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Analysis of Current State and Integrity Evaulation for the Air Tank of the Regulation System of Turbine A6 at Hydropower Plant Djerdap 1

ABSTRACT

Vertical Kaplan turbines with nominal power of 200 MW, made in Russia, have been installed at 6 hydroelectric generating sets of "Djerdap 1". Most of the components were made of steel in accordance with GOST and ASTM standards. During the rehabilitation of the hydroelectric generating set A6 non-destructive testing methods were performed on parent material and welded joints of the main oil/air tank and air tank with the auxiliary oil/air tank, which acts as pressure accumulator in the regulation system, in order to carry out the analysis of the current state and integrity evaluation for the regulation system of the turbine. Shells of all 3 tanks were made of steel Č 1205, while bottoms were made of russian steel St 20K. Tests were also performed on pipeline elements (pipes and elbows).

The results of non-destructive tests performed on air tank are presented in this paper. Mechanical damages were detected by visual inspection at parent material of the shell and at the upper bottom, as well as discontinuous and incompletely welded joints on the inside and outside of the tank. Surface linear crack type indications were detected through magnetic particle testing at intersections of welded joints on the inside of the tank. Internal crack type defects were detected through ultrasonic testing of welded joints

On the basis of test results the technology of reparatory welding / surface welding of parent material and welded joints was created, while on the basis of the analytical calculation of tank strength the evaluation of its integrity for the following 40 years of operation was obtained.

Keywords: air tank, tests, damage repair, strength calculation, integrity.

1. INTRODUCTION

Vertical Kaplan turbines with nominal power of 200 MW, made in Russia, have been installed at 6 hydroelectric generating sets of "Djerdap 1"[1]. Basic components of hydroelectric generating set A6 turbine are presented in *figure 1*. Most of the components were made of steel, in accordance with GOST and ASTM standards.

Regulation system supplies the turbine regulator with oil and regulates the movement of guide vane apparatus vanes. It also regulates the position of runner blades and number of revolutions of the turbine shaft, *figure 2*. Internal pressure in the regulation system is 4 MPa. In *figure 2* main oil/air tank, air tank and the auxiliary oil/air tank, which acts as pressure accumulator in the regulation system, are presented. Shells of all 3 tanks were made of steel Č 1205 [2], while bottoms were made of russian steel St 20K [3].

1.1 Basic Technical Properties of the Air Tank

According to the documentation of the manufacturer, basic technical properties of the air tank are as follows (*prilog 1*):

- manufacturer of the air tank .... „Litostroj", Ljubljana
- factory label of the tank 281
- year of manufacture 1970
- tank construction....... stationary, vertical, one-part, single-walled
- construction of the bottom .... torispherical, deep, one-part, factor $\beta = 2{,}2$
- manufacturing technology .... welding
- quality factor of the welded joint.................. $v = 1$
- operating pressure .... 4 MPa
- test pressure .... 5,2 MPa
- operating volume .... $V = 18 m^3$
- accumulated energy.................................. $p \cdot V_g = 40 \cdot 658 = 26320\ bar \cdot m^2$

- operating medium .... air
- operating temperature of air..... t_{min} = 20°C, t_{max} = 50°C
- vessel category II
- tank shell material .... Č 1205
- tank bottom material .... St 20K
- yield strength of shell material for 16-40 mm thick sheet metal .... $R_{02,0} = K_o$ = 250MPa
- yield strength of bottom material......for 21-40 mm thick sheet metal .... $R_{02,d} = K_d$ = 235MPa
- thickness of shell sheet metal........................36mm
- thickness of bottom sheet metal 40mm
- outer diameter of the shell............... D_{os} = 2480mm
- inner diameter of the shell............... D_{is} = 2408mm
- outer diameter of the cylindrical section of the bottom .... D_{ob} = 2480mm
- inner diameter of the cylindrical section of the bottom .... D_{ib} = 2400mm
- mass of the empty vessel.................. m = 12100 kg

