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STRESS STATE OF BOILER TUBES FOR STRUCTURAL INTEGRITY ASSESSMENT

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ABSTRACT
The change of state during and after water pressure proof test was monitored by strain gauges and acoustic emission. Residual stresses were measured by hole drilling method in critical zones of boiler drum and damaged tubes. In this way, initial (nil) stress state was established before placing the boiler into service. The initial level of residual stresses had reduced to after pressure testing, as a consequence of stress redistribution. Stresses calculated based on measured strains are elastic This was confirmed by acoustic emission measurements. Performed tests and analyses showed that boiler can be accepted as fit for service. During exploitation the boiler state can be evaluated comparing to the initial stress state.
Keywords: steam boiler, defects, experiment, stress state, fitness-for-purpose

1. INTRODUCTION
In many cases of in-service boiler failures, some well before the end of designed life cannot be explained only by applied operating condition (pressure and temperature), but effect of induced initial damages should also be analyzed, [1]. In order to increase steam production capacity in Oil Refinery Pančevo, a new 110 t/h boiler was installed. Misalignment of tube 13, made of St 35.8/I steel, is detected visually, and is caused during assembly. Also, tube 52 in the upper part of boiler, made of the same steel, was distorted due to plastic deformation. In order to assess boiler "fitness-for-purpose" with detected defects, additional tests were requested for evaluating the stress and strain state in critical zones during pressure proof test by cold water. For sake of comparison, the behaviour of undamaged tube 12 is also analyzed. These tests have to be performed from the outside in order to avoid change in boiler state by applying methods that will not jeopardize boiler tube integrity.
It was agreed to measure residual stresses by applying strain gauges by hole drilling method [2,3]. This test allows to establish initial (nil) stress state at boiler acceptance. The change of this state during operation can indicate fast damage development and can be used for boiler residual life assessment.

2. RESIDUAL STRESS TESTS
Residual stresses are determined by hole drilling method, [4,5]. Strain gauge rosettes HOTTINGER type 1,5/120 RY 61 are used. Temperature change is compensated by 3 strain gauges 6/120 LY 11. Measuring locations are chosen to get an insight in residual stress distribution in critical zones of boiler. Strain gauge location is presented in Fig. 1 for measuring location 1 on tube 52 (1 rosette). On measuring location 2, tube 13, measurements were performed before (rosettes ZN1 and ZN2) and after

pressure proof test (rosettes ZN3 and ZN4), Fig. 2. Strain gauge "1" is selected for referent direction, Fig. 3.

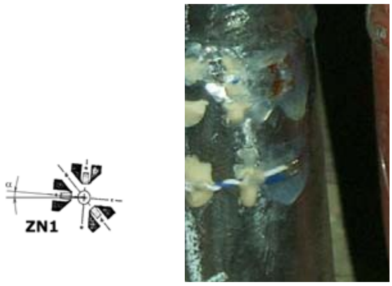

Figure 1. Measuring location 1 (plastically deformed tube 52 during assembly).

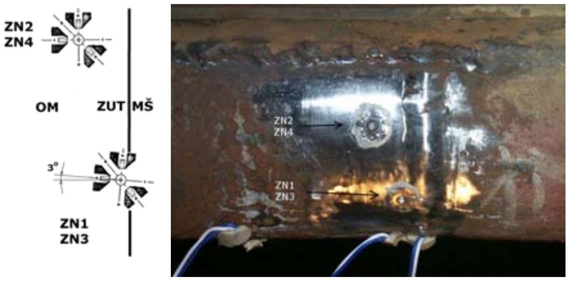

Figure 2. Measuring location 2 (tube 13, misalignment defect involved during welding in the assembly process).

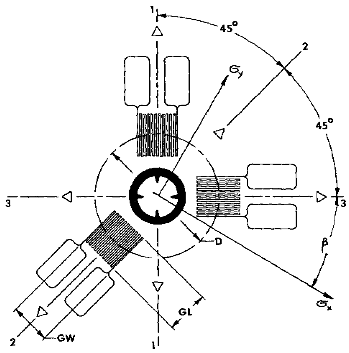

Figure 3. Directions of individual strain gauges in rosette 6/120 RY 11 and of normal stress components σ_x and σ_y.

