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# METHODOLOGY FOR RESIDUAL LIFE ESTIMATION OF DAMAGED STRUCTURAL ELEMENTS OF THE TOWER INSTALLATIONS FOR OIL AND GAS EXPLORATION

# METODOLOGIJA PROCENE PREOSTALOG VEKA ELEMENATA KONSTRUKCIJE TORNJA POSTROJENJA ZA ISTRAŽIVANJE NAFTE I GASA

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**Keywords**
- fatigue
- oil tower
- crack growth
- residual life estimation
- computation methodology

*Abstract*

*Attention in this paper is focused on the establishment of a suitable and computational methodology for estimating the remaining life of structural elements in the presence of initial damage. Damaged model occurs in the form of a cracked model for the analysis of crack growth in structural components of the tower installations for oil and gas exploration. In this work two numerical simulation approaches for crack propagation are presented. The first approach is based on the conventional Paris law of crack propagation, while the other utilizes the Strain Energy Density (SED) method during the crack growth analysis.*

*For material, steel S355 JR, used in the research, fatigue low-cycle material properties and Paris dynamic constants for crack propagation analysis have been determined experimentally. Two computational methods for crack propagation based on Paris and SED methods are illustrated by the representative structural element of the construction of the tower that is considered in the form of a plate with a hole and initial crack. For crack growth and residual life estimation here "in-house" software package "PP_VEK" is used. After verification of the Paris and SED models, the residual life of oil tower construction under real load spectrum is considered here.*

**Ključne reči**
- zamor
- naftni toranj
- rast prsline
- procena, preostalog veka
- kompjuterska metodologija

*Izvod*

*Pažnja u radu je usmerena na uspostavljanje pogodne i efikasne kompjuterske metodologije za procenu preostalog veka strukturalnih elemenata u prisustvu inicijalnih oštećenja. Oštećenja modela za analizu širenja prsline javljaju se kod elemenata konstrukcije tornja postrojenja za istraživanje nafte i gasa. U radu su prikazana dva pristupa numeričkih simulacija širenja prslina. Prvi je zasnovan na konvencionalnom Parisovom zakonu širenja prsline, a drugi koristi metodu gustine energije deformacije (Strain Energy Density – SED) pri analizi rasta prsline.*

*Za materijal, čelik S355 JR, koji je korišćen u istraživanju, eksperimentalno su određene, kako niskociklične karakteristike materijala, tako i konvencionalne Parisove konstante za analizu širenja prsline. Ilustrovane su dve računarske metode za analizu širenja prsline (Paris, GED) na primeru reprezentativnog strukturnog elementa konstrukcije tornja u obliku ploče sa otvorom i jednom početnom prslinom. Za rast prsline i procenu preostalog veka "u kući" je korišćen programski paket "PP_VEK". Nakon verifikacije Paris i GED modela dat je preostali vek strukturalnih elemenata konstrukcije naftnog tornja za realni spektar opterećenja.*

## INTRODUCTION

For components that are exposed to dynamic loads during operation, the initial damage in the form of cracks in critical parts of the structure may occur. The primary focus of this work is the construction type of tower facilities for oil and gas exploration. During operation, the tower plant, stressed with a variable load spectrum, which may cause initial damage in the form of cracks during operation, and their dissemination. To determine the critical locations, structural analysis is used based on finite element method (FEM). Detailed structural analysis of the stress state of the repair facility, based on FEM is given in references, /1/. In order to create a methodology - the procedures for estimating the remaining life of the tower plant structure for oil and gas exploration, it is necessary to define the following: selection of the structure and determination of critical points, range of stress and strain characteristics of the required material, the verification of the methods applied and the residual life of the tower (the application of the method of density strain energy SED, as built into the software PP_VEK).

## MINING OPERATIONS

### *Repair plant*

In order to ensure the smooth operation of oil and gas (in addition to drilling at a certain depth), it is necessary to make certain mining operations. This has been conducted once in two different cases, namely: head of the drilling wells for commissioning in exploitation and during exploitation, in order to eliminate defects and damage (equipment and land), which occurs during exploitation. These works are performed at the adopted plant for oil and gas research (repair plant, Fig. 1), /1-4/.

Figure 1. Tower of the repair facilities, /2/.
Slika 1. Toranj remontnog postrojenja, /2/

### *Tower*

The repaired tower plant /1, 2/, Fig. 1, is a steel truss supporting structure of complex geometries and technology, with a range of features that ensure the achievement of designed functions, such as the wearing of drilling tools, mining tool jams and the like.

