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EFFECT OF LOCALLY DAMAGED ELBOW SEGMENTS ON THE INTEGRITY AND RELIABILITY OF THE HEATING SYSTEM

UTICAJ LOKALNO OŠTEĆENIH DELOVA CEVNIH LUKOVA NA INTEGRITET I POUZDANOST TOPLOVODA

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Ključne reči
- sistem za grejanje
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Abstract

This paper presents the integrity and reliability evaluation of the heating system as a whole, based on results of metallographic tests performed on parent material and the ultrasonic measurement of wall thickness of elbows made of steel St 35.8.

Izvod

Prikazana je procena integriteta i pouzdanosti sistema grejanja zasnovana na metalografskoj analizi osnovnog metala i ultrazvučnog merenja debljine zida kolena od čelika St 35.8 (DIN 17175).

INTRODUCTION

Premature failure of structural components in heating systems is generally caused by simultaneous effect of a large number of technological, metallurgical, structural and exploitation factors. Therefore, convenient structural design that could provide mechanical safety and integrity under service conditions could be achieved only by adequate selection of materials and thorough knowledge, regarding the behaviour of parent material and welded joints under various operating regimes.

Elbows are being used in order to enable isometric modifications of pipelines for the transportation of hot water. Taking into account that elbows are plastically deformed due to manufacturing process, as well as that they are subjected to various mechanisms of degradation and transitory loads during service /1, 2/, it is clear that their integrity mostly depends on the integrity of the pipeline as a whole. Considering that elbows have to be designed in such a way to avoid fracture under any load, it is necessary to precisely assess the operational load in order to ensure the reliability of the heating system during service.

Corrosion damages mostly occur at elbows due environmental influence. Local damages that occur at pipe and elbow walls cause the decrease of pressure, volume, deformation ability and fatigue resistance of the material. Therefore, it is important to assess the influence of local wall thinning on structural integrity of the heating system and develop a procedure for evaluating service reliability. Elbows of the heating system are made of steel St 35.8, in accordance with standard DIN 17175, /3/. Chemical composition and mechanical properties of steel St 35.8 are presented in Tables 1 and 2.

Table 1. Chemical composition of steel St 35.8, according to /3/.

Steel	mass %				
	C	Si	Mn	max S	max P
St 35.8	≤ 0.17	0.10-0.17	1.40-0.80	0.020	0.025

Table 2. Mechanical properties of steel St 35.8, according to /3/.

Steel	YS (MPa)	TS (MPa)	A_5 (%)
St 35.8	235	360-480	25

Long service life, prolongation of the operating cycle, safety and reliability during operation are the goals that researchers, determining the state of the hot water pipeline, are aimed at. For that purpose, metallographic tests are carried out on parent material of three elbows, their geometry is checked, wall thicknesses are measured, the strength of elbows is calculated and the reliability of the heating system as a whole, is estimated.

EXPERIMENTAL PROCEDURE

Convenient structural design for elbows, which should ensure integrity and reliability of the hot water pipeline under specific conditions of use, could be achieved only by adequate selection of steel, taking into account the resistance of steel degradation due to the action of the fluid and fracture under various service regimes.

Metallographic testing of elbows

Metallographic testing of elbows is performed in the most critical area (most tensioned area) in order to determine the size and deformation of grains in the external and internal areas of elbows, in accordance with standard EN ISO 643, /4/. A specimen is tested with the elbow radius of 90°, outer diameter D = 323.9 mm, inner (nominal) diameter d = 300 mm, radius R = 305 mm, wall thickness t = 8 mm, and axial distance a = 467 mm, Fig. 1.

