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MODIFICATION OF FAILURE RISK BY THE USE OF HIGH STRENGTH STEELS IN PIPELINES

MODIFIKACIJA RIZIKA LOMA PRIMENOM ČELIKA POVIŠENE ĆVRSTOĆE U CEVOVODIMA

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Keywords
- high strength steels
- pipeline
- failure risk
- failure assessment diagram

Abstract

The use of new generation of pipe steels with high yield stress increases potentially the risk of brittle fracture. In order to evaluate this risk, safety factors associated with a surface crack and an operating pressure have been evaluated for three pipe steels: X52, X70 and X100. This evaluation has been made using a Failure Assessment Diagram and SINTAP procedure. This analysis has been extended to X120 pipe steel. The use of a Domain Failure Assessment diagram indicates that for this steel a risk of elastic plastic fracture exists. However, for pipe steels X52, X70 and X100, failure occurs potentially by plastic collapse.

Ključne reči
- čelik povišene čvrstoće
- cevovod
- rizik otkaza
- dijagram procene loma

Izvod

Primena nove generacije čelika za cevi, sa visokim naponom tečenja, povećavaju potencijalni rizik pojave krtog loma. U cilju procene rizika, stepeni sigurnosti vezani za površinsku prslinu i radni pritisak su sračunati za tri čelika za cevi: X52, X70 i X100. Ova procena je izvedena korišćenjem dijagrama procene loma i postupkom SINTAP. Ova analiza je proširena i na čelik za cevi X120. Primena dijagrama procene domena loma pokazuje da postoji rizik elastoplastičnog loma za ovaj čelik. Međutim, potencijalni lom plastičnim kolapsom je moguć za cevovodne čelike X52, X70 i X100.

INTRODUCTION

At present, requirement for natural gas is rapidly increasing internationally. Pipelines are used for natural gas transmission over long distance. Amelioration of gas transportation capacity is possible by increasing pipe diameters, operating pressure, gas cooling, decrease of the internal surface roughness and increase of service reliability. Several studies have shown that the most efficient factors on gas transportation capacity are in a decreasing order, pipe diameter, operating pressure distance between compression stations, compression rate and service temperature. By increasing the operating pressure and pipe diameter, the gas transportation capacity is increased and this results in obvious economic advantages. Table 1 summarizes the evolution of pipeline operating pressure and diameter over the last century.

Today several pipelines are built with 1420 mm pipe diameter. The use of these large diameter pipes requires high strength steels in order to avoid thickness difficult to weld and minimize steel weight. There are significant advantages of using higher grade line pipes, such as X100 even X120 grade pipeline, in constructing long distance pipeline, because it can improve transportation efficiency of the natural gas pipelines by increasing internal transportation pressure, and material cost can be saved correspondingly by reducing wall thickness of pipe body and consumable for girth welding. However, there are still many transportation safety problems in laying high strength pipelines. First of all, due to line pipes laid through complicated regions, such as earthquake region with high-risk, gas pipelines in service may endure large displacement and stress, the maximum flexure deformation at part of the pipeline reaches to 4~5 % when it is laid through multiple-region of earthquake and geology casualty.

Secondly, the increased pressure in modern pipelines also causes the danger of running ductile cracks as the result of the stored high energy content of the compressed gas.

Due to combined use of high strength steel, high operating pressure and large diameter pipe, risk of brittle failure has increased.

By comparing remaining safety factor due to presence of crack-like defects, it is possible to describe evolution of this risk versus time through evolution of pipe design. This is made in the following by using the Failure Assessment Diagram (FAD) and particularly, the SINTAP procedure.

Table 1. Evolution of transportation conditions in gas pipelines.
Tabela 1. Razvoj uslova transporta u gasnim cevovodima

Year	Operating pressure (bar)	Diameter (mm)	Annual capacity ($\times 10^3$ m^3)	Power gas consumption over 6000 km
1910	2	400	80	49 %
1930	20	500	650	31 %
1965	66	900	830	14 %
1985	80	1420	26000	11 %

MATERIAL

Three pipe steels have been studied: X52, X70 and X100. Chemical compositions of these steels are given in Table 2.