### *Mining operations*

During the repair overhaul of wells, the facility performs regular mining operations, /2, 5, 6/. Unforeseen mining operations are undesirable and very discouraging. Usually it is about saving the well for future oil and gas production. This is the next operation: instrumentation – a stuck tool in the borehole.

All these operations are performed as mechanical operations, called manoeuvres when lowering and removing columns of manufacturing pipe-tubing in and out of the hole, and then drilling the cement plug and pulling the tower over the jam.

These are the basic operations by which we come to the range of load and spectrum stress of the tower, which is used for calculating the lifetime.

### *Load spectrum /2/*

For the analysis of the century tower the load column manufacturing pipes (tubing) are taken with the following characteristics: depth (column length) 400 to 3000 m, taken in 2000 m, diameter tubing 1.35 to 4 inches, were taken 2 7/8 inch (73 mm), length 1 booze (2 consisted of tubing) 2×9 m, weight 1 booze 1.728 kN, the number of flies for the 2000 m is 111 and the maximum load of the tower column tubing and moving tackles and hooks is 211.8 kN.

Lowering the device is a basic operation. It consists in the formation of the column pipe-tubing, mutual continuing flies through threaded joints, to a final depth of the bore–hole.

Characteristics:

- initial load on the hook is 20 kN of their mass and moving tackles,
- additional load is the weight of booze (18 m) from 1.728 kN × 111 cycles – flies up to 211.808 kN,
- ultimate load hook of the tower is 211.8 kN,
- the number of events operations 1 × per day, on average.

Extraction of device operation is the opposite of landing. It consists in dismantling the column pipe, mutual dismantling flies to the final extraction. When this operation is done, it has a relieving of the tower at the baseline.

Characteristics:

- initial load on the hook is 211.8 kN, which is reduced during unfolding booze to 1.728 kN × 111 cycles – flies up to 20 kN,
- ultimate load hook of the tower is 20 kN,
- the number of operation events × 1 day, on average.

During repair of the wells, there is a need for cementing of certain parts of it, to get separate intervals for the execution of certain operations. After the execution of these operations, the following is the drilling of embedded cement plugs.

Characteristics:

- drilling cement plugs depth of 4 m,
- exercise testing 232 kN,
- the number of events operations 10 × per year, on average.

Instrumentation is an undesirable operation that is hard to define. This is an extreme operation, it becomes stuck in the borehole tool.

Characteristics:

- 5 × number of events per year, on average,
- takes about a month to repeat daily operations,
- impact load (kicker), 5 times a day and not every day.

Based on consideration of the report of work performed at plants, for further analysis the century tower is approved an average operation – load spectrum for one year of operation, as follows:

- 365 operations, lowering device,
- 365 operations, mining right,
- 10 operations, drilling cement plug, and
- 5 operations, instrumentation – stuck right in the hole.

For this range of real mining (mechanical) surgery will be determined by the remaining life of the tower.

## EXPERIMENTAL DETERMINATION OF MATERIAL PROPERTIES

### *Dynamic characteristics (Paris constants)*

For crack growth analysis in structural components, experimentally determined are: (1) the dynamic characteristics and (2) the low cyclic material characteristics of steel S355 JR, /2/. Without going into detail of how the determination should be emphasized:

Determining the fatigue crack growth rate *da/dN* and the fatigue threshold $\Delta K_{th}$, used to determine the dynamic characteristics of the material, is carried out as standard Charpy method of three-point bending specimens in a resonant high frequency pulsator. The testing is done in the controlled force. This pulsator achieves uni-directional sinusoidally changing torque loading in the range –70 to 70 Nm. The system for measuring crack growth, the FRACTOMAT and measuring foil, used for this purpose, are based on measurement of the change in electrical resistance properties.

Based on flow tests and the number of cycles *N* obtained depending on the length of the crack, fatigue crack growth rate *da/dN* is calculated. Depending on the applied variable load, $\Delta K$ is expressed by changing the stress intensity factor range, drawing the curve log(*da/dN*)–log($\Delta K$). Determination of dependence fatigue crack growth rate per cycle *da/dN* and stress intensity factor range $\Delta K$ boils down to determining the coefficient *C* and exponent of the Paris equation. Experimentally determined are Paris constants for steel S355 JR: $C = 1.97\cdot10^{-11}$, $m = 3.31$.

