Mladen Mladenović, Miodrag Arsić, Zoran Savić
Institute for materials testing, Bulevar vojvode Mišića 43, Belgrade, Serbija
miodrag.arsic@institutims.rs
Srđan Bošnjak, Nebojša Gnjatović
Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
sbosnjak@mas.bg.ac.rs

INFLUENCE OF DEGRADATION OF PARENT MATERIAL AND WELDED JOINTS ON THE INTEGRITY OF THE BREECHES PIPE LOCATED AT PIPELINE III OF HYDRO POWER PLANT 'PERUĆICA'

ABSTRACT
Hydro power plant 'Perućica', which comprises 7 hydroelectric generating units, each with installed power of 330 MW, is the oldest hydro power plant in Montenegro and was put in service in 1960. This high pressure hydro power plant is a complex hydroenergetic system, which consists of a 3335 m long concrete tunnel, surge with a broadening and overflow and three steel pipelines with two-sided Pelton turbines with horizontal shafts installed. Five turbines have nominal power of 38 MW, while two have nominal power of 58,5 MW (307 MW overall).
The biggest problem at hydro power plant 'Perućica' refers to the parent material and weld metal of the breeches pipe 1A located at pipeline III. Significantly lesser problems were detected at parent material and weld metal of breeches pipes 7B, 8A and 8B. Pipeline and breeches pipes were made of microalloyed steel 'Nioval 47' (steel mill 'Jesenice'). Stresses that occur at pipelines in service during the process of execution of functional tasks (stationary and dynamic loads) and during the disturbed process of exploitation (non-stationary dynamic loads) cause severe damaging of parent material and weld metal at structural components of breeches pipes (collars and anchors), thus endangering the integrity of pipeline structure as a whole. Role of the collar, which enables the leaning of the breeches pipe on the foundation, is to receive static and dynamic loads (mean pressure of up to 61 bar in pipeline axis, specific load that occurs due to the quantity of water in the pipeline, action of the force of gravity) and displacements which happen due to non-stationary dynamic loads that occur at the pipeline, while the anchor strengthens and balances the mass of the breeches pipe.
In this paper the results of non-destructive tests carried out on parent material and weld metal (collar and anchor) of breeches pipes with designations 1A, 7A, 8A and 8B and results of destructive tests performed on parent material of the anchor are presented. Tests that were carried out include visual testing (VT), magnetic particle testing (MT) and ultrasonic testing (UT), while destructive tests included determination of chemical composition, tensile properties, impact energy and hardness.
On the basis of results of test results it was determined that the main cause of occurrence of significant damages (degradation of parent material of the anchor and weld metal between the collar and anchor, as well as between the pipeline and the anchor) at the structure of the breeches pipe 1A of the pipeline III at the hydro power plant 'Perućica' is the fact that the breeches pipe did not lean on the collar, as was predicted by design, but on the anchor which, due to the size of its cross-section, could not endure all loads that occur at the breeches pipe during service. Damages that occurred on parent material and weld metal of breeches pipes 7B, 8A and 8B are directly caused by flaws in welding technology and conditions of exploitation. Executed researches showed that degradation of parent material and weld metal does not influence the integrity of the pipeline III as a whole.

Key words: breeches pipe, collar, anchor, material degradation, welded joint, integrity

1. INTRODUCTION

Hydro power plant 'Perućica', which comprises 7 hydroelectric generating units, each with installed power of 330 MW, is the oldest hydro power plant in Montenegro and was put in service in 1960. From the accumulations 'Krupac', 'Slano' and 'Vrtac' the water is being led to the hydroelectric generating sets by means of 3 pipelines under pressure of 61 bar in pipeline axis [1], figure 1. Pipeline I, 1.851 m long with diameters ranging from 1.8 – 2.2 m, supplies 2 hydroelectric generating sets (A1 and A2) with nominal power of 38 MW each. Pipeline II, 1.883 m long with diameters ranging from 2.1 – 2.2 m, supplies 3 hydroelectric generating sets (A3, A4 and A5) with nominal power of 38 MW each, while pipeline III, 1.931 m long with diameters ranging from 2.5 – 2.65 m, supplies 2 hydroelectric generating sets (A6 and A7) with nominal power of 58.5 MW each, figure 2. Pelton turbine is displayed in figure 3.

