# Influence of local damage of pipe elbows on the integrity and reliability of welded pipelines

**M. Arsić [1], A. Sedmak [2], Z. Savić [1], Ž. Šarkočević [2]**
[1] Institute for Materials Testing , Belgrade, Serbia
[2] Faculty of Mechanical Engineering, University of Belgrade, Serbia

**Keywords**

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## 1. Introduction

Pipe elbows are being used in order to enable isometric modifications of pipelines for the transportation of oil and gas. Knowing the fact that pipe elbows come out of the production process with local plastic deformations and that they are subjected to various degradation mechanisms and transitory loads during exploitation [1, 2], it is obvious that their integrity affects the integrity of the whole pipeline. Bearing in mind that pipe elbows have to be designed with a purpose to avoid the fracture regardless of the load they are subjected to, it is necessary to precisely estimate the load in order to secure the pipeline reliability during operation.

Erosion damage of pipe elbows, made of carbon steels, is generally caused by the fast fluid flow, and corrosion damage occurs as a result of the action of the operating fluid and because of the presence of carbon dioxide, hydrogen sulfide, chlorides and mercury in the watery environment. Local damage to the pipeline wall reduces the pressure, volume, deformation ability and fatigue resistance of the material. Therefore, it`s important to assess the influence of the local damage to the wall on the structural integrity of pipelines and develop the procedure for the assessment of its reliability during operation. Production of pipe elbows for oil industry is mostly based on the following standards and materials: API 5L (X42, X46, X52, X60), ASTM A 53 (Gr A, B,C), DIN 2470-I (St 37-0, St 44-0, St 52-0), BS 1387 (L,M,H), ISO 65 (L1, L2,M,H), EN 10240, EN 10208, GOST.

## 2. Experimental procedure

Convenient design solutions for pipe elbows, which would secure the stability and integrity of pipelines for the transportation of oil / gas, can be achieved only through adequate selection of steels, or in other words by knowing the resistance to degradation due to the action of the operating fluid (mixture) from the specific bearing and the resistance to fracture under various loading regimes. The main subject of these researches are pipe elbows made of API X42 steel [3].

### Tensile Testing

Tensile tests were carried out at room temperature through the use of standard specimens with parallely machined sides, according to ASTM A370 [4]. Basic mechanical properties of API X42 steel, according to API Spec 5L, are given in Table 1, and test results are presented in Figure 1.

Table 1. Mechanical properties of API X42 steel, according to API Spec 5L

| Steel | $R_e$ (MPa) | $R_m$ (MPa) |
|---|---|---|
| API X42 | min 289 | min 413 |

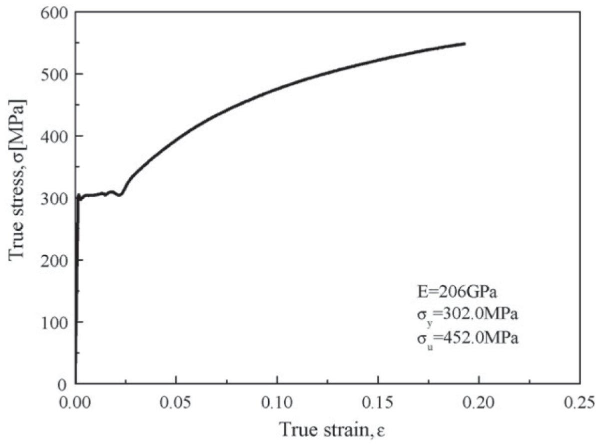


Figure1. True stress vs. true strain curve

### Metallographic Tests of Pipe elbows

Metallographic tests were carried out in the most critical zone (zone of highest tensile stress) due to determination of grain deformation in the internal and external zones of pipe elbows. The specimen with the elbow radius of 90°, diameter D = 219 mm, wall thickness S = 8.18 mm and axis distance a = 305 mm has been analyzed, Figure 2. Metallographic analysis of microstructure in specific zones is presented in Figure 3.

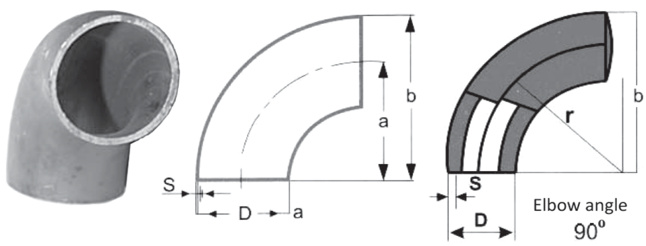


Figure 2. Tested sample with basic dimensions

In Figure 3a a big deformation of the grain in the direction of tensile strain (grain is elongated) can be seen, which is convenient only if the strain propagates toward the grain.