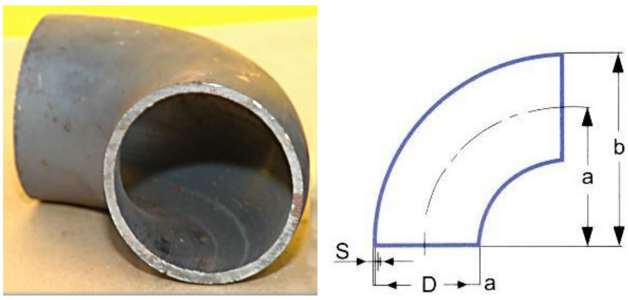
Metallographic analysis of the microstructure in specific areas is shown in Fig. 2. Large deformation of the grain in the tensioning direction can be seen in Fig. 2a (elongated grain), which is favourable only if the load acts in the direction of grain propagation. Microstructure of the internal area of the outer arc, presented in Fig. 2b, is also elongated, but less than the microstructure in the external area. In both areas of the internal side of the elbow, the grain suffered the deformation due to compression, which caused thickening, Figs. 2c and 2d.

Ultrasonic measurement of the elbow wall thickness

Wall thickness is measured on new elbow (specimen is shown in Fig. 2) and at 3 identical elbows which were in service for more than 8 years. Measurements were performed in accordance with standard EN 14127 /5/, by using the ultrasonic thickness measurement device KRAUTKRAMER DM-4. Measurement points at the external side of the elbow are distributed at distances of 30 mm, while measurement points at the internal side of the elbow are distributed at distances of 25 mm, Fig. 3.

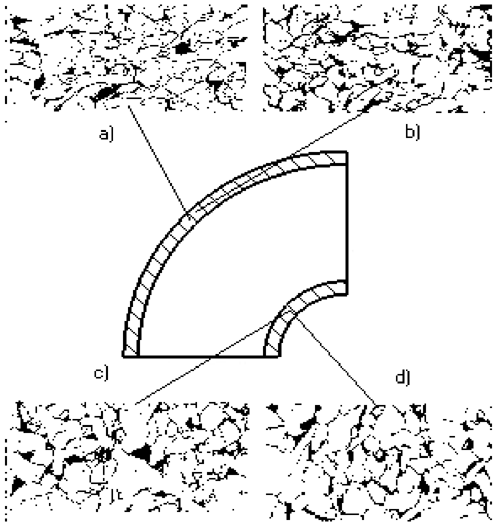
The smallest thickness measured at the external side of the brand new elbow is 8.5 mm, which is 3.4 % less than nominal thickness t = 8.8 mm, while the largest thickness measured at the internal side of the elbow is 9.14 mm, in areas 2" and 3', which is 3.9% more than nominal thickness.

The smallest thickness measured at the external side of 3 elbows which were in service was 8.1 mm, which is 9% less than nominal thickness t = 8.8 mm, while the largest thickness of 9.3 mm is measured at the internal arc, in areas 2" and 3', which is 6.3% more than the nominal thickness. Based on performed measurements it can be concluded that damages and local wall thinning are negligible. Corrosion causes most of the damaging. Taking into account the above mentioned, it is necessary to perform periodic inspections of elbow geometry, measure the thickness of walls and perform metallographic tests through the use of replica technique in order to evaluate structural integrity and reliability of elbows and pipelines.



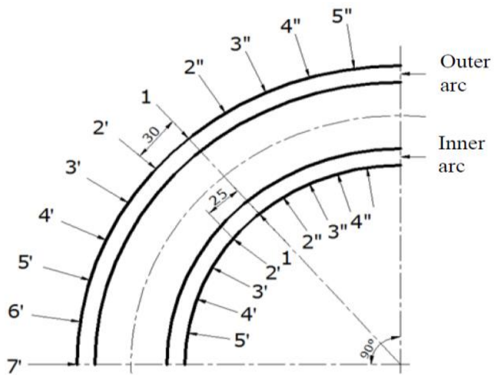
a) elbow sample b) elbow dimensions

Figure 1. Tested sample with basic elbow dimensions.