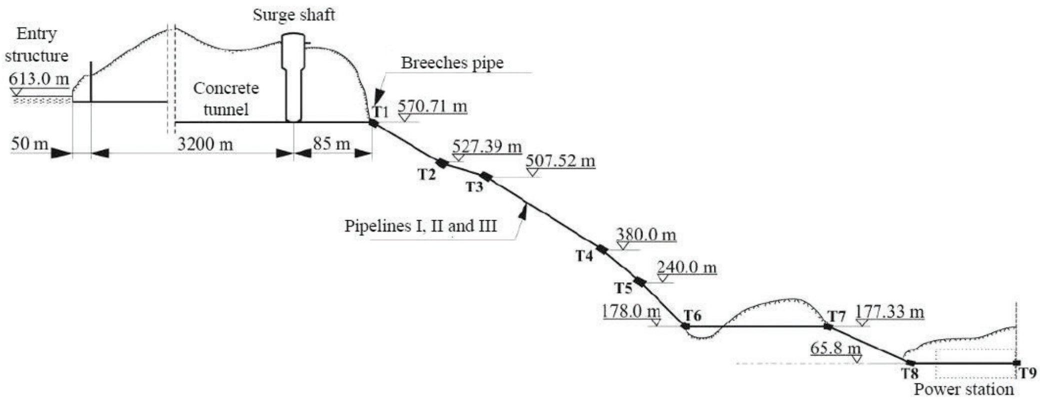
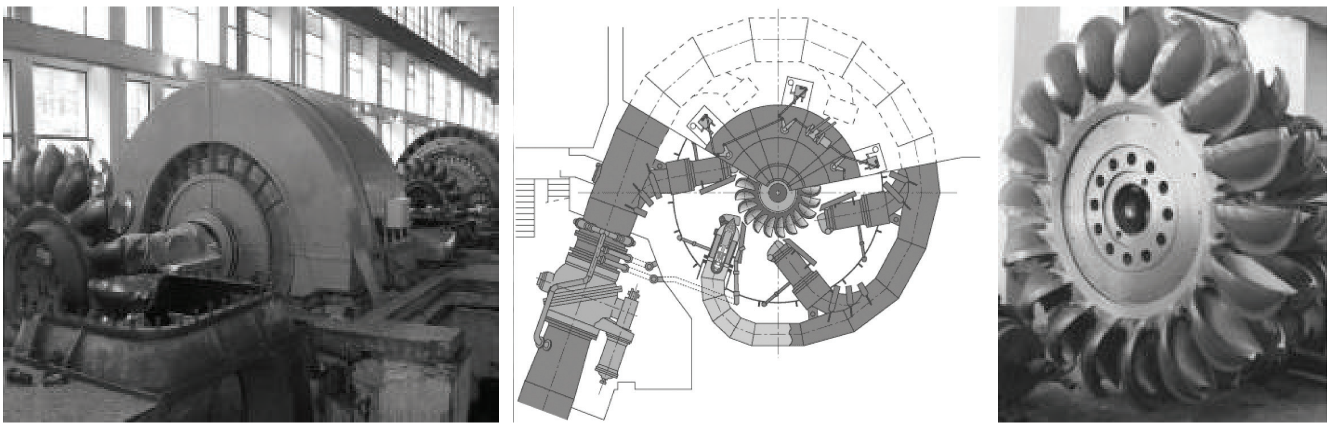


Figure 1. *Schematic appearance of hydro power plant 'Perucica'*

a) Pipelines b) Appearance of the pipeline and of the corresponding model c) Breeches pipe model

Figure 2. *Appearance of supply with corresponding models of the pipeline and of the breeches pipe*



