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STRUCTURAL INTEGRITY AND LIFE ASSESSMENT OF OIL DRILLING RIG PIPES USING ANALYTICAL METHOD

PROCENA INTEGRITETA I VEKA BUŠEĆIH CEVI ZA NAFTU PRIMENOM ANALITIČKE METODE

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- analytical methods
- failure assessment diagram
- Paris law

Ključne reči
- bušeće cevi
- analitičke metode
- dijagram analize loma
- Parisov zakon

Abstract

Structural integrity and life assessment of oil rig pipes using analytical method is presented and applied to an oil drilling rig pipe. The new concept based on risk evaluation according to probability and consequence of failure is used. Analytical expressions for surface cracks, provided by Raju and Newman, are used to calculate stress intensity factors for different crack geometries. Furthermore, the rig welded pipe failure probability is estimated by simple application of the Failure Assessment Diagram (FAD) and used together with potential consequences to evaluate the risk level by application of risk matrix. The same logic is employed in the case of cyclic loading, i.e. fatigue crack growth, by using Paris law to calculate crack length depending on the number of cycles. Simple numerical integration is applied to take into account the change of the geometry parameter Y due to increasing depth of a surface crack.

Izvod

U radu je prikazana primena analitičke metode u oceni integriteta i veka konstrukcija bušećih cevi. Korišćen je novi koncept zasnovan na proceni rizika preko verovatnoće i posledica otkaza. Analitički izrazi za površinske prsline koje su definisali Raju i Newman su korišćeni za proračun faktora intenziteta napona za različite geometrije prsline. Štaviše, verovatnoća otkaza zavarenih bušećih cevi je procenjena jednostavnom primenom Dijagrama analize loma (Failure assessment diagram - FAD), u kombinaciji sa potencijalnim posledicama kako bi se ocenio nivo rizika primenom matrice rizika. Ista logika je primenjen i za slučaj cikličnog opterećenja, odnosno rasta zamorne prsline, primenom Parisovog zakona za proračun dužine prsline u zavisnosti od broja ciklusa. Primenjena je jednostavna numerička integracija kako bi se uzela u obzir promena geometrijskog parametra Y usled povećanja dubine površinske prsline.

INTRODUCTION

Defects and cracks in oil and gas pipelines are common consequence of corrosion, and more specifically, hydrogen embrittlement, /1/. Cracks in welded pipelines are typically located in welded joints, although crack-like defects can also occur in the base material, /2/. The most common causes of failure of welded pipes in the oil industry are a wrong choice of materials and welding technology, deviation from the predicted properties of materials and welded joints, wrong method of calculating the pipe (pipeline), and deviation from the foreseen conditions of exploitation (load, temperature, working medium), /3/. Thus, to ensure structural integrity, in-service defects must be understood and controlled, /4/.

From the point of view of loading, besides the static, fatigue loading requires a completely different approach to ensure safe exploitation, /5/. Therefore, pipelines as pressure equipment must be designed and constructed to guarantee safety and security in all loading conditions. For this reason, a number of standards are developed, and introduced as mandatory that relate to the selection of materials, construction, production, and testing in accordance with the purpose of the facility and danger to the environment in case of failure. Welded pipes in oil and gas wells are a high responsible structure, so it is important to know the resistance to fracture (residual strength) of pipes or pipelines in exploitation when there are cracks or other damage that can lead to failure. Using fracture mechanics parameters obtained on the basis of experimental research, the remaining life of protective welded tubes made of API J55 steel with an external axial surface crack is estimated, /6-10/. At the same time, range of amplitude stress and crack size effects on remaining fatigue life are analysed using the extended finite element method (XFEM) as one of the new calculation techniques for crack growth, created as a result of numerous research in the last few decades, /11-13/. This technique enables presentation of discontinuity independent finite element mesh and recently has had wide application, /14-17/.