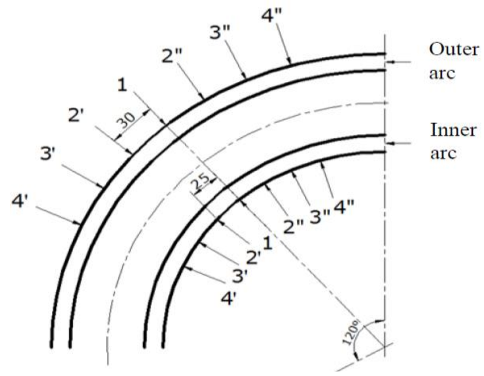


a), b) microstructure of external and internal area at the outer arc; c), d) microstructure of external and internal area at the inner arc

Figure 2. Microstructure of specific elbow areas



a) brand new elbow ∅300/90° - 323.9 mm



b) elbow in service ∅300/90° - 323.9 mm

Figure 3. Measurement points on elbows.

ELBOW STRENGTH ESTIMATION

Allowable stresses for pressure equipment have to be limited taking into account predictable causes of degradation of parent material and welded joints under operating conditions. Safety factors need to be used that eliminate strength reduction that occurs in manufacture or due to operating conditions, loads, calculation model, as well as properties, and behaviour of material. The above-mentioned demands could be fulfilled by using one of the following methods of strength estimation, or their combination, aided by suitable experimental tests:

– empirical formulas and/or national standards,
– analytical procedures,
– numerical procedures,
– fracture mechanics (in case of existing damage of structure).

In order to assess the integrity of the heating system, the analytical calculation of strength for elbows by using theory of elasticity is carried out. Mean circumferential stress at the walls of the elbow, subjected to the action of internal pressure, is calculated taking into account the balance of forces in the pressurized space F_{PE}, Fig. 4a, where force F_{PI} is predominant, and the stress which is predominant within material $F_{\sigma u}$ with the resulting force $\sigma \cdot F\sigma/A$ at the side of the curve located in the wall with thickness t.

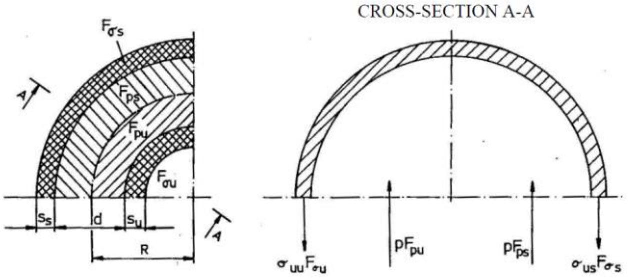


Figure 4. Balance of forces for determining the wall thickness, subjected to internal pressure.

Table 5. Data used for calculating wall thickness.

Operating pressure	p = 0.4 MPa (40 bar)
Operating temperature	t = 100 °C
Internal diameter of pipe	d = 305 mm
External diameter of pipe	D_e = 323.9 mm
Radius of elbow	R =300 mm
Nominal wall thickness of pipe	t = 8.8 mm
Yield strength	YS =215 MPa (T = 100°C)
Tensile strength	TS =360 MPa (T = 100°C)
Safety factor	S = 1.5

Taking into account the theory of elasticity, the following is obtained at the inner curve of the arc:

$$\sigma_{uu}\left(R-\frac{d}{2}-\frac{s_u}{2}\right)\pi s_u = p\left(R-\frac{d}{2}\right)\pi\frac{d}{2}\text{ , 13.35 > 8.99 kN}$$

$$\sigma_{uu} = p\frac{d}{2s_u}\frac{2R-\frac{d}{2}}{2R-d-s_u} = 0.4\frac{305}{2\cdot 8.8}\cdot\frac{2\cdot 300-\frac{305}{2}}{2\cdot 300-305-8.8} = 10.88\text{ MPa}$$

at the outer curve of the arc:

$$\sigma_{us}\left(R+\frac{d}{2}+\frac{s_s}{2}\right)\pi s_s = p\left(R+\frac{d}{2}\right)\pi\frac{d}{2}\text{ , 41.49 kN > 27.87 kN}$$

$$\sigma_{us} = p\frac{d}{2s_s}\frac{2R-\frac{d}{2}}{2R-d+s_s} = 11.22\text{ MPa}$$