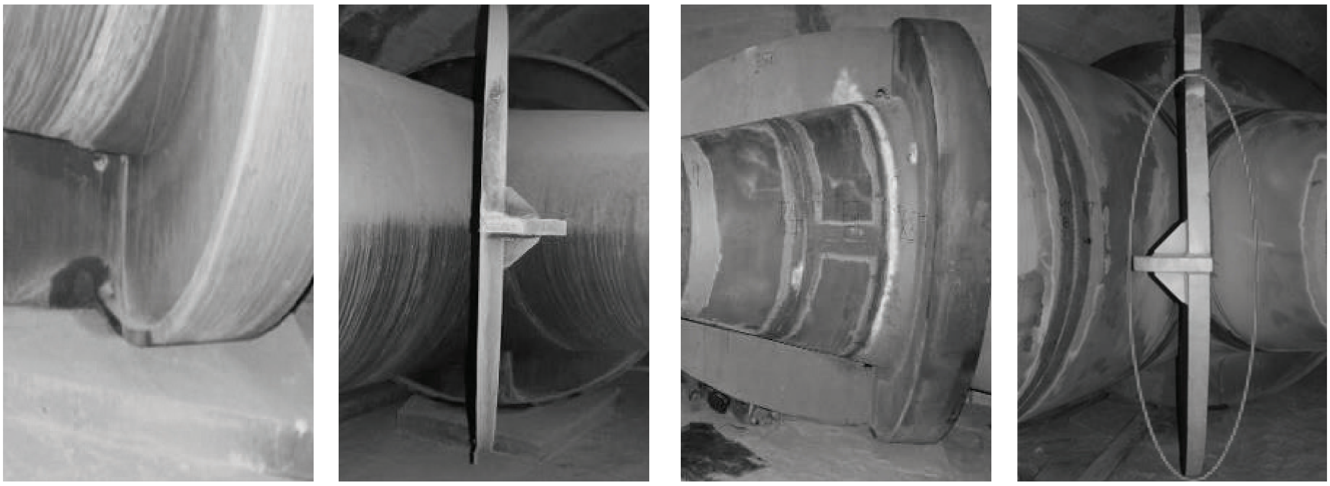
a) Hydroelectric generating sets b) Appearance of the cross-section of the a Pelton turbine c) Runner

Figure 3. *Appearance of the Pelton turbine*

Significant problems at hydro power plant 'Perućica' refer to the parent material and weld metal of the breeches pipe 1A located at pipeline III. Significantly lesser problems were detected at parent material and weld metal of breeches pipes 7B, 8A and 8B. Pipeline and breeches pipes were made of microalloyed steel 'Nioval 47' (steel mill 'Jesenice'). Stresses that occur at pipelines in service during the process of execution of functional tasks (stationary and dynamic loads) and during the disturbed process of exploitation (non-stationary dynamic loads), cause severe damaging of parent material and weld metal at structural components of breeches pipes (collars and anchors), thus endangering the integrity of structure of pipeline III as a whole, figure 4. Role of the collar, which enables the leaning of the breeches pipe on the foundation, is to receive static and dynamic loads (mean pressure of up to 61 bar in pipeline axis, specific load that occurs due to the quantity of water in the pipeline, action of the force of gravity) and displacements which happen due to non-stationary dynamic loads that occur at the pipeline, while the anchor strengthens and balances the mass of the breeches pipe, figure 5a. Significant propagation of damages at the supporting structure of the breeches pipe 1A, especially at parent material of the anchor and welded joint between the collar and the anchor, as well as between the pipeline and the anchor, led to the situation that the breeches pipe was leaning not on the collar, but on the anchor, figure 5b.

Integrity of structures is a relatively recent scientific and engineering discipline, and it in a broader sense comprises state analysis and behaviour diagnostics, estimation of remaining service life and rehabilitation of structures which means that, apart from the usual situation which refers to the evaluation of the structural integrity when a flaw gets detected through the use of non-destructive testing, this discipline also includes the analysis of the stress state of the structure.

Figure 4. *Appearance of the pipeline III with breeches pipes*



a) Proper mutual position of the collar and the anchor

b) Improper mutual position of the collar and the anchor

Figure 5. *Proper mutual position of the collar and the anchor (fig. 5a) and damaging of the anchor caused by bending due to improper mutual position of the collar and the anchor (fig. 5b)*

2. EXPERIMENTAL TESTS

In order to determine the cause of degradation of parent material and weld metal at structural components (collar and anchor) of breeches pipes with designations 1A, 7A, 8A and 8B at pipeline III non-destructive and destructive tests were carried out. Non-destructive tests that were carried out include visual testing (VT), magnetic particle testing (MT) and ultrasonic testing (UT), while destructive tests included determination of chemical composition, tensile properties, impact energy and hardness.