Table 2: Chemical composition of the studied steels.
Tabela 2. Hemijski sastav analiziranih čelika

	C	Mn	Si	Cr	Ni	Mo	S	Cu
X52	0.206	1.257	0.293	0.014	0.017	0006	0.009	0.011
X70	0.125	1.68	0.27	0.051	0.04	0.021	0.005	0.045
X100	0.059	1.97	0.315	0.024	0.23	0.315	0.002	0.022

Tensile properties (average values) are given in Table 3 and typical stress–strain curves in Figure 1. One notes that yield stress of the studied steel is higher than the standard requirements and elongation at fracture is strongly reduced when the yield stress increases.

Table 3. Tensile properties of studied steels X52, X70 and X100.
Tabela 3. Zatezne osobine analiziranih čelika X52, X70 i X100

	Young's modulus (GPa)	Yield stress (MPa)	Ultimate strength (MPa)	Elongation at fracture %
API 5L X52	194	437	616	23.14
API 5L X70	215	590	712	18.3
API 5L X100	210	866	880	6.75

Fracture toughness K_{Ic} and δ_c have been determined using compact tension specimen, according to French standards NF A 03-180, /2/ (K_{Ic}), and NF A 03-182, /3/, (δ_c). Specimen dimensions are extracted from 3 different pipes as given in Table 4.

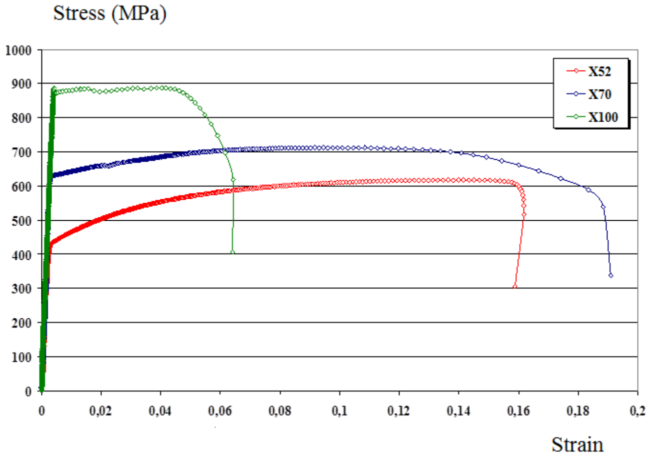

Figure 1. Stress-strain curves of API 5L X52, X70 and X100 pipe steels.
Slika 1. Krive napon-deformacija za cevovodne čelike API 5L X52, X70 i X100

Table 4. Diameter, thickness and material of the 3 studied pipes.
Tabela 4. Prečnik, debljina i materijal 3 analizirana cevovoda

Steel	Diameter, (mm)	Thickness, (mm)
API 5L X52	610	11
API 5L X70	710	12.7
API 5L X100	950	16

One note that the pre-crack is along the longitudinal direction of the pipe. Critical load has been determined using acoustic emission which determines crack initiation (subscript *i*). The obtained critical load correlates well with the traditional offset procedure failure load. Individual and mean values are listed in Table 5.

Table 5. Fracture toughness of studied steels X52, X70 and X100.
Tabela 5. Žilavost loma analiziranih čelika X52, X70 i X100

Steel	Specimen	$K_{I,i}$ (MPa√m)	$K_{I,mean}$ (MPa√m)	δ_i (mm)	$\delta_{i,mean}$ (mm)
API 5L X52	CT1 CT2	97.59 93.49	95.54	0.21 0.14	0.18
API 5L X70	CT1 CT2	117.99 119.19	118.59	0.102 0.123	0.112
API 5L X100	CT1 CT2	159.98 143.66	151.82	0.125 0.091	0.108

FAILURE ASSESSMENT DIAGRAM AND SINTAP PROCEDURE

In a failure assessment diagram, the basic fracture mechanics relationship with three parameters: applied stress (σ_{app}), defect size (a), and fracture toughness (K_{Ic} or J_{Ic}) is replaced by a two-parameter relationship $f(k_r, S_r)$. Stress and defect size are combined into the applied stress intensity factor (K_{app}) or applied J parameter (J_{app}) and the parameter k_r and S_r are non-dimensional, according to the following initial definitions:

$$k_r = \frac{K_{app}}{K_{Ic}} \quad \text{and} \quad S_r = \frac{\sigma_{app}}{\sigma_u} \tag{1}$$

where σ_u is the ultimate strength. In the plane $\{S_r; k_r\}$, a given relationship $k_r = f(S_r)$ limits the safe zone and the failure zone (Fig. 2). Initially, the relationship between non-dimensional stress intensity factor k_r and non-dimensional stress S is issued from a plasticity correction, able to describe any kind of failure, continuously from brittle fracture to plastic collapse.

