by calculation), it can be concluded that the integrity of existing elbows is not threatened.

Numerical analysis performed by finite element method

Three-dimensional analysis is performed by finite element method using software package Abaqus in order to analyse the stress state in straight pipes and elbows and to determine the effect of incomplete welded joint on their integrity. The analysis is carried out taking into account that the external diameter of the pipeline fragment is D_e = 270 mm, while nominal wall thickness is e_n = 8 mm.

Incomplete welded joints that are analysed are shown in Fig. 7. The elbow is created by joining smaller pipe segments. Pipe and elbow models with various sizes of the lack of root penetration are also analysed (Fig. 7, $a \times b$ = 2 × 2, 2 × 1, 1 × 2, 1 × 1, 0.1 × 2 and 0.1 × 1 mm).

Numerical analyses regarding the stress state of pipes and elbows subjected to internal pressure, stress state of the elbow subjected to bending moment and the effect of damage that stretches in the circumferential direction in relation to the resistance to bending have been carried out by the finite element method.

Results of numerical analysis regarding the stress state of straight pipe segments subjected to internal pressure have shown that the value of Von Mises stresses is significantly smaller than the value of yield strength, /13/. Equivalent plastic strain fields have shown that the test pressure does not cause occurrence of plasticity in straight pipe walls, while minimal plasticity takes place in an extremely small area of the elbow walls, /13/.

Numerical analyses of the stress state that occurs due to moments that 'close' and 'open' the elbow have shown that the value of Von Mises stresses is close to- or larger than the value of the yield stress, /13/. For a pipe subjected to internal pressure and bending, the areas with large values of stress are even larger, /13/. It is also determined that the bending moment does not depend on the size of the lack of root penetration, /13/.

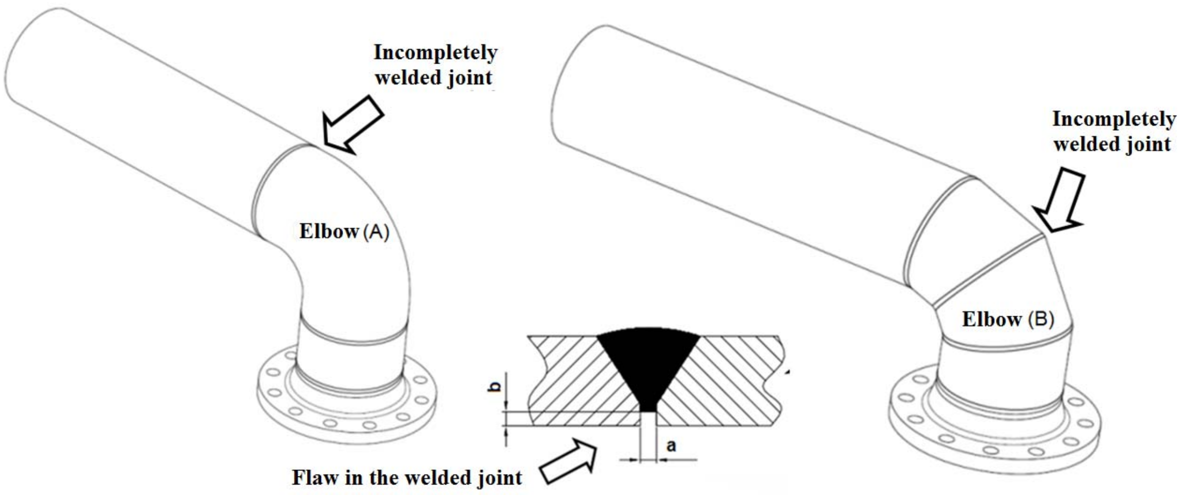


Figure 7. The analysed incomplete butt-welded joints.

CONCLUSION

Structural integrity is a relatively recent scientific and engineering discipline which in a broader sense comprises state analysis and behaviour diagnostics, service life assessment and the rehabilitation of structures, meaning that beside the usual situation where it is required to assess the integrity of structures when flaws are detected by non-destructive testing, this discipline also comprises the stress state analysis of the crackless structure. This approach is especially important for welded structures subjected to working conditions suitable for crack initiation.

Pipe wall thicknesses are measured on all pipeline components with a 10% scope of testing, and it is determined that they are 5-10% smaller than the nominal thicknesses.

From analytical calculation of pipe and elbow strength it is determined that the integrity of the existing pipeline is not threatened. Results of numerical analysis regarding the stress state of straight pipe segments due to internal pressure have shown that the value of Von Mises stresses is drastically lower than the yield strength.

Numerical analyses of the stress state that occurs due to moments that 'close' and 'open' the elbow have shown that the value of Von Mises stresses is close to- or larger than yield stress. For a pipe subjected to internal pressure and bending, areas with large values of stress are even larger.

ACKNOWLEDGEMENT

Authors wish to thank the Ministry of Education, Science and Technological Development for supporting projects TR 35002 and TR 35006.

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