Pipelines for transporting and distributing fluids can be classified into oil and gas pipelines, Fig. 1. Small diameter

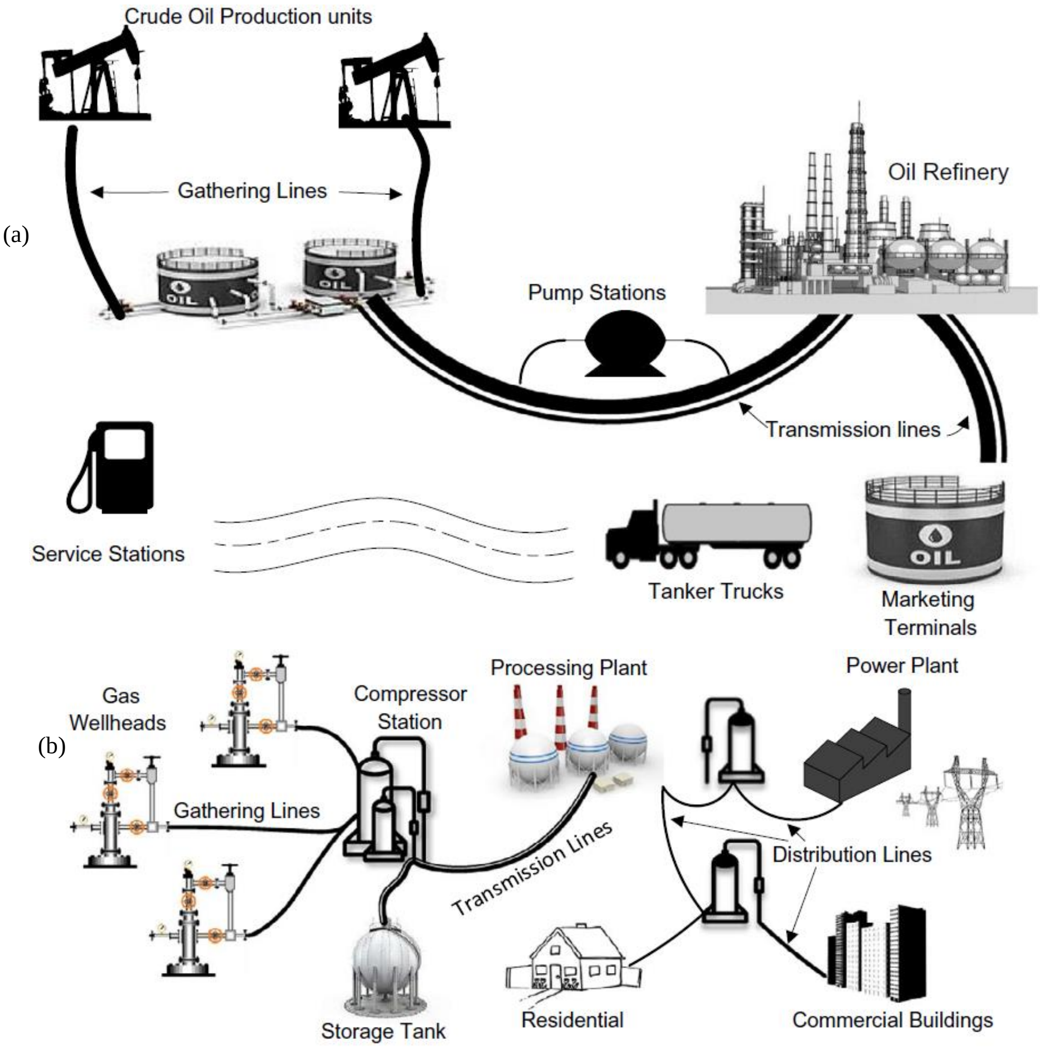

Figure 1. Oil and gas pipeline system: a) oil pipeline system; b) gas pipeline system.

gathering lines collect the product (crude oil, liquefied petroleum products,) from where it is extracted, after moving to a gathering facility, it moves to feeder pipelines of relatively large diameters that transport the product to refineries. Pipelines can have seam or seamless pipes, and their specifications defined by the API standard, /18/.

RISK-BASED ASSESSMENT OF STRUCTURAL INTEGRITY AND LIFE OF PIPELINES

Risk based assessment of structural integrity and life is a new approach introduced and applied successfully recently, /19-24/. It employees basic linear elastic fracture mechanics (LEFM) parameters, modified for small plastic zone at the crack tip (Dugdale model) to construct the limit curve in the failure assessment diagram (FAD), /25/. In any case, the evaluation of stress intensity factors is of crucial importance, as shown in /26/, where so-called Raju-Newman method is shown to be at the closest agreement with FEM results.