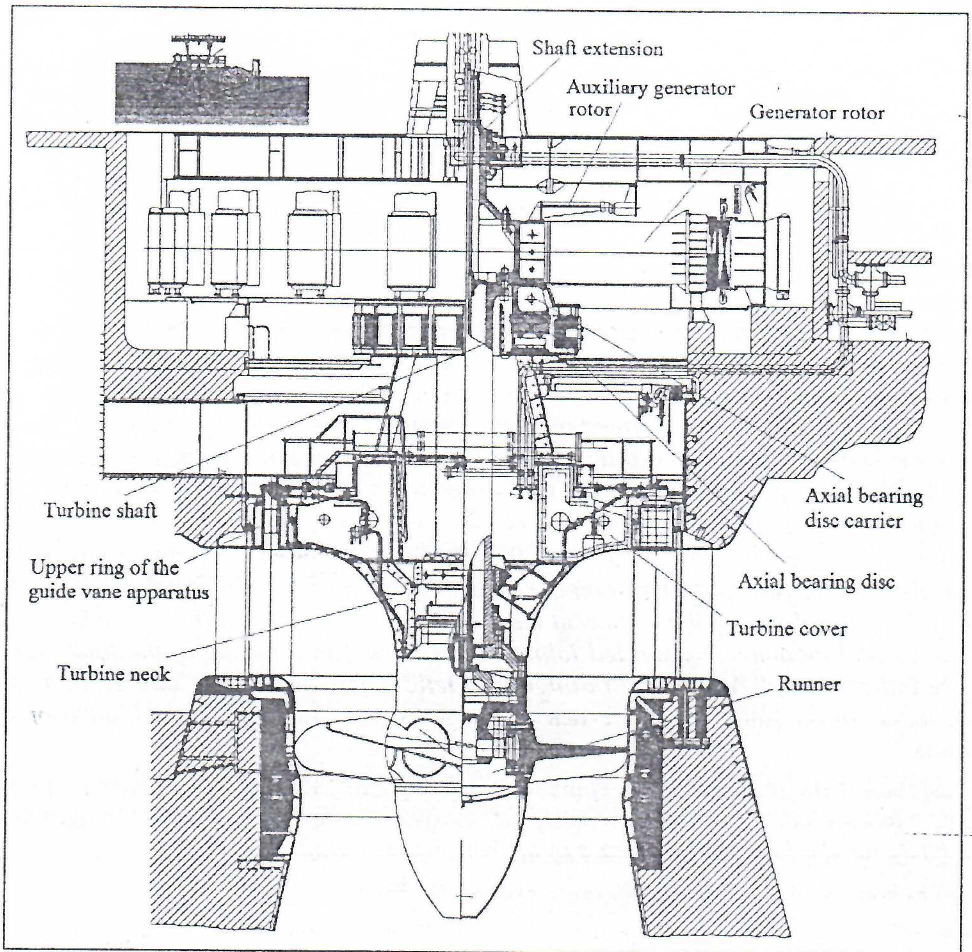


Figure 1. - *Appearance of the vertical Kaplan turbine, nominal power 200 MW*

2. NON-DESTRUCTIVE TESTS

In order to carry out the analysis of the current state and evaluate the integrity of the air tank, which is a component of the regulation system of A6 turbine at hydro power plant "Djerdap 1", non-destructive tests were performed. These tests were supposed to confirm the adopted value of quality factor of the welded joint v = 1, because for this value no damages on parent material and welded joints of pressure equipment are allowed. Tests were performed by operators that meet the requirements of standard [4].