Microstructure of the internal zone on the inner side of the pipe (Figure 3b) is also elongated, but not as much as the structure in the outer zone. On the inner side of the elbow grain suffered a pressure deformation and thickened in both zones, as presented on Figure 3c and 3d.

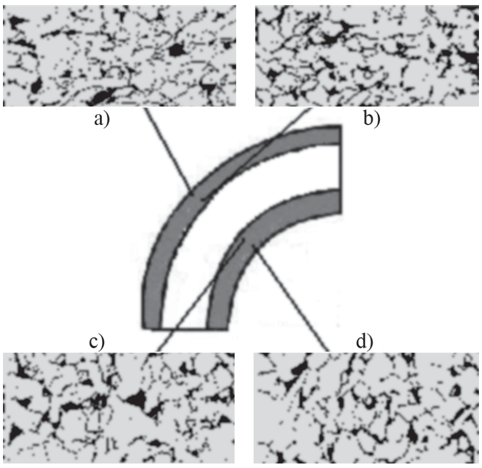


Figure 3. Microstructure of specific zones of the pipe elbow: a), b) microstructure of the external and internal zone on the outer side of the pipe elbow; c), d) microstructure of the external and internal zone on the inner side of the pipe elbow

**Ultrasound Measurement of Pipe Elbow Wall Thickness**

Wall thicknesses have been measured on a brand new pipe elbow (sample is presented in Figure 2) and on 3 identical (made by one manufacturer) which have been in use for more than 8 years.

Measurements have been performed in accordance with standard SRPS ISO 200.95.055 [5] by an ultrasonic flaw detector KRAUTKRAMER DM-4. Spacing between the nearest measurement locations on the outer side of the pipe elbow was 30 mm, and on the inner side of the pipe elbow 25 mm, Figure 4.

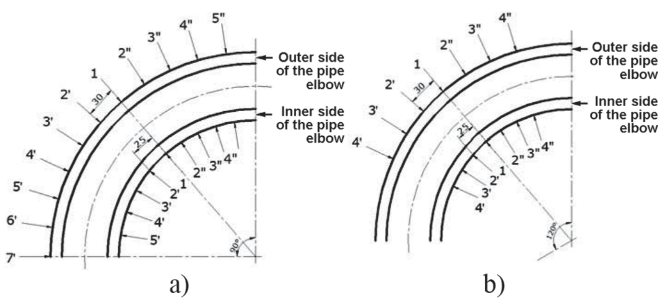


Figure 4. Measurement locations on pipe elbows: a) new pipe elbow 219/90 - 305 mm; b) used pipe elbow 219/90 - 305 mm

The smallest wall thickness on the new sample was measured on the outer side of the pipe elbow and its value was 7.9 mm, which is 3.4% less than nominal thickness S = 8.18 mm, and the largest thickening of 8.5 mm occured on the inner side of the pipe elbow in zones 2'' and 3', which exceeds nominal thickness by 3.9 %.

The smallest wall thickness on 3 samples in use was measured on the outer side of pipe elbows and its value was 7.5 mm, which is 8.1 % less than nominal thickness S = 8.18 mm, and the largest thickening of 8.7 mm occured on the inner side of pipe elbows in zones 2'' and 3', which exceeds nominal thickness by 6.3 %. On the basis of performed measurements it was concluded that damages and decreases in wall thickness of pipe elbows are mostly concentrated in the zone of tensile straining and in the neutral zone. Erosion and corrosion contribute heavily to the amount of damage. Therefore, it`s necessary to periodically check the geometry of pipe elbows, measure wall thicknesses and perform metallographic tests through the use of the replica method in order to assess structural integrity and reliability of pipe elbows and whole pipelines.

## 3. Strength calculation of pipe elbows

Mean circumference stress which occurs in walls of the pipe arch subjected to internal pressure gets calculated through the use of the balance of forces in space under pressure $F_{ps}$ ($F_{ps}$ - area under pressure), Figure 5a, in which force pFp exists, and the stress which exists within the material of cross-section $F_{\sigma u}$ with the resulting force $\sigma \cdot F_{\sigma u}$ on the side of the curve located in the wall whose thickness is S.