### *Low cyclic fatigue (LCF) material properties*

Low cyclic fatigue at room temperature, exhibited on ten tubes labelled with B1 to B10 of the servohydraulic MTS system, Table 1, /2/. Low cyclic fatigue resistance test is made with amplitude levels of deformation $\Delta\varepsilon/2$ = 0.5, 0.6, 0.8, 0.9 and 1.0%. It utilizes a regime of controlled deformation by a factor of cycle asymmetry, $R_\varepsilon = -1$.

Systematized cyclic features of the steel S355 JR are shown in Tables 1 and 2, and certain testing of its resistance to low cyclic fatigue in conditions of controlled deformation, the asymmetry factor $R_\varepsilon = -1$, is also given in Table 2.

Table 1. Data on the stabilized hysteresis for specimens of S355 JR steel.
Tabela 1. Podaci o stabilizovanim histerezama za epruvete od čelika S355 JR

| specimen | $\Delta\varepsilon_t/2$ | $S_{\max}$ (MPa) | $S_{\min}$ (MPa) | $\Delta\varepsilon_p$ | $\Delta\varepsilon_p/2$ | $\Delta\varepsilon_e/2$ | $\Delta S/2$ (MPa) | $N_f$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| B2 | 0.005 | 351.8 | –354.6 | 0.002794 | 0.001397 | 0.003603 | 353.2 | 2970 |
| B4 | 0.006 | 374.2 | –376.8 | 0.004018 | 0.002009 | 0.003991 | 375.5 | 1840 |
| B6 | 0.007 | 401.3 | –404.9 | 0.005442 | 0.002721 | 0.004279 | 403.1 | 985 |
| B8 | 0.008 | 429.1 | –432.6 | 0.007232 | 0.003616 | 0.004384 | 430.9 | 623 |
| B10 | 0.009 | 457.8 | –461.3 | 0.009325 | 0.004663 | 0.004337 | 459.6 | 312 |

Table 2. Low cycle fatigue properties of S355 JR steel.
Tabela 2: Niskociklične zamorne karakteristike čelika S355 JR

| Material properties | Value |
|---|---|
| Modulus of elasticity, $E$ (MPa) | 208200 |
| Cyclic strength coefficient, $K'$ (MPa) | 1490.1 |
| Strain strengthening exponent during cyclic loading, $n'$ | 0.22043 |
| Fatigue strength coefficient, $\sigma_f'$ (MPa) | 1261.9 |
| Fatigue strength exponent, $b$ | –0.08128 |
| Fatigue ductility coefficient, $\varepsilon_f'$ | 0.10530 |
| Fatigue ductility exponent, $c$ | –0.53275 |

## RESIDUAL LIFE ASSESSMENT METHODS OF THE TOWER STRUCTURE

In this paper, two approaches are used for the numerical simulation of crack growth and the fatigue life of damaged structural elements:

1. First estimate of the remaining life of structural elements using conventional crack growth laws, /7-12/.
2. Assessment of residual life of structural elements using the strain energy density (SED), /13, 14/.

Both approaches are based on crack growth analysis under cyclic loading. The essential difference of the two procedures is that the first, i.e. conventional approach for crack growth analysis using dynamic characteristics of the material (Paris constants, etc.), while the SED method uses low cyclic material properties.

Software package PP_VEK – residual life of structural elements, is used for fatigue crack growth and residual life assessment, for any form of damage to structural elements in the form of cracks, for cyclic loading with constant amplitude and under the influence of load spectrum.

The user can choose by which method to analyse crack propagation. There is a choice of (1) the conventional law of expansion (Paris, Forman, and so on) or (2) the law of crack propagation based on strain energy density (SED). Depending on the selection and propagation of cracks, which one may want to use in the analysis, there are certain required geometric characteristics and material properties the user should enter. The same procedure shall be followed with cyclic loads, whether it is with a constant amplitude or spectrum loading.

Furthermore, the results of application of conventional law and strain energy density (SED) crack propagation that are incorporated in the software, as well as a comparison of computational estimation of residual life by using representative damaged structural elements is given in Fig. 4.

### *Residual life estimation of structural elements using conventional crack growth laws*

Conventional laws of crack propagation have been almost exclusively used for the evaluation of residual life of structures in the presence of initial damages in the form of cracks in the previous years, such as the Paris law, /7/:

$$\frac{da}{dN}=C(\Delta K)^m \tag{1}$$

where: $a$–crack length; $N$–number of cycles; $K$–stress intensity factor; $C$, $m$–material parameters.