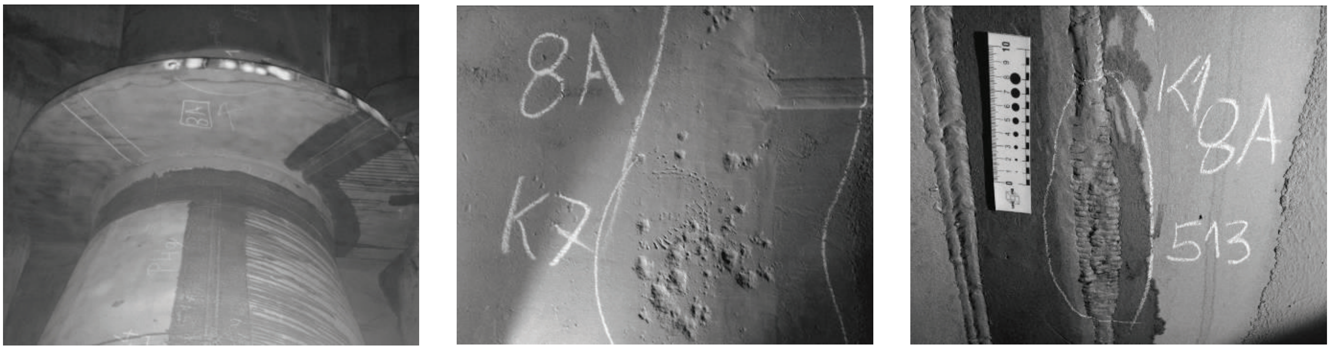
2.1 Non-destructive tests

Examples of damages that occurred at parent material of components of breeches pipes 1A, 7A, 8A i 8B detected by visual testing [3] are presented in figures 6-8, while examples of damages that occurred at parent material and weld metal of breeches pipes detected through the application of magnetic particle testing [4] are presented in figure 9. By ultrasonic testing [5] it was determined that cracks, presented in figures 10, 11 and 12, are 13 – 32 mm deep when it comes to parent material and 25 - 52 mm when it comes to weld metal at structural components of breeches pipes.

Figure 6. *Appearance of characteristic damages that occurred at parent material and weld metal of breeches pipe 1A*

a) Characteristic damages that occur at parent material of the collar and the anchor b) Characteristic damages that occur at weld metal

Figure 7. *Appearance of damages that occur at parent material and weld metal of the collar and the anchor of the breeches pipe 7B*



a) Characteristic damages that occur at parent material of the collar and the anchor b) Characteristic damages that occur at weld metal

Figure 8. *Appearance of damages that occurred at parent material and weld metal of the collar and the anchor of the breeches pipe 8A*

a) Characteristic damages that occur at parent material of the collar and the anchor

b) Characteristic damages that occur at weld metal

Figure 9. *Appearance of damages that occurred at parent material and weld metal of the collar and the anchor of the breeches pipe 8B*