A typical representation of a failure assessment diagram is given in Fig. 1.On the same figure, the load safety factor F_s is defined according to:

$$F_s = \frac{\text{OB}}{\text{OC}} \tag{2}$$

The advantages of the use of the Failure Assessment Diagram are:
- the use of a unique tool for any critical situation (in other way, several failure criteria need to be used from LFM, EPFM and LA),
- to get, for any non-critical situation, the safety factor F_s.

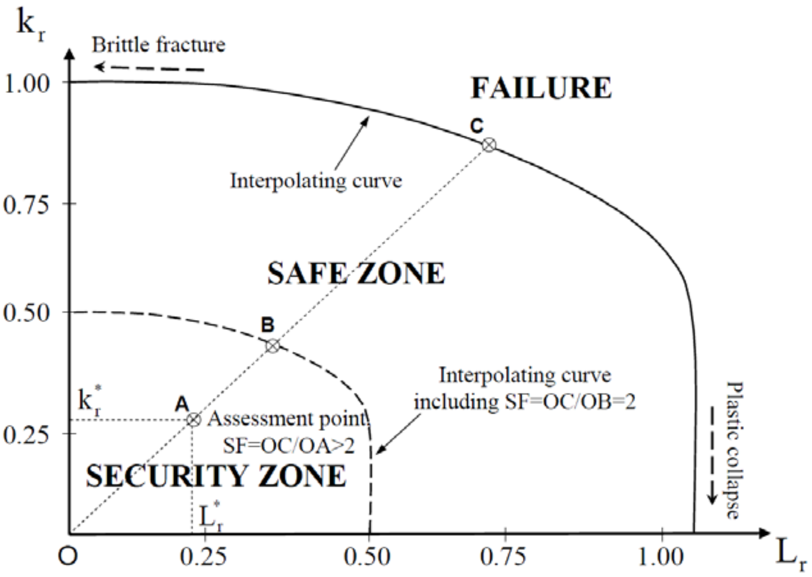

Figure 2. Typical presentation of Failure Assessment Diagram (FAD). Definition of safety factor.
Slika 2. Tipičan dijagram procene loma (FAD). Definicija stepena sigurnosti

The SINTAP procedure is derived from the initial failure assessment diagram. However, definitions of non-dimensional parameters are a little different: the k_r parameter is derived from the applied J_{app} parameter and fracture toughness J_{Ic}

$$k_r = \sqrt{\frac{J_{app}}{J_{Ic}}} \tag{3}$$

and the S_r parameter is replaced by the L_r parameter

$$L_r = \frac{P}{PL} = \frac{\sigma_{ref}}{\sigma_0} \tag{4}$$

where P is the applied load, PL the limit load. The material behaviour is assumed to follow the Ramberg-Osgood relationship:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{5}$$

where ε_0 and σ_0 are respectively the reference strain and stress and n is the strain hardening exponent. The reference stress is given by:

$$\sigma_{ref} = \frac{P}{P_0}\sigma_0 \tag{6}$$

where P_0 is the reference load. The applied J parameter is obtained by assuming proportionality between J_{app} and the elastic value of J parameter, J_{el}. The coefficient of proportionality is derived from the constitutive non-dimensional stress strain relationship of the material.

The relationship between k_r and L_r is considered as a limit curve obtained from numerous experimental data. This limit curve is more physically an interpolation curve between brittle fracture representative assessment point and plastic collapse. In this method, failure near plastic collapse is represented by data in the “tail” of the diagram.

There are several similar Failure Assessment Diagram procedures, i.e. EPRI in USA; R6 in UK, RCCMR in France with a small and more and less conservative difference in the safe zone area. The SINTAP /4/ procedure is the result of a European project of a multi-disciplinary approach in order to get a unified multi-level method useful for SME to large companies. The level hierarchy depends on knowledge of description of stress strain curve and fracture toughness. Lower levels are used with simple description of stress strain curve but with higher conservatism. The mathematical expressions of SINTAP procedure for the lowest and more conservative (basic level) is given as below:

$$f(L_r) = \begin{cases} \left[1+\frac{L_r^2}{2}\right]^{-\frac{1}{2}}\left[0.3+0.7e^{\left(-\mu\times L_r^6\right)}\right], & 0 \le L_r \le 1 \\ \left[1+\frac{1}{2}\right]^{-\frac{1}{2}}\left[0.3+0.7e^{(-\mu)}\right]\times L_r^{\frac{N-1}{2N}}, & 1 \le L_r \le L_r^{\max} \end{cases} \tag{7}$$

where $f(L_r)$, $L_r^{\max}$ L_r, σ_Y, are interpolating function, non-dimensional loading parameter, maximum value of non-dimensional loading or parameter, yield stress, respectively.