2.1 Visual Inspection

Mechanical damages were detected by visual inspection, carried out in

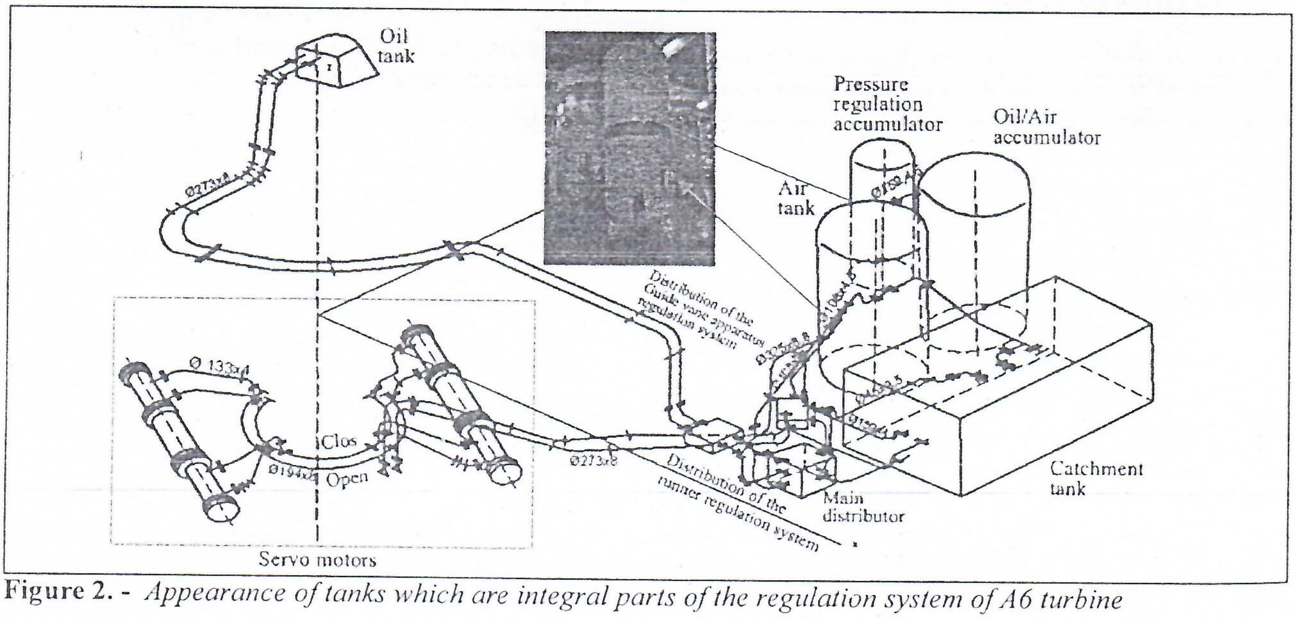
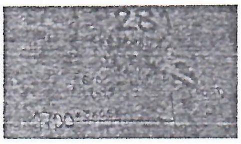
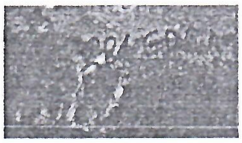


Figure 2. - *Appearance of tanks which are integral parts of the regulation system of A6 turbine*

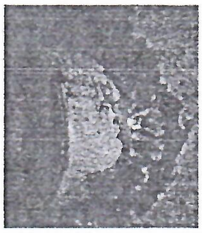


a) Mechanical damage at the shell

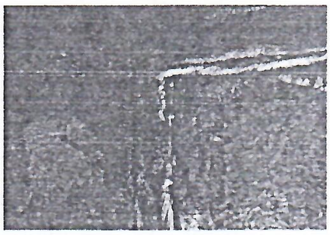


b) Mechanical damage at the upper bottom

Figure 3. - *Appearance of characteristic damages at shell and upper bottom sheet metal*



a) Welded joint on the inside of the tank

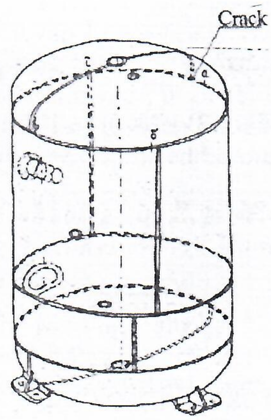


b) Welded joint on the inside of the tank

c) Welded joint on the outside of the tank

d) Welded joint on the outside of the tank

Figure 4. - *Appearance of discontinuous and incompletely welded joints*



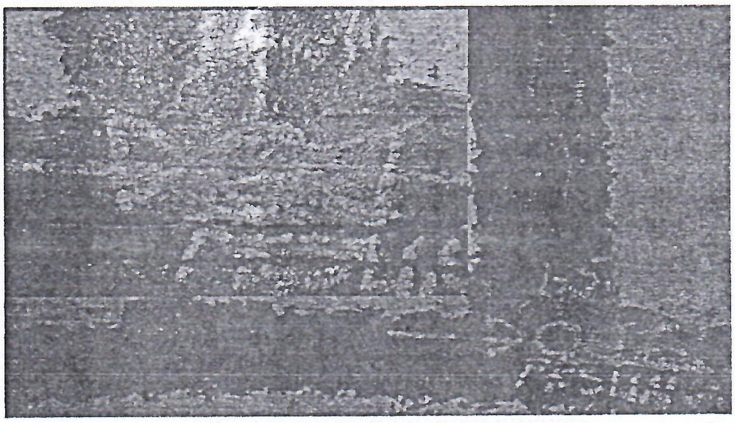
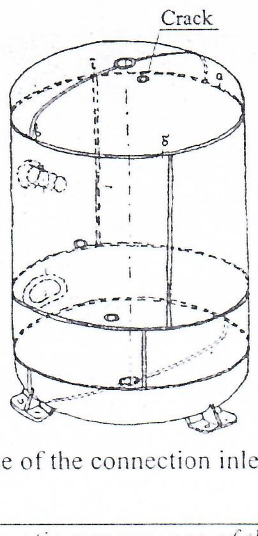
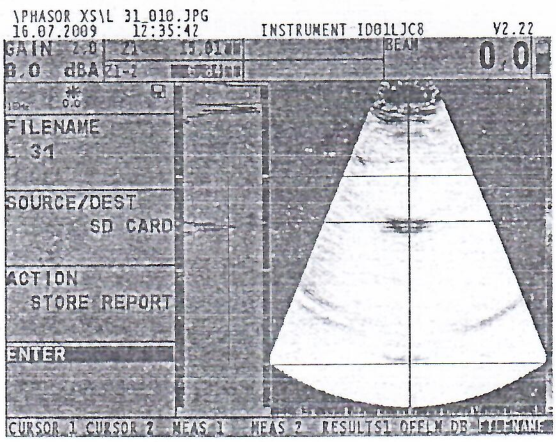