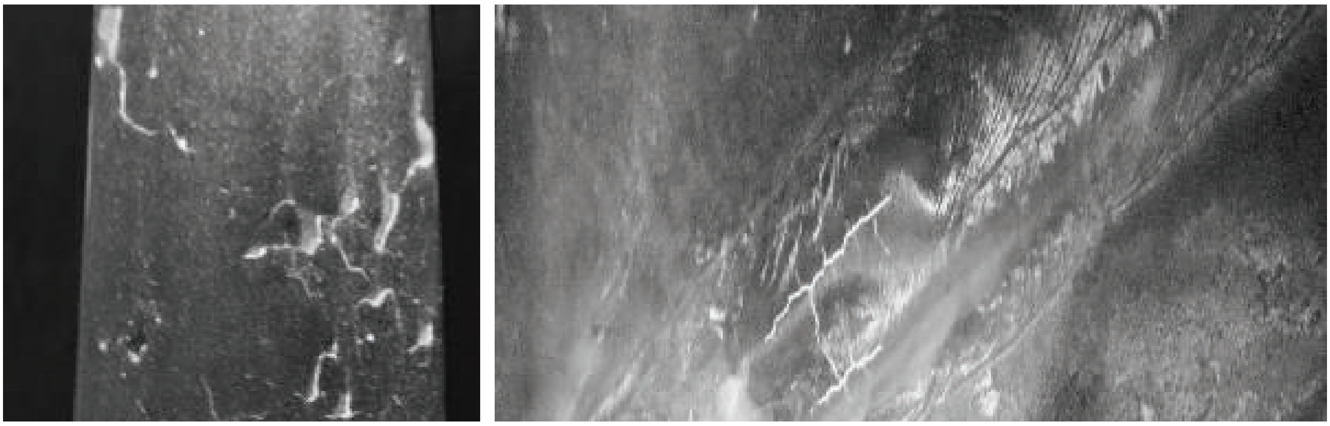


Figure 10. *Characteristic damages that occurred in the area of parent material and weld metal of components of breeches pipes 1A, 7A, 8A and 8B*

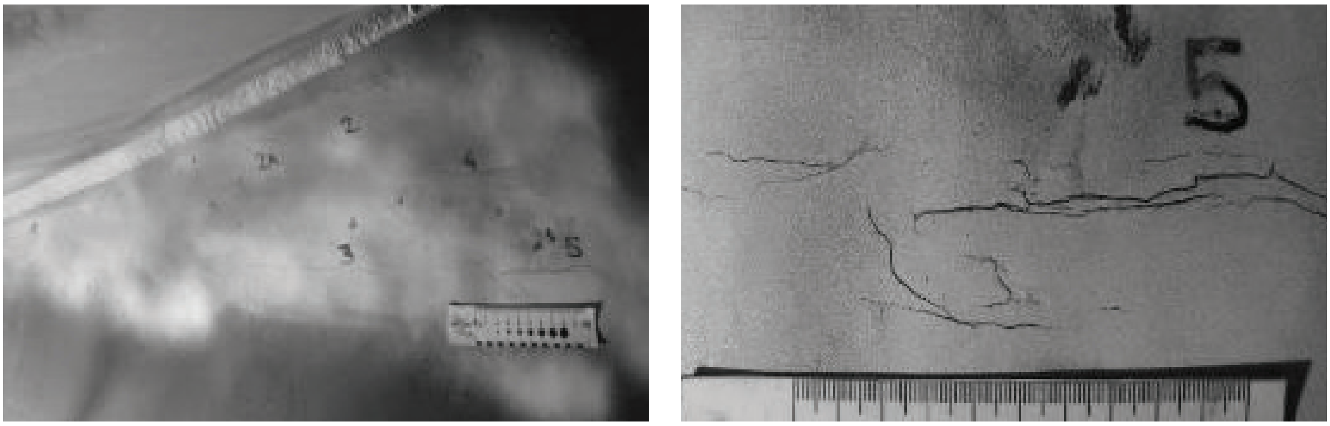
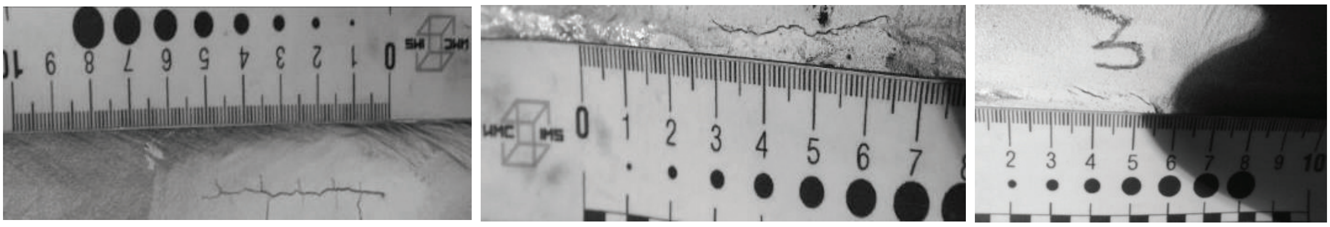


Figure 11. *Characteristic examples of cracks detected at parent material of components of breeches pipes 1A, 7A, 8A and 8B*



a) Cracks at the surface of weld metal   b) A crack in the heat affected zone   c) A crack in parent material

Figure 12. *Appearance of characteristic damages that occurred at the surface of parent material, heat affected zone and weld metal of breeches pipes 1A, 7A, 8A and 8B*

2.2 Destructive tests

Results of quantometric analysis carried out on a sample of microalloyed steel 'Nioval 47', presented in table 1, respond to the chemical composition stated by steel manufacturer [1].