Stress intensity factor by the Raju and Newman method

Longitudinal semi-elliptical surface cracks are most critical in pipelines, Fig. 2. According to Raju and Newman the stress intensity factor at the mid-point of a longitudinal semi-elliptical surface crack under internal pressure is:

$$K_I = \left(\frac{pR^2}{R_0^2 - R^2}\right)\sqrt{\frac{\pi a}{Q}}\left[2G_0 + 2\left(\frac{a}{R_0}\right)G_1 + 3\left(\frac{a}{R_0}\right)^2 G_2 + 4\left(\frac{a}{R_0}\right)^3 G_3\right]$$

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65} \quad \text{for} \quad a/c \le 1.$$

where: Q is shape factor /27/; and the other quantities are defined in Fig. 2. The corresponding coefficients G_0-G_3 are determined by matching of the results with finite element analysis results in the case of a/c = 0.2, 0.4, 1.0; t/R = 0.1, 0.25, and a/t = 0.2, 0.5, 0.8, as presented in /27/.

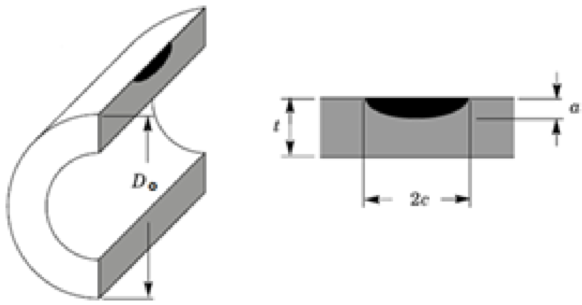

Figure 2. Pipe with external surface crack: D_0 - outer diameter; t - wall thickness; a - crack depth; c - crack half-length.

Failure assessment diagram

Failure assessment diagram basically uses the limit curve to separate safe and unsafe regions as shown in Fig. 3.

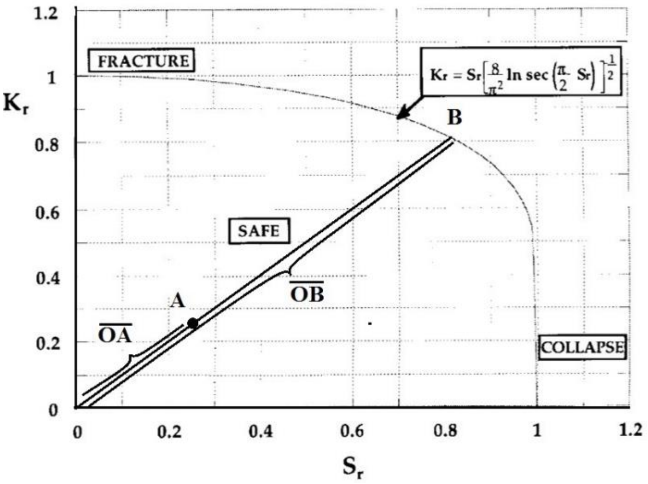

Figure 3. FAD with service point A and corresponding point B on limit curve, /6/.

The axes are defined by non-dimensional ratios, as follows: *x*-axis by S_r (plastic collapse ratio), and *y*-axis by K_r (brittle fracture ratio). The parameter S_r is defined as:

$$S_r = \frac{\text{reference stress}}{\text{yield stress}} = \frac{\sigma_{ref}}{\sigma_c} .$$

Reference stress is calculated according to design or operating load, taking into account cross-section reduction due to crack presence. σ_c is the yield strength or any stress between yield and ultimate strength. The second parameter K_r, linked to the stress intensity factor criterion, is defined as

$$K_r = \frac{\text{applied stress intensity factor}}{\text{material's fracture toughness}} = \frac{K_I}{K_{mat}} ,$$

where: K_I is stress intensity factor; K_{mat} fracture toughness of the material. These two parameters define the assessment point in FAD, corresponding to operating stress and component geometry, including crack geometry.