### *Numerical examples: computation crack growth analysis using conventional law expansion*

To view the application of the conventional law of crack growth an representative (structural) element with opening and initial crack in the zone of stress concentration is selected, Fig. 2. The second element is made of the same material as the tower itself and the uniaxial tensile load so that it is representative of the illustration and the establishment of a methodology for analysing the crack propagation and residual life of the tower.

It is considered as a problem of crack extension in a representative element with a hole and a crack at the bore, Fig. 2. The following geometrical characteristics are given: $W = 50$ mm, $r = 5$ mm, $t = 5$ mm, $a_0 = 3.5$ mm.

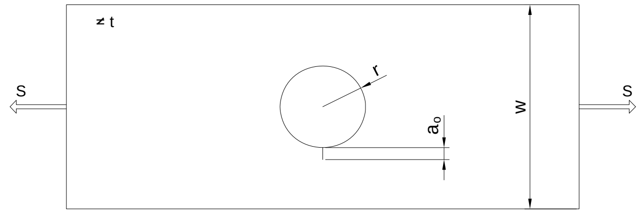


Figure 2. Geometry of a representative element with opening and initial crack.
Slika 2. Geometrija reprezentativnog elementa sa otvorom i inicijalnom prslinom

Analysis of crack propagation presented by the representative element, shown in Fig. 2, is carried out with the aforementioned program PP_VEK – residual life of structural elements. Paris law is used for the analysis of crack propagation.

The representative element, Fig. 2, is loaded under cyclic stress of constant amplitude, the maximum stress is $S_{\max} =$ 80 MPa (taken from previous studies /1/) and minimum stress $S_{\min} = 8$ MPa (calculated using stress ratio $R = 0.1$).

As a result of budget analysis of the crack growth using the software package PP_VEK shows all the necessary input data, including the geometry characteristics of the considered representative element of the initial crack, the appropriate crack growth law and necessary material properties, as well as the type of variable loading. All the time the program gives values of stress intensity factors $K_{\mathrm{I}}$ and corrective functions $Y$ for an increasing crack length of 0.5 mm, a critical crack length.

For the given example entered are the following data: the Paris constants ($C$, $m$), specimen size, crack length (starting from 3.5 mm and a critical 17 mm, which are obtained constructively, Fig. 2), the crack growth rate is 0.5 mm, the maximum and minimum stress (stress difference and stress ratio $R = 0.1$), the threshold of fatigue, fracture toughness and modulus of elasticity of the material.

As a result of the primary output from the above table a relationship is obtained between the crack length depending on the number of cycles, or a dependency – $N$, (Fig. 4).

### *Residual life of structural elements using the strain energy density method (SED)*

### *Formulation of models for residual life estimation using SED*

While predicting the life of the structural element with initial damage it is necessary to establish the functional dependency between the crack propagation gradient $da/dN$ and the stress intensity factor $K_{\mathrm{I}}$.

The severest damage accumulation occurs in the process zone /13, 15/, therefore it is necessary to define and calculate the energy that causes damage in the process zone. For the zone around the crack tip (process zone) it is possible to define the energy generated through plastic strain $\omega_p$ in a cycle using the length unit as a function of stress intensity factor range $\Delta K_{\mathrm{I}}$:

$$\omega_p=\left(\frac{1-n'}{1+n'}\right)\frac{\Delta K_{\mathrm{I}}^2}{E I_{n'}}\psi \tag{2}$$

where: $n'$–cyclic strain hardening exponent, $E$–Young`s modulus, $I_{n'}$, $\psi$–constants that depend on the cyclic strain hardening exponent $n'$.

Since the dependency on energy generated due to plastic strain $\omega_p$ as a function of $\Delta K_{\mathrm{I}}$ is established, it is necessary to establish the dependency between the crack propagation gradient $da/dN$ and $\omega_p$. While establishing the dependency, a fact that the crack propagates if the energy that generates due to plastic strain during the cycle reaches the energy absorbed during the same cycle $W_c$ must be taken into account:

$$\frac{da}{dN}=\frac{\omega_p}{W_c} \tag{3}$$

In Eq.(3) the energy absorbed during the cycle $W_C$ can be defined if the stress-strain relation, or the material behaviour equation, are known. An adequate relation for material behaviour which includes both elastic and plastic behaviour is known as the Ramberg-Osgood equation, /16/:

$$e_a=\frac{S_a}{E}+\left(\frac{S_a}{k'}\right)^{1/n'} \tag{4}$$

where: $e_a$–strain amplitude, $S_a$–stress amplitude and $k'$–cyclic strength coefficient.