The strains, relaxed during hole drilling by specially designed tool, are registered through electronic device UPM 40 based on strain gauge indications in the rosette: $\Delta\varepsilon_a$ for strain gauge 1, $\Delta\varepsilon_b$ for strain gauge 2 and $\Delta\varepsilon_c$ for strain gauge 3 (Fig. 3). The obtained results for strain components enabled determining values of principal normal stresses σ_1 and σ_2 by using the formula:

$$\sigma_{1,2} = -A^* \left(\Delta\varepsilon_a + \Delta\varepsilon_c\right) \pm B^* \sqrt{\left(\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b\right)^2 + \left(\Delta\varepsilon_c - \Delta\varepsilon_a\right)^2} \qquad (1)$$

Values for A^* and B^* are given for different elasticity modules, E, and Poisson's ratios, ν, [1]. These values refer to geometric parameters of rosette RY61 and hole diameter 2a = 1.5 mm.

Mutually perpendicular directions of principal normal stresses σ_1 and σ_2 are determined by angle θ:

$$\tan 2\theta = \frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a}; \quad \theta = \frac{1}{2}\arctan\frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a} \qquad (2)$$

3. RESIDUAL STRESS TEST RESULTS

Results of residual stress measurement in location 1 (tube 52) and locatin 2 (tube 13) are given in Table 1. Symbol θ_1 in Table 1 is the angle between maximal principal residual stress and tube longitudinal axis.

Table 1. Residual stress measuring results

Measuring location	Strain gauge			Stress, MPa		Angle, °
	1	2	3	σ_1	σ_2	θ_1
1 (tube 52 - ZN1	-65	-88	-110	163.2	135.3	-0.6
Before pressure proof test						
2 (tube 13 - ZN1	-37	-79	-108	146.0	101.3	-5.2
2 (tube 13 - ZN2	-43	-71	-103	143.1	105.9	1.9
After pressure proof test						
2 (tube 13 - ZN3	-27	-58	-86	114.7	78.1	-1.5
2 (tube 13 - ZN4	-35	-67	-90	123.9	89.4	-4.6

4. STRAIN MONITORING DURING PRESSURE PROOF TEST AND THE OBTAINED RESULTS

Change of deformation during pressure proof testing was monitored by using individual strain gauges 10/120 LY 11 HOTTINGER. Temperature compensation was performed by four similar gauges. Measuring zones were selected with the owner to gain insight in principal stress and to assess maximal stress in defected regions detected during assembly, [6,7]. The behaviour of undamaged tube 12 is also tested for comparison. Four measuring zones were defined:

- zone I on tube 13, locations 1 to 4, and zone II on tube 12, locations 5 to 7;
- zone III on boiler drum, measuring location 8;
- zone IV on tube 52, measuring locations 9 to 11.

Strains are measured step-wise at predetermined pressure level up to maximal stress of 71.5 bar that is achieved in the cold water pressure proof test. Principal normal stresses, σ_1, are calculated based on measured strains, by using the formula

$$\sigma_1 = E \cdot \varepsilon \qquad (3)$$

The dependence of principal normal stresses, σ_1, vs. applied pressure, p, for all measuring locations, is given in Fig. 5.

5. ANALYSIS OF RESULTS

The measured residual stress is at 44% yield strength level on tube 52. The measured residual stress was 39% of yield strength in welded joint HAZ and BM of tube 13. Due to residual stress relaxation by plastic deformation in the stress concentration region, the residual stress has reduced to 32% of yield strength, after the proof pressure test.

Stress calculations from microstrains measured by strain gauges during the pressure proof test showed elastic behaviour of material (Fig. 4) in all zones of tubes and boiler drum, with maximal value of 99.3 MPa in boiler drum and 66 MPa in tube 52.