Now, one can make a risk based assessment of structural integrity using the approach introduced in /19/ to determine probability/frequency of an event, shown in Fig. 3, and applied later in several pressure vessel problems /7-10, 19-23/. The core of this approach is risk estimation by using risk matrix, where event frequency/probability and potential consequences are defined in five categories (Fig. 4), with instructions on how to define a consequence category. Probability is determined according to the position of working point in FAD in relation to the point on the limit curve, Fig. 3, as introduced and explained in /6/. Reasoning behind is based on the fact that probability of failure is proportional to defect size. In other words, for no defect there is no failure; for unacceptable defect probability is 1; and for all other defects in between, probability is proportional to defect size. Therefore, probability here is defined as the ratio AB/OB, Fig. 3.

	Potential consequences				Event Frequency				
	People	Property	Environment	Reputation	A Negligible	B Low	C Moderate	D Medium	E Large
1	Insigni ficant injuries	Loss up to 10 K€	Minor damage to environment	Insignificant consequences. Employees awareness.					
2	Minor injuries	Loss from 180 K€ to 540 K€	Minor consequence and damage to environment. Small costs..	Mild consequences. There is a concern at the local level.					
3	Serious injuries	Loss from540 K€ to 1,8 M€	Moderate consequence. Short-term damage to environment..	Minor consequences. There is a concern at the regional level					
4	Permanent incapabilit y	Loss from 1,8 K€ to 50 M€	Major consequences. Big damage to environment. Large costs.	Moderate consequenes. There is a concern at the national level.					
5	Death	Loss over 50 M€	Dire consequences. Lomg-term and big damage. Huge costs.	Dire consequence..Concern and reaction at the international level.					

LOW RISK LEVEL

MODERATE RISK LEVEL

HIGH RISK LEVEL

Figure 4. FAD with explanation of potential consequences.

RISK BASED REMAINING LIFE ASSESSMENT

Crack growth to critical size depends on the loading and crack growth rate, as defined by Paris law for metals and alloys, which establishes the relationship between fatigue crack growth *da/dN* and stress intensity factor range Δ*K*:

$$\frac{da}{dN}=C(\Delta K)^m=C\left(Y\left(\frac{a}{W}\right)\Delta\sigma\sqrt{\pi a}\right)^m,$$

where: $Y(a/W)$ is geometry factor depending on crack length; coefficient C and exponent m are material parameters. Paris law is then integrated and transformed to calculate the number of cycles from initial a_0, to critical a_{cr} crack length:

$$N=\frac{2}{(m-2)C\left(Y\left(\frac{a}{W}\right)\Delta\sigma\right)^m\pi^{m/2}}\left(\frac{1}{a_0^{\frac{m-2}{2}}}-\frac{1}{a_{cr}^{\frac{m-2}{2}}}\right).$$

The probability of failure can be estimated as the ratio between N and the design, i.e. life number of cycles.

OIL RIG PIPE PROTOTYPE

Testing of the prototype is conducted on a pressure vessel with defects of circular shape, /28/. The vessel is made from a part of casing pipe made by HF welding of API J55 steel, closed at both ends, with nominal dimensions: diameter 139.7 mm; wall thickness 6.98 mm, Fig. 5. In the experiment performed in scope of Ph.D. thesis /28/, strain gauges and rosettes are used to evaluate the J integral by so-called direct measurement technique. Surface defects of lengths D = 26, 28, 30 mm and depths a = 1.75, 3.5, 5.25 mm /28/ are made in different cross sections, A-D, Fig. 5. For the analysis in this paper the largest crack is used, a = 5.25 mm, $2a$ = 30 mm.

Structural integrity assessment

In order to calculate K_I and S and to compare with K_{Ic} and S_c, and get the corresponding point in FAD, following data for service pressure p = 10 MPa is used:

- crack depth: a = 5.25 mm; crack length $2c$ = 30 mm,
- circumferential stress $S = pr/t$ = 100 MPa,
- cross section reduction (5.25×30)/(6.98×702) = 0.032, net stress S_{net} = 100/0.968 = 103.3 MPa,
- critical stress, taken at midpoint between yield and tensile strength, S_c = (537 + 585)/2 = 563 MPa for the new material, S_c = (376 + 559)/2 = 467.5 MPa for the old one, so the abscissa for the new material is S_{net}/S_c = 103.3/563 = 0.18, whereas S_{net}/S_c = 103.3/467.5 = 0.22 for the old one.