If the material behaviour equation is presented by Eq.(4), the energy absorbed during the cycle $W_c$ represents the area below the curve in the $S$–$\varepsilon$ coordinate system, or:

$$W_c=\frac{4}{1+n'}\sigma_f'\varepsilon_f' \tag{5}$$

where: $\sigma_f'$–fatigue strength exponent, $\varepsilon_f'$–fatigue ductility coefficient.

Finally, if Eq.(3) is placed into Eqs.(2) and (4), the functional dependency between crack propagation gradient and stress intensity factor is established. Subsequently, that dependency can be integrated from initial crack length $a_i$ to final crack length $a_c$ in order to obtain the relation which could be used for the life prediction of structural elements that contain initial damage:

$$N = \frac{(1-n')\psi}{4EI_{n'}\sigma'_f\varepsilon'_f}\int_{a_I}^{a_c}(\Delta K_I - \Delta K_{th})^2 da \qquad (6)$$

where $\Delta K_{th}$ is the threshold range of the stress intensity factor. $\Delta K_{th}$ is a material constant but it is sensitive to the stress ratio $R = S_{\min}/S_{\max}$. A relation between $\Delta K_{th}$ and $R$ is given below based on experimental results:

$$\Delta K_{th} = \Delta K_{th0}(1-R)^{\gamma} \qquad (7)$$

where $\Delta K_{th0}$ is the threshold range of stress intensity factor for stress ratio $R = 0$, and $\gamma$ is a material constant that varies from 0 to 1 /17, 18/. For most of the materials, $\gamma$ comes out to be 0.71. Equation (6) presents the law of crack propagation based on strain energy density method. It is obvious that in this dependency, the cyclic characteristics of the material from the low-cycle fatigue domain are being used instead of dynamic parameters from more conventional laws for crack propagation by Paris, Forman and others. The main advantage of this approach is the use of the same cyclic material characteristics being used for life prediction until the occurrence of initial crack for the analysis of crack propagation.

*Definition of the stress intensity factor*

Equation (6) which refers to the crack propagation gradient and life prediction until failure occurs are formulated as functions of stress intensity factor $\Delta K_{\mathrm{I}}$. Stress intensity factor (SIF) includes the geometry of a structural element and the type of outer loading in the calculation. In the analytical relation for stress intensity factor:

$$K_{\mathrm{I}} = YS\sqrt{\pi a} \qquad (8)$$

where $Y$ stands for the corrective function that describes the geometry of a structural element and the type of loading, $a$–crack length, $S$–stress. Numerical examples have been analysed with the uniaxial loading that affects the cracked structural element, Fig. 2. Since the structural element contains a hole of radius $r$ and a single crack of length $a_0$, the corrective function for uniaxial loading appears like this /15/:

$$Y = zY_wY_{b1} \qquad (9)$$

and

$$z = \frac{1}{2}\sqrt{\frac{1}{\cos\left(2r\frac{\pi^2 w}{180}\right)}}, \quad Y_w = \sqrt{\frac{1}{\cos\left(\frac{\pi}{2}\frac{(2r+a)}{(w-a)}\right)}} \qquad (10)$$

$$Y_{b1} = 0.70833 + 1.29275\mathrm{e}^{\frac{-(a/w)}{0.17197}} + 0.29223\mathrm{e}^{\frac{-(a/w)}{4.81617}} + 1.10057\mathrm{e}^{\frac{-(a/w)}{1.04267}} \qquad (11)$$

where $r$ is the radius of the hole and $a$–length of crack. The analytical expression for SIF, /9/, is verified by using finite element method (FEM).

To validate the analytical equation for SIF /8/, here the finite element method is used. The stress intensity factor in (8) is calculated by using the finite element method. More precisely, the stress intensity factor is calculated by using singular finite elements for various crack lengths. Based on discrete values of the stress intensity factor calculated by using the finite element method, the analytical formula in polynomial form is derived for the stress intensity factor necessary for the analysis of crack propagation so to validate the analytical equation for SIF (8). Namely, Fig. 3 presents the stress distribution of the damaged structural element for crack length $a = 0.00127$ m.