PIPE DEFECT AND ASSOCIATED STRESS INTENSITY FACTOR

We have chosen to study a surface longitudinal semi-elliptical crack in the wall of a pipe. This can represent the defect in a conservative way, the crack-like defect approach, the most current type of defect detected in a pipe, such as corrosion defects, gouges, scratches etc.

The stress intensity factor for such a crack is given by the general formula:

$$K_I = \frac{pR_{\text{int}}}{t}\sqrt{\pi a}\frac{M}{\Phi} \tag{8}$$

Where p is the internal pressure, R_{int} is the internal radius of the pipe, t is the wall thickness, a the crack depth, M the geometrical factor correction, and Φ the elliptic integral of second species,

$$\Phi = \int_0^{\pi/2} 1 - \frac{c^2 - a^2}{c^2} \sin^2 \theta d\theta \qquad (9)$$

An approximate value of this elliptic integral is given by:

$$\Phi^2 = 1 + 1.464 (a/c)^{1.6s} \qquad (10)$$

RESULTS

Three cases have been studied and corresponding to different steels. Operating pressure is considered higher for X100 steel because it is used for new generation of pipelines working at higher operating pressure and with larger diameter (Table 6).

Table 6. List of the studied cases.
Tabela 6. Ispitivani slučajevi materijala

Steel	$2R_{int}$ (mm)	t (mm)	Operating pressure (bar)	Crack depth (mm)	Crack ratio (a/c)
API 5L X52	610	11	70	2.2	0.4
API 5L X70	710	12.7	70	2.54	0.4
API 5L X100	950	16	100	3.2	0.4

k_r parameter has been determined using Eqs.(1) and (8) and L_r using Eq.(1). For each case, an assessment point with coordinates (L_r^*, k_r^*) is reported in a failure assessment diagram (Fig. 4). Each steel has its own failure assessment diagram because the μ parameter is different for each steel. However the difference is relatively small, particularly for $L_r < 0.8$. We note that the three assessment points are in the safe zone i.e. below the failure curve given by Eq.(1). Then, using the procedure described in Fig. 4, the safety factor is then determined and reported in Table 7.

Table 7. Safety factor according to pipe steel.
Tabela 7. Stepen sigurnosti s obzirom na čelik cevovoda

Steel	API 5L X52	API 5L X70	API 5L X100
Safety factor	3.38	3.87	3.23

One notes that safety factors are more than 2 for all steels. According to this conventional value, the pipe is safe and the defect does not need to be repaired.

DISCUSSION

The previous results indicate that the safety factor decreases when we change the pipe design using high strength steel, like X100. In this case, we increase the pipe diameter, thickness, and operating pressure simultaneously with the pipe yield stress. In order to have an idea of the consequence of the new pipe design with API 5L X120 steel, the safety factor is determined using the following data (Table 8).

Table 8. API 5L X120 steel pipe design conditions.
Tabela 8. API 5L X120 cevovodni čelik - uslovi za projektovanje

Diameter (mm)	Thickness (mm)	Operating pressure (bar)	Crack depth (mm)	Crack ratio (a/c)
1420	23	120	4.6	0.4

The diameter has been chosen as the largest actual pipe diameter and the thickness is compatible for the seam welding of the X120 pipe with the submerged arc welding (SAW) method, with one pass each for the inside and outside welds, which had been employed for conventional grades. The operating pressure has the expected value for future design.

Due to the unavailability of X120 pipe steel, mechanical properties (yield stress and ultimate strength) are obtained from /6/ and are reported in Table 9. Fracture toughness is deduced from two required values of the critical CTOD δ_c in base metal and in welds at temperature –20°C, given in Table 9. CTOD is converted into fracture toughness using the following LFM relationship:

$$K_c = \sqrt{\sigma_y \delta_c E} \qquad (11)$$

Table 9. Mechanical properties of API 5L X120 steel.
Tabela 9. Mehaničke osobine čelika API 5L X120

Yield stress (MPa)	Ultimate strength (MPa)	CTOD Base metal (mm)	CTOD Welds (mm)
908	981	0.14	0.08

The required Crack Tip Opening Displacement (CTOD) is calculated on an assumption of the existence of a surface-breaking crack 2 mm in depth at a seam weld toe and possible shape irregularity and stress distribution. As a result, it is concluded that a CTOD of 0.08 mm or more is good enough. Since a defect equal to or larger than 2 mm is detected at a non-destructive inspection and an internal defect up to 4 mm in width will be permissible under the same value of critical CTOD.