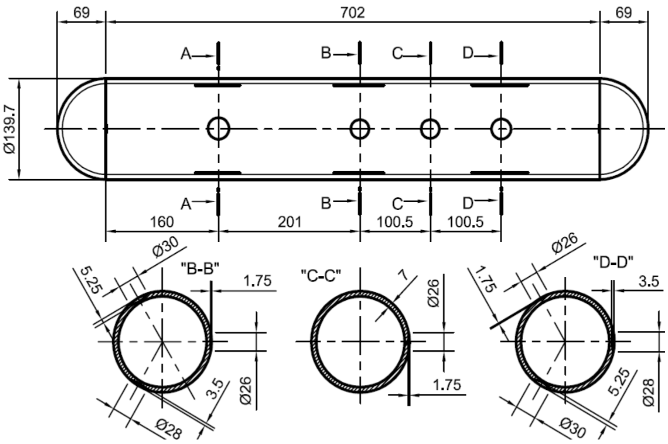

Figure 5. Oil rig pipe prepared for testing, /28/.

Stress intensity factor for surface edge crack in a cylinder can be obtained using different methods for geometry factors, depending on crack size, /26, 29/. According to the procedure explained in /26/: F_{total} = 2.71, K_I = 1100 MPa√mm for $2c$ = 30 mm, while K_{Ic} = 2908 MPa√mm for the old BM, and 3836 MPa√mm for the new one. Therefore, coordinates for service points in FAD are (0.18, 0.29) for the new BM and (0.22, 0.38) for the old one, Fig. 6. Corresponding risk levels are defined in Table 1, indicating the low risk level for both states of material. One should keep in mind that K_{tot} is calculated for crack growth into depth, which is not the way deep cracks grow, since they grow dominantly into the length, but it is more critical, anyhow, and relevant for pipe integrity assessment.

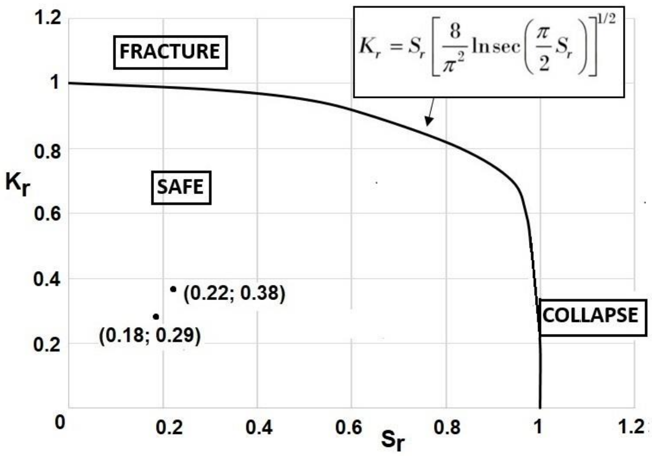

Figure 6. FAD points for new (0.18, 0.29) and old (0.22, 0.38) material.

Table 1. Position of assessment points in the risk matrix.

		Consequence category					
		1 – very low	2 - low	3 - medium	4 - high	5 - very high	Risk legend
Probability category	≤ 0.2 very low						Very low
	0.2-0.4 low			new 0.36 / old 0.27			Low
	0.4-0.6 medium						Medium
	0.6-0.8 high						High
	0.8-1.0 very high						Very High

Residual life assessment

Integration of Paris law is performed in steps where C_p and m_p denote real data used here: $C_p = 1.23 \cdot 10^{-13}$, $m_p = 3.931$ for new material, and $C_p = 2.11 \cdot 10^{-15}$, $m_p = 6.166$ for old material /28/. For the initial external damage, the length $2c = 30$ mm and depth $a = 5.25$ mm, calculation is done in MS Excel® for the new and the material from exploitation, as well as for stress ratio $R = 0.79$, as shown in Table 2 and in Fig. 7 (crack depth a vs. number of cycles N). One can see the significant reduction of residual life for old material, cca. 3.7 times. One should also notice that the presented calculation is not realistic for crack depths approaching wall thickness but is still useful to quantify the effect of material state.