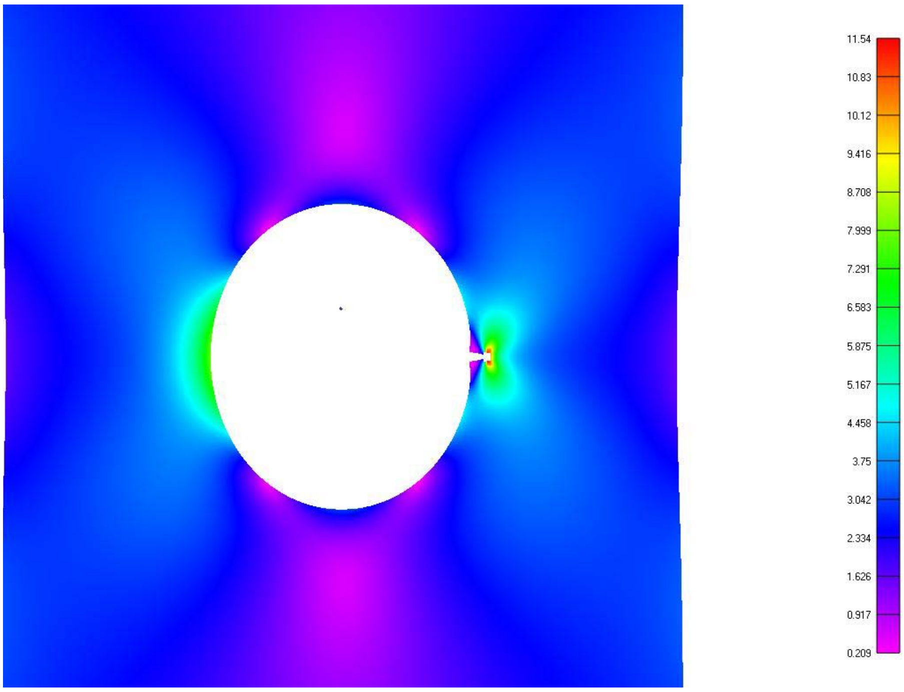


Figure 3. Stress distribution for structural element with a circular hole and a crack ($F = 5200$ N and $a = 0.00127$ m) using FEA.
Slika 3. Analiza napona za reprezentativni element sa otvorom i prslinom koristeći MKE ($F = 5200$ N i $a = 0.00127$ m)

Table 3. Comparison of FE and analytical solutions.
Tabela 3. Poređenje analiza MKE i analitičkih rešenja

|  | $a_0$ (mm) | $K_I^{FEM}$ | $K_I^{Anal}$ (Eq.8) | Δ (%) |
|---|---|---|---|---|
| 1 | 1.27 | 12.8 | 12.23 | 4.45 |
| 2 | 2.5 | 15.4 | 15.6 | −1.30 |
| 3 | 4 | 17.4 | 18.24 | −4.83 |
| 4 | 6 | 19.6 | 21.07 | −7.50 |

After the stress analysis, SIF for various values of crack length can be determined by FEM. The obtained values are given in Table 3.

Comparisons in Table 3 shows good agreement between analytical and numerical results of stress intensity factors for different values of crack length *a*. Due to this, the relation for the corrective function (Eq.(9) with (10) and (11)) can be used in the formulated procedure for crack growth prediction of the damaged structural element presented in Fig. 3.

*Numerical results of crack growth based on SED*

As a result of budget analysis, crack propagation based on strain energy density, using the software package PP_VEK, has presented all the necessary input data, which includes geometry features considered as representative elements of the initial crack and the crack growth law based on strain energy density (SED), as it is necessary for the cyclic characteristics of the material, as well as the type of variable load (whether it is cyclic loading with a constant amplitude, or a load spectrum).

As a primary output of the derived relationship between crack length depending on the number of cycles, the *a*–*N* dependence is obtained, Fig. 4.

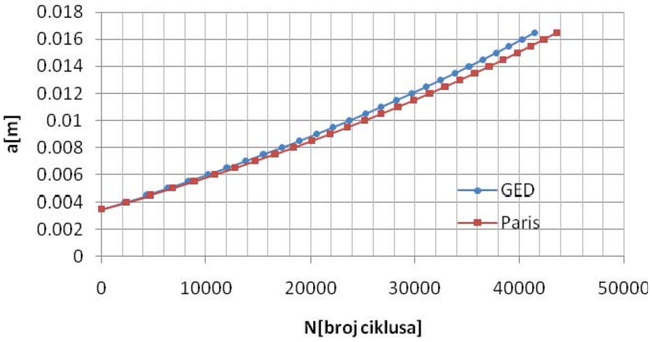


Figure 4. Analysis of crack propagation using conventional law expansion (Paris) with method SED for tower material S 355 JR.
Slika 4. Analiza širenja prsline primenom konvencionalnog zakona širenja (Paris) sa metodom SED za materijal tornja S 355 JR

*Comparison (verification) of results in propagation models using different approaches*

The subject of analysis is an example of plate with a hole and an initial crack. Here are shown comparative results of crack growth using two completely different approaches, /2/, Figure 4:

1. Conventional Paris crack growth law,
2. Strain Energy Density method

From the diagram in Fig. 4, illustrating the crack propagation using the conventional Paris law crack propagation and strain energy density (SED) good agreement is evident.