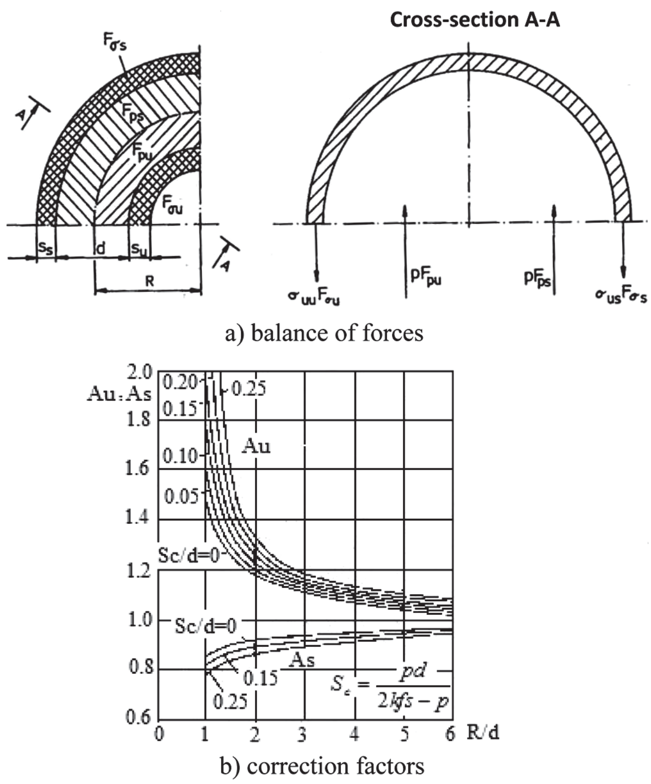


Figure 5. Determination of pipe elbow wall thickness under the influence of internal pressure

According to the theory of elasticity the following equation is obtained:

$$\sigma_{uu} \cdot (R - \frac{d}{2} - \frac{s_u}{2}) \cdot \pi \cdot s_u = p \cdot (R - \frac{d}{2}) \cdot \pi \cdot \frac{d}{2}, \quad (1)$$

$$\sigma_{uu} = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u}, \quad (2)$$

$$\sigma_{us} \cdot (R + \frac{d}{2} + \frac{s_s}{2}) \cdot \pi \cdot s_s = p \cdot (R + \frac{d}{2}) \cdot \pi \cdot \frac{d}{2}, \quad (3)$$

$$\sigma_{us} = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d + s_s} \qquad (4)$$

According to the hypothesis regarding the complex tangential stress, with lesser mean main stress (in the radial direction) σ = -p/2, equation for mean strain inside the wall looks like this:

- on the inner side of the curve:

$$\sigma_{vu} = \sigma_{uu} - \sigma_r = p \cdot \frac{d}{2 \cdot s_u} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} + \frac{p}{2} = \frac{K}{S} \qquad (5)$$

- on the outer side of the curve:

$$\sigma_{vs} = \sigma_{us} - \sigma_r = p \cdot \frac{d}{2 \cdot s_s} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R + d + s_s} + \frac{p}{2} = \frac{K}{S} \qquad (6)$$

Taking into account the assumption that strain equals the allowable stress (K), or $\sigma_v$ = K/S, the equation for the determination of the smallest allowable wall thickness value is obtained:

$$s_u = \frac{d}{2 \cdot \left(\frac{K}{S}\right) \cdot p - 1} \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} = s_o \cdot \frac{2 \cdot R - \frac{d}{2}}{2 \cdot R - d - s_u} \qquad (7)$$

or:

$$s_s = \frac{d}{2 \cdot \left(\frac{K}{S}\right) \cdot p - 1} \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} = s_o \cdot \frac{2 \cdot R + \frac{d}{2}}{2 \cdot R + d + s_s} \qquad (8)$$

where:

$$s_o = \frac{d}{2 \cdot \left(\frac{K}{S}\right) \cdot p - 1} \qquad (9)$$

$S_0$ - the smallest wall thickness of the straight pipe

The minimum allowable wall thickness value, according to the theory of elasticity and taking into account geometric characteristics of pipe elbows, conditions of exploitation and quality of the material, is $S_s$ = 2.73 mm (pipe elbows whose radius value is R= 305 mm).