Table 2. Data from MS Excel (M_f, E_k, s, M_T, M_{Tm} and F_{total}) as defined in /26/.

a (mm)	c/a	a/t	a/c	Mf	Ek	s, θ=π/2	MT	MTm	Ftotal	K1 (MPa√mm)	ac old (mm)	ac new (mm)	N old (θ=π/2)	N new (θ=π/2)
5.25	2.857	0.752	0.35	1.095	1.258	2.425	1.049	1.082	2.709	1100	0.152	0.268	0	0
5.94	2.525	0.851	0.396	1.090	1.317	3.220	1.062	1.153	2.969	1282	0.119	0.210	726775	1998254
6.63	2.262	0.949	0.442	1.085	1.380	4.611	1.077	1.300	3.578	1633	0.080	0.141	887300	3106618
6.9	2.173	0.988	0.46	1.084	1.406	5.383	1.083	1.404	4.048	1885	0.064	0.113	910552	3286451
7.0	2.142	1.002	0.467	1.083	1.416	5.709	1.085	1.456	4.288	2011	0.058	0.102	916103	3325312

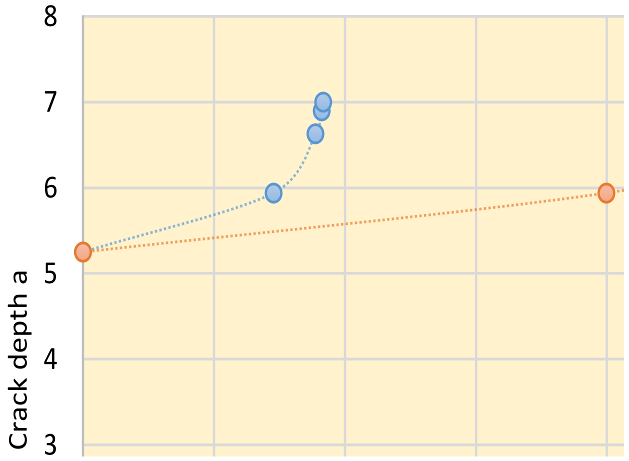

Figure 7. Crack depth a, vs. number of cycles N.

CONCLUSIONS

Based on the presented results, we conclude the following:

The simple engineering procedure based on analytical calculation of fracture mechanics parameters can be successfully applied to risk-based assessment of structural integrity of components with simple geometry, such as rig oil drilling pipes.

Residual life can be also assessed by using the simple analytical procedure, based on integration of Paris law, enabling evaluation of the effect of material state. This procedure is very useful in engineering practice, especially if the effects, as material state, are to be analysed.

ACKNOWLEDGEMENT

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NAJAVA 21. GODIŠNJE SKUPŠTINE DIVK 10. JUNA 2022.

21. redovna godišnja skupština *Društva za integritet i vek konstrukcija „Prof. dr Stojan Sedmak“ (DIVK).*

Mesto: Svečana sala Instituta za ispitivanje materijala (IMS), Beograd, Bulevar vojvode Mišića 43.

Datum: petak, 10.6.2022. god. od 13:00.

Dnevni red:

1. Izveštaj Upravnog odbora o radu DIVK u periodu od 11.6.2021-10.6.2022.
2. Finansijski izveštaj za 2021. godinu
3. Izveštaj Nadzornog odbora
4. Izveštaj o radu časopisa „Integritet i vek konstrukcija“ u 2021. godini
5. Plan rada u 2022. godini
6. Razno, tekuća pitanja

APPROACHING THE 21ST ANNUAL DIVK ASSEMBLY ON JUNE 10, 2022

The 21st Annual Assembly of the *Society for Structural Integrity and Life 'Prof. Dr Stojan Sedmak' (DIVK).*

Venue: Assembly Hall of the Materials Testing Institute (IMS) in Belgrade, Bulevar vojvode Mišića 43.

Date: Friday, June 10, 2022, at 13:00.

Agenda:

1. Board Report on DIVK activities in the period from June 11, 2021 to June 10, 2022.
2. Financial Report for 2021.
3. Report from the Supervisory Board
4. Report on the activities of the journal 'Structural Integrity and Life' in 2021.
5. Planned activities in 2022.
6. Miscellaneous, current issues.