*Residual life estimation of the tower for real load spectrum*

Based on the average of the mining operations for one year, typically executed by any repair facility, its load diagram, in Table 4, gives the real spectrum (block) stress, which equals to one year of plant operation.

Table 4. Real spectrum stress (one block).
Tabela 4. Realni spektar napona (jedan blok)

| Stress level | $S_{min}$ (MPa) | $S_{max}$ (MPa) | cycles |
|---|---|---|---|
| Level 1 | 0 | 42.84 | 40515 |
| Level 2 | 0 | 42.84 | 40515 |
| Level 3 | 44.87 | 46.89 | 40 |
| Level 4 | 48.5 | 80.8 | 5 |
| Level 5 | 80.8 | 121.3 | 25 |

In consideration of the basic model of the tower taken M1 (i.e. the load on the hook), at the top of the tower is 1250 kN and load case III, with a maximum value of 252.62 MPa stress, /1/.

For other values of the load on the tower, stress values are obtained by scaling those given in Table 4. Then, the programme for remaining life (SED) provides remaining structural life of the tower, which is given in Table 5.

As you can see, the final result is obtained, the number of blocks = 7, and 7 years for the material S 355 JR, because each block contains the approved number of operations that occur in service during one year.

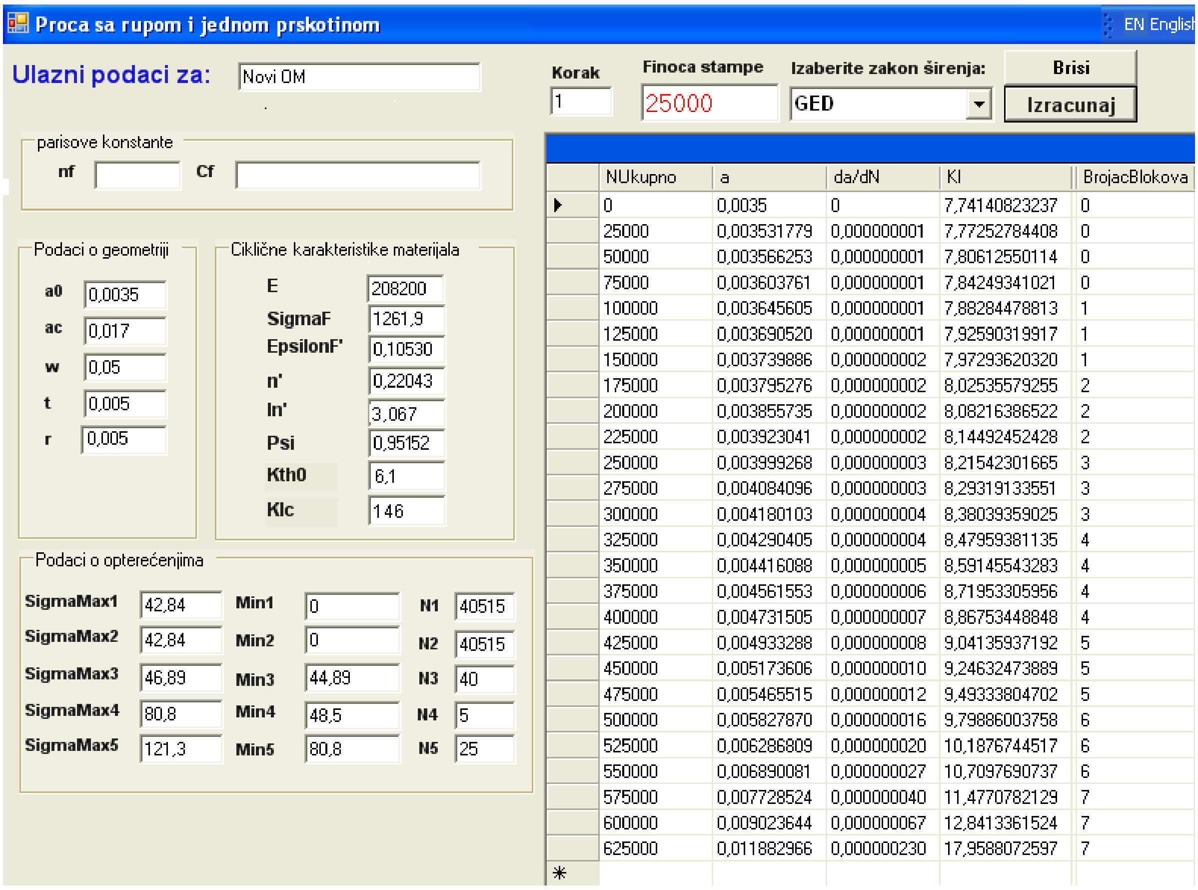
## METHODOLOGY

Through an experimental study of low cyclic fatigue characteristics of the material on one hand, and the use of budgetary procedures for the analysis of crack propagation in LCF material (method SED) on the other hand, this paper establishes a complete general methodology – procedures for residual life assessment of complex structures such as tower type facilities for oil and gas exploration, /2/.

It consists of the following stages:

- Testing of mechanical properties of the materials of the tower.
- Determination of critical points in the exploitation of the finite element method (FEM) and the calculation of static and dynamic behaviour of the tower.
- Determination of stress strain state of the tower (spectrum of stress) during operation.
- Determination of cyclic characteristics of low cyclic fatigue.
- Determination of Paris constants and fracture toughness of the material.
- Determination of crack growth parameters.