## 4. Analysis of the influence of erosion and corrosion damage on strength and residual lifetime of cylindrical parts of pipe elbows

Procedure for determination of strength and residual lifetime of cylindrical parts of pipe elbows (and pipes) with erosion and corrosion damage is based on the following principles:

- strength of cylindrical parts of pipe elbows damaged by corrosion and erosion throughout the whole exploitation period until their replacement should not be less than design strength,
- strength of cylindrical parts of pipe elbows damaged by corrosion and erosion should not be determined only at the time of the regular inspection, but also anticipated for the period until the next regular inspection,
- history of development for every single damage caused by erosion and corrosion should be taken into account for the calculation, or in other words time of use of the pipeline damaged by erosion and corrosion and growth kinetics of damage,
- use of simplifications during the application of the procedure confirms the results obtained through the use of conservative methods.

Area weakened due to the influence of erosion and corrosion gets determined on the basis of results of the condition inspection regarding the pipe elements. In order to simplify the procedure damaged area is presented in the form of a rectangle, Figure 6.

$$A_i = L_i\,(S - S_i) \qquad (10)$$

where:

$L_i$ - overall length of erosion and corrosion damage in the direction of the pipe,
S - nominal thickness of the pipe wall,
$S_{pr}$ - design thickness,
$S_i$ - minimum thickness of the pipe wall.

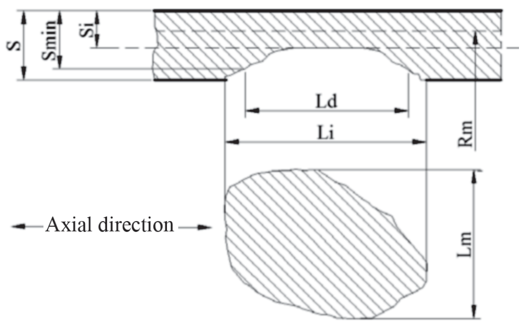


Figure 6. Diagram of a pipe segment with erosion / corrosion damage

Boundary value of allowable length of erosion / corrosion damages on cylindrical parts of pipe elbows which are considered not to reduce the capacity is obtained from the following equation:

$$L_{dop} = 8 \cdot \sqrt{R \cdot s_{\min}} \qquad (11)$$

where R - radius of the pipe.

One considered cylindrical parts of pipe elbows and pipes allowable length of corrosion damage is $L_{dop}$ = 97.4mm ($S_{min}$ = 2.73mm). As far as examined cylindrical parts of pipe elbows and pipes are concerned, no significant erosion or corrosion damage longer than allowed was detected.

Estimation of duration of safe exploitation, if the condition from the previous equation is fulfilled, is obtained from the following equation:

$$T = \frac{s - s_{pr}}{s - s_i} \cdot \frac{T_i}{K}; \; K_f = (i_u + 1.4)/(i_u + 1) \qquad (12)$$

where:

Ti - period of exploitation of pipe section before the last inspection,

$K_f$ - possible error correction factor,

$i_u$ - total number of inspections of erosion and corrosion damage during the exploitation of the pipe.

Period of reliable exploitation of the pipe system damaged by erosion and corrosion ΔT is determined by the following equation:

$$\Delta T = T - T_i \qquad (13)$$

Presented procedure has a practical value, because it enables the determination of the period of reliable exploitation of the pipe system and the assessment of the period between 2 inspections (by NDI methods) or before replacement. However, for the application of this procedure it is necessary to create an active database.

## 5. Reliability assessment of pipe elbows and pipes

For the reliability assessment of pipe elbows and pipes (without a database), a probabilistic "strength - strain" model is used, based on the change in character of strength and strain, which occur in the form of accidental values or accidental time functions [6]. Sum of all influential external factors is categorized as strain, and the sum of internal properties of the material is categorized as strength, which quantitatively categorize level of protection from external factors of the material. Failure represents the accidental condition which complies with to the defined level of strain exceedance in relation to strength.

Variables which affect reliability are so diverse in character that it is possible to directly investigate every single case, and therefore it is necessary to understand what happens within the material under various load conditions, what is the outcome of these processes and which ``material parameter`` is critical.

Three variables have to be considered during the reliability assessment: internal diameter ($D_u$ = 204 mm), pressure of the operating fluid in the pipe (p = 1.3 Mpa) and pipe wall thickness (t).