Ones notes that the safety factor decreases when the yield stress of the pipe steel increases together with diameter, thickness and operating pressure. Evolution of failure type when increasing yield stress of pipe steels can be predicted by using a Domain Failure Assessment Diagram (DFAD).

A domain failure assessment diagram is a failure assessment diagram divided into three zones of potential failure type: brittle fracture, elastic-plastic failure, and plastic collapse. A DFAD is limited by the failure assessment curve that gives the limit of a safe and an unsafe pipe. The safe area is divided conventionally into three zones:

Zone I: if the assessment point lies in this zone, increasing the applied pressure leads to brittle fracture.

Zone II: where increasing the applied pressure leads to elastic-plastic fracture.

Zone III: where plastic collapse occurs by increasing the service pressure.

Based on the Feddersen diagram /8/, the limit of these three zones is defined conventionally as follows:

Zone I $0 < L_r < 0.62 \cdot L_{r,y}$
Zone II $0.62 \cdot L_{r,y} < L_r < 0.95 \cdot L_{r,L}$
Zone III $0.95 \cdot L_r^{\max} < L_r < L_r^{\max}$

where $L_{r,y}$ is associated with the yield pressure and $L_r^{\max}$ is the maximum value of L_r. In Figure 4, in a domain failure assessment diagram are reported the assessment point of the 4 studied pipe steels. One notes that X52, X70 and X100 have a fully ductile failure potential. However, the X120 steel has as a more pronounced risk of elastic plastic failure.

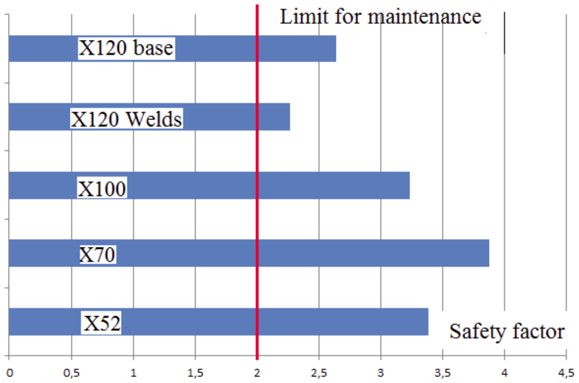

Figure 3. Values of safety factors associated with different pipe steels.
Slika 3. Vrednosti stepena sigurnosti za različite cevovodne čelike

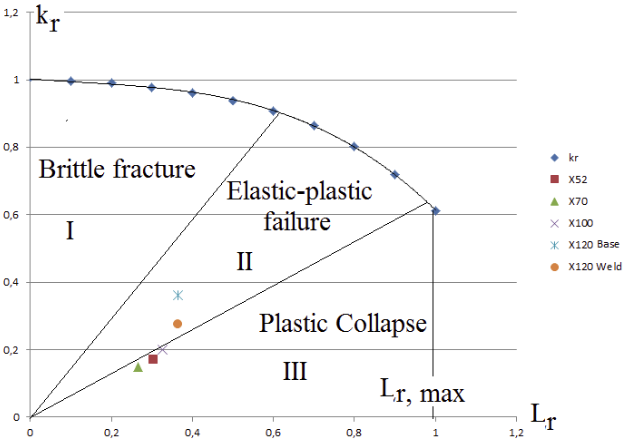

Figure 4. Domain FAD and assessment points for studied pipe steels.
Slika 4. FAD domen loma i tačke procene za istražene čelike

CONCLUSION

The risk of failure for a steel pipe has been evaluated through a conventional defect type. Under operating pressure, the safety factor is always over the conventional value of 2. It can be concluded that it is not necessary from a fracture mechanics point of view to repair this defect.

The use of a domain failure assessment diagram gives in addition the potential risk of brittle or elastic fracture. It has been seen that X120 has an elastic-plastic failure potential risk. In this case, it seems necessary to evaluate in addition the risk of a brittle running crack. This risk is associated with high stored energy due to the large pipe diameter and high operating pressure.

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