Steel	Chemical composition (mass percentage)												
Nioval 47	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	V	Sn	Nb	Al
	0.17	0.41	1.48	0.012	0.002	0.12	0.09	0.21	0.02	0.07	0.007	0.045	0.061

Table 1. *Results of chemical analysis carried out on delivered sample*

From the delivered sample of anchor material 3 standard specimens were extracted in 3 mutually perpendicular directions for tensile testing. Diameter of the measurement area was 8 mm, which is in accordance with the standard [6]. Testing was performed on the machine for tensile, compression and bend testing, produced by company A.J. Amsler from Switzerland, with the maximum measurement range of 98,1 kN. Test results, shown in table 2, do not deviate from those stated by the manufacturer of micro-alloyed steel 'Nioval 47'.

Sample position	Specimen	Yield strength Re [N/mm^2]	Tensile strength Rm [N/mm^2]	Elongation A5,65 [%]	Contraction Z [%]
Direction of rolling	Surface layer	507	643	30.00	65.48
	Middle layer	516	650	26.50	59.36
	Lower layer	503	643	27.00	60.94
Perpendicular to the direction of rolling	Surface layer	486	630	25.75	66.94
	Middle layer	511	648	27.50	60.94
	Lower layer	487	622	22.50	65.48
z-direction	Surface layer	463	506	6.67	12.89
	Middle layer	469	640	14.00	24.88

Table 2. *Tensile test results, obtained at the temperature of 20°C, in accordance with SRPS EN 6892-1*

Results of standard hardness tests performed at the surface and along the cross-section of polished plates extracted from adequate samples in accordance with standard [7] are presented in table 3. On the basis of obtained results it can be concluded that they do not deviate significantly from those prescribed by the steel manufacturer.

Impact energy tests were performed by Charpy pendulum "Alfred Amsler", with range of 0-300 J, using the V2-notch specimens with dimensions of 10x10x55 mm taken from 3 mutually perpendicular directions of the sample, in accordance with the standard [8]. Test results, presented in table 4, are satisfactory.

Measurement position	Hardness [HBW 5 /750/20"]	Mean value [HB]
At the surface	217, 219, 217	218
Along the cross-section	211, 193, 202	202

Table 3. *Results of hardness testing, in accordance with SRPS ISO 6506-1*

Sampling position	Specimen	Temperature T [^{o}C]	Impact energy $KV_{2/300}$ [J]	Mean value [J/cm^t]
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	

Table 4. *Impact energy test results, in accordance with SRPS EN 10045-1*

3. CALCULATION OF STRENGTH OF PIPELINE III IN THE AREA OF BREECHES PIPE 1A

According to the directive for pressure equipment [9], for the design and evaluation of pipeline integrity during service calculation methods based on empirical formulas, analytical procedures andfracture mechanics are most commonly being used. Integrity evaluation of pipeline III in service, based on results of non-destructive tests and carried out after the repair by fine grinding and welding / surface welding, is also based on the analytical calculation of strength that refers to the critical section of the pipeline, being the section in the area of breeches pipe 1A.

Calculation of strength of pipeline III in the area of breeches pipe 1A, taking into account that mentioned section is subjected to the action of internal pressure, was carried out in accordance with standard EN 13445-3 [10].