Equation for the calculation of the mean strain for given pipe wall thickness:

$$\bar{\sigma} = \frac{\bar{D}_u \cdot \bar{p}}{2 \cdot \bar{t}} \tag{14}$$

Variance of strain depends on the variance of some variables:

$$\sigma = f(\bar{D}, \bar{p}, s) = f(x_1, x_2, x_3) \tag{15}$$

When no intercorrelation exists, variance of strain when 3 variables exist is:

$$s_\sigma^2 = \sum_{i=1}^{3} \left( \frac{\partial f_i}{\partial x_i} \right)^2_{x_i = \bar{x}}, \; s_{x_i}^2 = \left( \frac{\partial \sigma}{\partial D_u} \right)^2_{D_u = \bar{D}_u} \cdot s_D^2 + \left( \frac{\partial \sigma}{\partial p} \right)^2_{p = \bar{p}} \cdot s_p^2 + \left( \frac{\partial \sigma}{\partial t} \right)^2_{t = \bar{t}} \cdot s_t^2 \tag{16}$$

$$s_\sigma^2 = \left( \frac{\bar{p}}{2 \cdot \bar{t}} \right)^2 \cdot s_D^2 + \left( \frac{\bar{D}_u}{2 \cdot \bar{t}} \right)^2 \cdot s_p^2 + \left( -\frac{\bar{D}_u \cdot \bar{p}}{s \cdot \bar{t}^2} \right)^2 \cdot s_t^2 \tag{17}$$

Under the assumption that changes in strength and strain obey the normal distribution law and that there is no intercorrelation, reliability of welded joints is obtained from the following expression:

$$R = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_m^\infty e^{-\frac{x^2}{2}} \cdot dx \tag{18}$$

where the value of m is taken from the adequate table:

$$m = -\frac{\bar{R}_{ZS} - \bar{\sigma}}{\sqrt{s_{ZS}^2 + s_\sigma^2}} \tag{19}$$

Through the calculation of the equation (18) the value of reliability of undamaged cylindrical parts of pipe elbows and pipes (wall thickness t = 8.18 mm) is obtained (R = 0.99), and for damaged pipes (wall thickness t = 7.5 mm) value of reliability is 0.86.

On the basis of earlier analyses and indicators regarding the endangerment of pipe systems for oil / gas transportation, determined reliability for 3 pipe elbows and pipes between them can be considered acceptable for the period of forthcoming 8 years, after which certain inspections should be carried out. It is strongly recommended that inspections should be carried out as often as possible, because the costs of inspections and analyses of pipeline condition are trivial in comparison with consequences which may occur if only a part of the pipe system collapses. Aside from material losses, the environment would be endangered too (air, soil and water).

## 6. Introduction of technical regulations and standardization in order to prevent the environmental pollution

There are many standards today which define the quality of material for the production of pipes and pipe elbows in oil industry, production requirements, pipe joints (welded joints and couplers), surface protection (internal and external) and a few procedures, technical regulations and standards which refer to the safety of oil and gas objects from the aspect of environmental protection. A basis for their introduction could be the European Pressure Equipment Directive PED 97/23/EC [7], because it refers to the manufacturers of vessels under pressure, reservoirs, heat exchangers, steam generators, boilers, industrial pipeline installations, safety equipment and pipe fittings for pipes under pressure, as well as to the storage and transportation of oil and gas.

## Conclusions

Long service life, extension of operation cycle length, safety and reliability are the main objectives to be reached, and for that purpose researches regarding the procedure for the determination of the condition of pipelines for the transportation of oil/gas are being conducted. For that purpose mechanical properties of the basic material were examined, and as far as 3 pipe elbows are concerned, aside from the examination of mechanical properties, their geometries have been checked, wall thicknesses have been measured, strength calculation has been carried out and reliability assessed.

Probabilistic reliability analysis enables us to assess how close the engineering assessment comes to reality. Results of the probabilistic assessment confirm the importance of:

- Determining accurate input data,
- Applying analytical models which minimally differ from reality,
- Determining the reliability of critical welded joints on the basis of the realistic analysis.

Introduction of the information system and creation of adequate databases is of utmost importance for the preventive maintenance and the assessment of quality and reliability of pipelines in oil industry.

Presented methodological approach for the condition analysis of pipe elbows can be properly used in the production or modernization of the existing structures and for planning of the scope of works and overhaul schedule, as well as for the acquisition of spare parts and materials.

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