Figure 5. - *Location of the crack at the intersection of welded joints on the inside of the upper bottom*



a) Appearance of the connection inlet with a crack



b) Flaw indication echo

Figure 6. - *Schematic appearance of the air tank and connection inlet at which the crack was detected*

accordance with standard [5] and acceptance criteria [6], at parent material of the shell and at the upper bottom (*figure 3*). It was also detected that welded joints on the inside and outside of the tank are discontinuous and incomplete, *figure 4*.

2.2 Magnetic Particle Testing

Surface linear crack type indication, 5 mm long, was detected through magnetic particle testing, performed in accordance with standard [7] and acceptance criteria [8], at the intersection of welded joints on the inside of the upper bottom of the air tank (*figure 5*).

2.3 Ultrasonic Tests

By ultrasonic testing, performed in accordance with standard [9], a 15 mm deep crack along the entire circumference of the welded joint at one of the connection inlets was detected, which is not allowed according to acceptance criteria defined by standard [6]. Schematic appearance of the air tank and connection inlet at which the crack was detected are presented in *figure 6*.

2.4 Ultrasonic Determination of Shell and Bottom Metal Sheet Thickness

The following values of air tank shell and bottom metal sheet thickness were determined through ultrasonic testing, in accordance with standard [10]:

- minimum thickness of shell sheet metal....t_s = 35,8 mm
- minimum thickness of sheet metal of the cylindrical section of the bottom....................... t_{csb} = 40,0 mm
- minimum thickness of sheet metal of the torispherical section of the bottom ....t_{tsb} = 38,7 mm
- minimum thickness of sheet metal of the spherical section of the bottom....................... t_{ssb} = 37,4 mm

2.5 Radiographic Testing of Intersecting Welded Joints

Homogeneity of intersecting butt welded joints at the air tank has been tested through the application of standard [11]. Test results showed that the quality of welded joints meets the requirements defined by standards [6, 12].

3. AIR TANK REPAIR TECHNOLOGY

According to the manufacturer's data, air tank shell is made of steel Č 1205, in accordance with SRPS C.B4.014, while upper and lower bottom are made of russian steel St 20K, in accordance with GOST 5520-6. On the basis of data that refer to chemical composition and mechanical properties, presented in *tables 1* and *2*, it can be concluded that both types of steel belong to the same category.

3.1 Weldability Analysis for Steels of Which the Shell and Bottoms Are Made of

Repairs were performed in zones of parent material and welded joints at the shell and bottoms of the tank with mechanical damages through the application of the appropriate welding / surface welding technology. Taking into account the limited weldability of steels involved, caused by their chemical composition, the preheating temperature for 40 mm thick metal sheet was obtained according to Seferian. Based on the calculation it was determined that preheating should be performed at T_P = 160 °C.

$$360[C]_h = 360C + 40(Mn + Cr) + 20Ni + 28Mo = \\ = 360\cdot 0,24 + 40(0,85 + 0,3) + 20\cdot 0,3 = 138,4 \quad (1)$$

$$[C]_h = \frac{138,4}{360} = 0,3844 \quad (2)$$

$$T_p = 350\sqrt{[C] - 0,25} = 350\sqrt{0,46 - 0,25} = 160^oC \quad (3)$$

$$[C] = [C]_h + [C]_d = 0,384 + 0,0768 = 0,46 \quad (4)$$

$$[C]_d = 0,005\cdot d\cdot [C]_h = 0,005\cdot 40\cdot 0,384 = 0,0768 \quad (5)$$