Strains measured on rosettes and the calculated residual stresses (σ_1 and σ_2) show relatively high values (σ_1 = 163 MPa and σ_2 = 135 MPa) at measuring location 1 (tube 52, Table 2), indicating that tube plastic deformation affects residual stress level. Calculated residual stresses in tube 13, are relatively high, but they are quite close. It is interesting that after the pressure proof test, residual stresses were reduced, thus confirming that the applied pressure had caused the redistribution of residual stresses.

Strains measured by strain gauges during pressure proof testing and the calculated principal stresses show that in none of the measuring locations has the yield strength been exceeded, meaning that material behaviour is linear elastic up to the maximal test pressure of 71.5 bar. Principal stresses are low in all zones and ranged from 26 MPa at measuring location 1 (tube 13) to about 53 MPa at measuring location 3 in zone I, Fig. 4a, from 52 MPa in measuring location 7 to 66 MPa in measuring location 6 in zone II (tube 12), Fig. 4b. Higher stresses in undamaged tube 12 compared to stresses on tube 13 shown that the induced defect of the misaligned tube 13 did not affect structural integrity, so it can be disregarded at boiler acceptance. In zone IV, the principal stresses are very low and uniform as a result of plastic deformation in tube 52, Fig. 4d. The maximal principal stress is found at measuring location

8, zone III, Fig. 4c, as expected, since the strain gauge is placed in the hoop direction of maximal strains on the boiler base metal. Principal stress values in regions of detected defects in the assembly, as well as in regions with no defect are within the limits of relative measurement error, and are lower than the minimal yield strength of the built-in material.

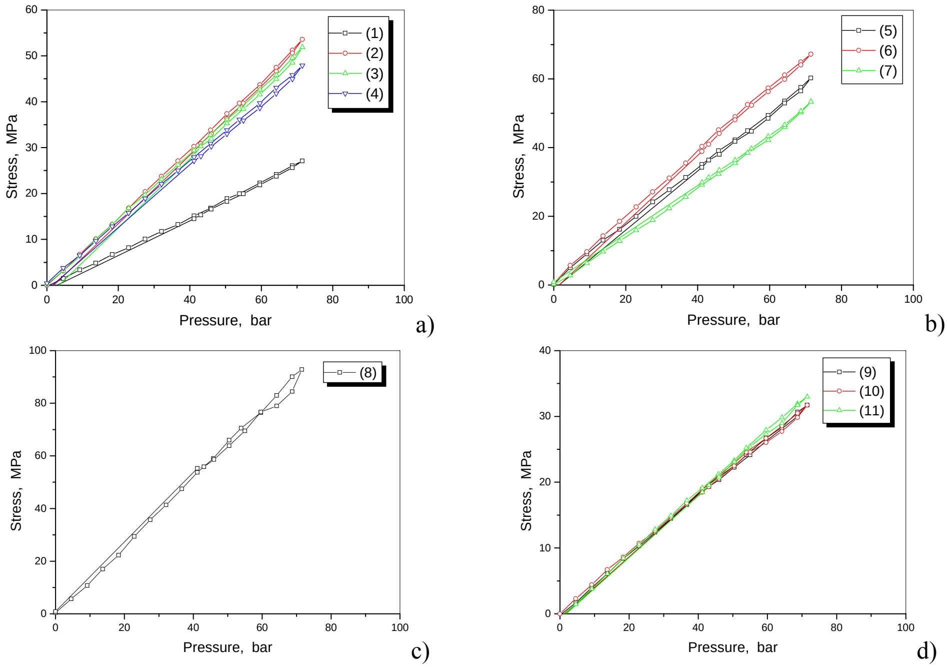

Figure 4. Dependence stress–pressure.

6. CONCLUSION

Considering test results and performed analyses one can derive the following conclusions:

- Relative high residual stress values are obtained in experimental tests in measured zones of boiler tubes, but do not jeopardize boiler integrity in critical regions, in tubes 52 and 13, respectfully. The pressure proof test produced stress equilibrium by redistributing the stresses.
- Measured strains by strain gauges and calculated principal stresses in measurement zones have shown that in the pressure proof test to the level of 71.5 bar, tube and upper boiler drum materials showed strictly elastic behaviour.
- The established initial stress state is useful for monitoring boiler behaviour during exploitation.

7. REFERENCES

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