According to the hypothesis for tangential stress, with lower value of main stress in the radial direction ($\sigma = -p/2$), mean stress within the elbow wall is obtained by following equations at the inner curve of the arc:

$$\sigma_{vu} = \sigma_{uu} - \sigma_r = p\frac{d}{2s_u}\cdot\frac{2R-\frac{d}{2}}{2R-d-s_u} + \frac{p}{2} \le \frac{R_{eH}}{S}\text{ ,}$$

$$42.89\text{ MPa} < 107.5\text{ MPa}$$

at the outer curve of the arc:

$$\sigma_{vs} = \sigma_{us} - \sigma_r = p\frac{d}{2s_s}\cdot\frac{2R-\frac{d}{2}}{2R+d+s_s} + \frac{p}{2} \le \frac{R_{eH}}{S}\text{ ,}$$

$$3.89\text{ MPa} < 107.5\text{ MPa.}$$

Taking into account that the load is equal to allowable stress (R_{eH}), or that $\sigma_v = R_{eH}/S$, necessary thickness of the internal and external elbow wall are obtained from:

$$s_u = \frac{d}{2\left(\frac{R_{eH}}{S}\right)p-1}\cdot\frac{2R-\frac{d}{2}}{2R-d-s_u} = s_0\frac{2R-\frac{d}{2}}{2R-d-s_u} = 4.2\text{ mm}$$

$$s_s = \frac{d}{2\left(\frac{R_{eH}}{S}\right)p-1}\cdot\frac{2R+\frac{d}{2}}{2R+d+s_s} = s_0\frac{2R+\frac{d}{2}}{2R+d+s_s} = 3.04\text{ mm}$$

where:

$$s_0 = \frac{d}{2\left(\frac{R_{eH}}{S}\right)p-1} = \frac{305}{2\left(\frac{215}{1.5}\right)} = 2.68\text{ mm ,}$$

minimum wall thickness of the cylindrical section of pipe.

For known geometric characteristics of elbows (radius R = 305 mm, $R \approx d$), predefined service conditions and quality of material, as well as taking into account the theory of elasticity, the lowest necessary elbow wall thickness is supposed to be s_0 = 2.68 mm.

CORROSION DAMAGE EFFECTS ON STRENGTH AND RESIDUAL SERVICE LIFE OF ELBOWS

The procedure for determining strength and residual service life of cylindrical segments of elbows with corrosion damages is based on the following principles:

- strength of cylindrical segments of elbows with corrosion damages should not be lower than design strength during the entire service period, until replacement,
- strength of cylindrical segments of elbows with erosion and corrosion damages should not be determined only in the moment of regular inspections, but should also be predicted for the period until the next regular inspection,
- prehistory of the development of every single damage caused by erosion and corrosion, or, to put it differently, period of service of the pipeline with erosion and corrosion damages and kinetics of damage propagation should be taken into account when performing the calculation,
- simplifications used during the application of procedures should enable conservative results.

Locations on cylindrical segments of elbows that weaken due to corrosion are determined based on individual results that refer to the condition of pipe elements. In order to simplify the procedure, Fig. 5, the area where damages-occurred is represented as a rectangular area: $A_{i\max} = L_i(s - s_i)$ = 226.8(8.8 – 2.68) = 1841.6 mm^2, where: L_i < 268 mm is the overall length of corrosion damage in the direction of the pipe; s = 8.8 mm, nominal pipe wall thickness; s_{de} = 7.1 mm, design pipe wall thickness; $s_i = s_{\min} = s_0$ = 2.68 mm – minimal wall thickness of cylindrical segment of elbow.

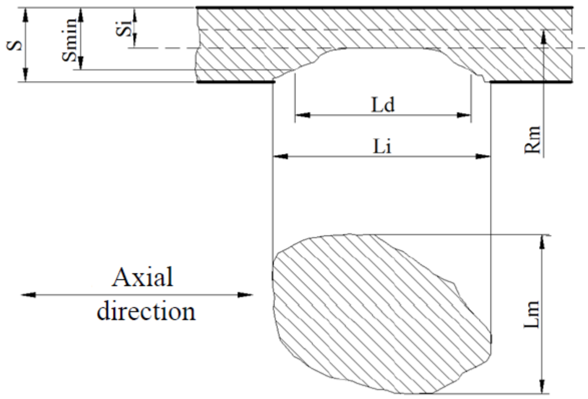


Figure 5. Pipe segment with erosion and corrosion damages.