3.1 Selection of Welding Procedure and Filler Material

Based on parameters which determine the welding procedure (weldability of parent material, energetic

Table 1. - *Chemical composition of shell and bottom parent material in mass %*

Material	Standard	C	Si	Mn	P	S	Cr	Ni	Cu
Č 1205	SRPS C.B4.014	≤ 0,2	≤ 0,35	0,45	≤ 0,045	≤ 0,045	≤ 0,30	≤ 0,30	≤ 0,30
St 20K	GOST 5520-62	0,16-0,24	0,15-0,30	0,55-0,85	≤ 0,04	≤ 0,04	≤ 0,30	≤ 0,30	≤ 0,30

Table 2. - *Mechanical properties of shell and bottom parent material*

Material	Standard	Yield strength YS [N/mm^2]	Tensile strength TS [N/mm^2]	Elongation A5 [%]	Impact strength KV_{0C} [J], KCU [KJ/m^2]
Č1205	JUS C.B4.014	≥ 250	410-510	≥ 22	$KV_{20} \geq 40$
St 20K	GOST 5520	≥ 240	≥ 410	≥ 24	KCU ≥ 65

Table 3. - *Chemical composition of the electrode in mass %*

Electrode	Standard	C	Si	Mn	Cr	Ni	Mo	Cu
OK 67.70	SS EN 1600	≤ 0,03	0,7	0,9	23,0	13,0	2,8	≤ 0,3

Table 4. - *Mechanical properties of the electrode*

Electrode	Standard	Yield strength Re [N/mm^2]	Tensile strength Rm [N/mm^2]	Elongation A5 [%]	Impact strength KV_{0C} [J]	Impact strength KV_{0C} [J]
OK 67.70	SS EN 1600	510	610	32	50 (at +20^{0}C)	32 J (at −20^{0}C)

possibilities of the procedure, geometric complexity of the structure and comparative economic analysis), for the repair of damaged zones at the shell and the upper bottom of the tank procedure 111 [13] and electrode OK 67.70 were selected according to standard SS EN 1600, in order to avoid heat treatment after welding. Chemical composition and mechanical properties of electrode OK 67.70 (ESAB, Sweden) are presented in *Tables 3* and *4*.

3.2 Repair of Mechanical Damages on Parent Material and of the Crack in Weld Metal

Flaws detected through non-destructive testing were removed by gouging. Zones in which gouging occured were properly prepared afterwards (no sharp edges were allowed), prior to repair welding / surface welding. Zone in which gouging was performed was also degreased and dried before welding.

3.3 Technology of Reparatory Welding / Surface Welding in Zones Where Damages and Flaws Were Detected

Repair welding / surface welding in zones where damages and flaws were detected at the air tank was carried out in accordance with the following technology:

- preheating at 160 °C was performed through the application of butan, in the radius of 300 mm around the zone in which gouging was performed on the outside of the tank,
- before the use electrodes were dried at 350 °C for 2 hours,
- drying was performed not more than once, due to the possibility of cracking of electrode coating during the repetition of the procedure.
- electrodes were stored in individual heaters at 100 - 120 °C before use,
- in accordance with manufacturer's recommendation, during welding/surface welding the constant current power supply was used (welding machine), while electrodes were connected to the + pole,
- in accordance with the technical chart of electrode OK 67 70, first layer was applied through the use of the electrode with 2.5 mm diameter and current intensity of 50 - 90 A,
- other layers were applied through the use of the electrode with 3.2 mm diameter and current intensity of 50 - 90 A.
- width of the weld was less than 2.5 x d, where d is the diameter of the electrode,
- welding/surface welding was performed through the use of short arcs, with continuous elimination of slag,
- special attention was paid to the filling of craters during the cessation of the arc,
- welding/surface welding was performed at temperatures higher than 5 °C and in conditions devoid of significant air streaming,
- during the repair welding/surface welding the following procedures for the decrease of residual stresses and deformations were applied:
  - every layer of the weld was treated by the pneumatic hammer with the rounded top with 3-5 mm radius,
  - at zones with large cross-sections in which gouging was performed, after the application of every layer welding/surface welding of the bottom and sides with the 180° rotation of laying direction was carried out,
  - for narrow and long zones in which gouging was performed backstep welding/surface welding was carried out,
  - after the completion of welding / surface welding, all weld face reinforcements higher than the plane of parent material were removed by grinding,
  - after the completion of grinding, repaired zones were treated by the pneumatic hammer with the rounded top with 3-5 mm radius (grinding was performed on weld metal, heat affected zone and 10 mm of parent material outside the HAZ).