According to [1], basic technical properties of pipeline III in the area of breeches pipe 1A are:

lowest measured value of yield strength of pipeline material (20^{o}C)	YS = 463 MPa
lowest measured value of tensile strength of pipeline material (20^{o}C)	TS = 616 MPa
highest external pipeline diameter	D_e = 2100 mm
lowest internal pipeline diameter	D_i = 2040 mm
lowest measured pipeline housing sheet metal thickness	t_h = 30 mm
operating pressure at pipeline axis	p = 6.1 MPa
welded joint coefficient	z = 0.8

$$\frac{D_o}{D_i} = \frac{2100}{2040} = 1.03 < 1.2 \quad \text{– condition that proves the applicability of the standard} \qquad (1)$$

3.1 Calculation of pipeline strength with respect to the internal pressure

By calculating the strength with respect to the internal pressure [10], through the use of equation (2), it was proved that required thickness of the cylindrical housing of pipeline III in the area of breeches pipe 1A is sufficient, or to put it differently it was determined that the calculated value of sheet metal thickness is not higher than the lowest value of thickness.

$$t = \frac{D_o \cdot p}{2 \cdot f \cdot z + p} + \delta_e + c = \frac{2100 \cdot 6.1}{2 \cdot 256.67 \cdot 0,9 + 6.1} + + 0.8 + 1.0 = 29.2.mm \ < 30 \ [\text{mm}] \qquad (2)$$

Value 0.8 in equation (2) stands for the addition for allowable deviation of sheet metal thickness, while value 1.0 stands for the addition required due to the occurrence of damages caused by corrosion. Coefficient of strength f stands for the lower of 2 values obtained from expressions defined in equation (3):

$$\text{f} = \min\left(\frac{YS_{0.2}}{1,5}; \frac{TS}{2,4}\right) = \min\left(\frac{463}{1,5}; \frac{616}{2,4}\right) = (308.67; 256.67) \qquad (3)$$

Taking into account the fact that cracks which exist on the surface of parent material were not completely removed by fine grinding, calculation of the strength of pipeline III in the area of breeches pipe 1A (calculation of the lowest allowable sheet metal thickness value) was carried out by adoption of minimum values of yield strength and tensile strength for material 'Nioval 47', as well as joint quality factor specified for quality class 'C' of the welded joint.

CONCLUSION

Test results showed that the main cause of damage occurrence at the load carrying structure of breeches pipe 1A at pipeline III of hydroelectric power plant ''Perućica'', or in other words of degradation of parent material of the anchor and weld metal between the collar and the anchor and between the pipeline and the anchor is the fact that breeches pipe started to lean not on the collar, as defined by the project, but on the anchor which could not endure all loads that occur during service. Degradation of parent material and weld metal of breeches pipes 7B, 8A and 8B occurred during the manufacture and exploitation of the pipeline.

ACKNOWLEDGEMENT

Authors wish to thank the Ministry of education, science and technological development of the Republic of Serbia for financing the project EVB: TR –.35006

REFERENCES

[1] Documentation of pipeline manufacturer, Steel mill 'Jesenice', Slovenia, 1960.

[2] Sedmak S., Arsić M., Bajić D., Mladenović M., Savić Z., Koprivica S.: "Analysis of causes of degradation of parent material and weld metal of breeches pipe at hydro power plant 'Perućica'", *Integritet i vek konstrukcija / Structural Integrity and Life*, (ISSN 1451-3749), 181616135), Editor in Chief: Prof. dr Aleksandar Sedmak, Publishers: Society for structural integrity and life and Institute for materials testing, 2015, Vol. 15, No. 3, pp. 147-151, online at http://www.divk.org.rs/ivk/

[3] SRPS EN ISO 17637: Non-destructive testing of welds - Visual testing of fusion-welded joints, 2012.

[4] SRPS EN 17638: Non-destructive testing of welds. Magnetic particle testing, 2017.

[5] SRPS EN 17640: Non-destructive testing of welds - Ultrasonic testing - Techniques, testing levels, and assessment, 2012.

[6] SRPS EN 6892-1: Metallic materials - Tensile testing - Part 1: Method of test at room temperature, 2017.

[7] SRPS ISO 6506-1: Metallic materials. Brinell hardness test. Test method, 2016.

[8] SRPS EN ISO 148-1: Metallic materials - Charpy pendulum impact test - Part 1: Test method, 2017.

[9] The Pressure Equipment Directive 97/23/EC, European Parliament, 1997.

[10] SRPS EN 13445-3, Unfired pressure vessels - Part 3: Design, 2015.