Boundary value for the allowable length of corrosion damage on cylindrical segments of elbows, considered not to decrease the load carrying capacity, is obtained from:

$$L_{dop} = 8\sqrt{R \cdot s_{\min}} = 8\sqrt{300 \cdot 2.68} = 226.8 \text{ mm}$$

where: R – radius of the pipe.

For considered cylindrical segments of elbows and pipes, allowable length of the corrosion damage is L_{dop} = 226.8 mm ($s_{\min}$ = s_0 = 2.28 mm). At inspected cylindrical segments of elbows and pipes no significant continuous corrosion damage of length exceeding allowable length is detected.

Assessment of residual service life, t, if the condition from the previous equation is met, is obtained from:

$$t = \frac{s - s_{pr}}{s - s_i} \cdot \frac{t_i}{K_f} = \frac{8.8 - 7.1}{8.8 - 2.68} \cdot \frac{8}{1.2} = 6.7 \text{ years},$$

$$K_f = \frac{i_u + 1.4}{i_u + 1} = \frac{1 + 1.4}{1 + 1} = 1.2,$$

where: t_i = 8 years – service period of pipe section before the last inspection; K_f = 1.2 – error correction factor; i_u = 1 – overall number of inspections performed in the corrosion damage area during service.

The calculation has practical significance, because it determines the period of reliable operation of the hot water pipeline and evaluates the period until next inspection (non-destructive tests) or replacement. Nevertheless, for this application, the existence of an active database is necessary.

EVALUATION OF ELBOW RELIABILITY

For reliability assessment of elbows and pipes (no database) the probabilistic model ‘strength-stress’ is applied, based on presenting the character of strength and stress change taking into account the form of random quantities or random functions of time, /6/. All external influential factors are considered as stresses, while material properties that quantitatively characterize its degree of protection from external factors are considered as strength. Failure represents the random state which corresponds to defined degree of excess of stress in relation to strength.

Variables affecting reliability are so diverse that it is possible to directly investigate every single case, therefore it is necessary to understand what happens within the material under various stresses, what would the end result of these alterations be, and which material parameter is critical in order to be considered and applied. Three variables are considered while assessing reliability: internal diameter d = 305 mm; pressure of working fluid in the pipe p = 0.4 MPa and pipe wall thickness t = 8.1 mm /1, 2/. Wall thickness is designated with t in order to avoid the correspondence with standard deviation (S). Mean stress within the pipe wall is:

$$\bar{\sigma} = \frac{\bar{D}_u \cdot \bar{p}}{2 \cdot \bar{t}}$$

Assuming that variations of strength and stress obey the law of normal distribution and that there is no mutual correlation, the reliability of elbows is obtained from:

$$R = \frac{1}{\sqrt{2\pi}} \int_m^\infty e^{-\frac{x^2}{2}} dx, \quad m = -\frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{s_{ZS}^2 + s_\sigma^2}}$$

Using numerical integration, a high value of reliability, R = 0.99, is obtained for undamaged cylindrical segments of elbows and pipes (for measured thickness of pipe wall and wall of cylindrical segment of elbow t = 8.8 mm), while the reliability for damaged pipes and cylindrical segments of elbows (wall thickness 8.1 mm) is R = 0.86.

Based on experience gathered from earlier analyses and indicators that refer to the vulnerability of hot water pipelines, the determined reliability for 3 elbows and the pipes in between, could be considered acceptable for an upcoming period of 8 years, after which specific tests should be carried out.

CONCLUSIONS

Results of probabilistic analysis show the importance of:
– determination of exact input data,
– application of analytical models,
– determination of reliability of critical welded joints.

The presented methodological approach for the analysis of state of elbows can be used during the manufacture of new or modernization of existing structures, as well as for plans that refer to the scope of works, overhaul period, spare parts and materials.

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