3.4 Non-Destructive Testing of Repair Welds / Surface Welds

Non-destructive testing of repair welds/surface welds was carried out by operators trained in accordance with standard [4]. No flaws were detected through visual inspection performed in accordance with standard [5], acceptance level 'B' [6], and through penetrant testing performed in accordance with standard [14], acceptance level '1' [15].

4. INTEGRITY EVALUATION OF THE AIR TANK

According to the pressure equipment directive [16], for design and evaluation integrity during exploitation it is necessary to use calculation methods based on empirical formulas, analytical procedures and fracture mechanics. Integrity evaluation of the air tank during exploitation was carried out through the analytical calculation of strength of the shell and upper bottom based on their technical properties after the completion of reparatory welding/surface welding.

4.1 Calculation of shell strength in relation to the internal pressure

Calculation of shell strength in relation to the internal pressure has been performed through the use of standard [17].

$$\frac{D_{So}}{D_{Uo}} = \frac{2480}{2408} = 1,03 < 1,2 \quad \text{– this condition proves the applicability of the standard} \tag{6}$$

Calculation proved that thickness of the shell of air tank, after performed repairs, is sufficient:

$$s_o = \frac{D_{so} \cdot p}{20 \cdot \frac{K_o}{S} \cdot \nu + p} + c_1 + c_2 = \frac{2480 \cdot 40}{20 \cdot \frac{250}{1.5} \cdot 1,0 + 40} + 1 + 1 = 31,4 \leq s_{o\min} \tag{7}$$

4.2 Calculation of bottom strength in relation to the internal pressure

Calculation of bottom strength in relation to the internal pressure has been performed through the use of standard [18].

4.2.1 Thickness calculation of the cylindrical section of the bottom

Calculation proved that thickness of the cylindrical section of the bottom of air tank, after performed repairs, is sufficient:

$$s_{cdd} = \frac{D_s \cdot p}{20 \cdot \frac{K_d}{S} \cdot \nu + p} + c_1 + c_2 = \frac{2480 \cdot 40}{20 \cdot \frac{235}{1,5} \cdot 1,0 + 40} + 1 + 1 = 33.3 \leq s_{cdd\min} \tag{8}$$

4.2.2 Thickness calculation of the torispherical section of the bottom

Calculation proved that thickness of the torispherical section of the bottom of air tank, after performed repairs, is sufficient:

$$s_{tdd} = \frac{D_s \cdot p \cdot \beta}{40 \cdot \frac{K_d}{S} \cdot \nu} + c_1 + c_2 = \frac{2480 \cdot 40 \cdot 2,2}{40 \cdot \frac{235}{1,5} \cdot 1,0} + 1 + 1 = 36,6 \leq s_{tdd\min} \tag{9}$$

4.2.3 Thickness calculation of the spherical section of the bottom

Calculation proved that thickness of the spherical section of the bottom of air tank, after performed repairs, is sufficient:

$$s_{sdd} = \frac{D_{ss} \cdot p}{40 \cdot \frac{K_d}{S} \cdot \nu + p} + c_1 + c_2 = \frac{4860 \cdot 40}{40 \cdot \frac{235}{1,5} \cdot 1,0 + 40} + 1 + 1 = 32,8 \leq s_{sdd} \tag{10}$$

In equations 6 – 10 factor S is the safety factor, factor c_1 is allowable deviation of material thickness in accordance with standard [19], while factor c_2 is corrosion addition in accordance with standard [20].

INSTEAD OF A CONCLUSION

Integrity of structures is a relatively new scientific and engineering discipline which, generally, comprises the state analysis, behavioural diagnostics, service life evaluation and rehabilitation of structures. It means that, aside from the usual situation in which the integrity of the structure needs to be evaluated when the defect is detected, this discipline also comprises the stress state analysis of the crackless structure. This approach is especially relevant for welded structures subjected to operating conditions suitable for crack initiation, such as fatigue and corrosion.

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