- Comparison (verification) of applied methodology (Paris, SED) for the residual life of the tower (stacking diagrams *a*–*N* for these methods).
- Determination of the residual life of the tower for the real range of the load (applied strain energy density SED, built in software PP_VEK).
- Analysis of the results of residual life assessment of the tower structure.

Table 5. Results of crack propagation in realistic range of load material S 355 JR, method SED.
Tabela 5. Rezultati analize širenja prsline za realni spektar opterećenja, materijal S 355 JR, po metodi SED



Proca sa rupom i jednom prskotinom

Ulazni podaci za: Novi OM

Korak: 1
Finoca stampe: 25000
Izaberite zakon širenja: GED

parisove konstante
nf:
Cf:

Podaci o geometriji
a0: 0,0035
ac: 0,017
w: 0,05
t: 0,005
r: 0,005

Ciklične karakteristike materijala
E: 208200
SigmaF: 1261,9
EpsilonF': 0,10530
n': 0,22043
In': 3,067
Psi: 0,95152
Kth0: 6,1
KIc: 146

Podaci o opterećenjima
SigmaMax1: 42,84 Min1: 0 N1: 40515
SigmaMax2: 42,84 Min2: 0 N2: 40515
SigmaMax3: 46,89 Min3: 44,89 N3: 40
SigmaMax4: 80,8 Min4: 48,5 N4: 5
SigmaMax5: 121,3 Min5: 80,8 N5: 25

| NUkupno | a | da/dN | KI | BrojacBlokova |
|---|---|---|---|---|
| 0 | 0,0035 | 0 | 7,74140823237 | 0 |
| 25000 | 0,003531779 | 0,000000001 | 7,77252784408 | 0 |
| 50000 | 0,003566253 | 0,000000001 | 7,80612550114 | 0 |
| 75000 | 0,003603761 | 0,000000001 | 7,84249341021 | 0 |
| 100000 | 0,003645605 | 0,000000001 | 7,88284478813 | 1 |
| 125000 | 0,003690520 | 0,000000001 | 7,92590319917 | 1 |
| 150000 | 0,003739886 | 0,000000002 | 7,97293620320 | 1 |
| 175000 | 0,003795276 | 0,000000002 | 8,02535579255 | 2 |
| 200000 | 0,003855735 | 0,000000002 | 8,08216386522 | 2 |
| 225000 | 0,003923041 | 0,000000002 | 8,14492452428 | 2 |
| 250000 | 0,003999268 | 0,000000003 | 8,21542301665 | 3 |
| 275000 | 0,004084096 | 0,000000003 | 8,29319133551 | 3 |
| 300000 | 0,004180103 | 0,000000004 | 8,38039359025 | 3 |
| 325000 | 0,004290405 | 0,000000004 | 8,47959381135 | 4 |
| 350000 | 0,004416088 | 0,000000005 | 8,59145543283 | 4 |
| 375000 | 0,004561553 | 0,000000006 | 8,71953305956 | 4 |
| 400000 | 0,004731505 | 0,000000007 | 8,86753448848 | 4 |
| 425000 | 0,004933288 | 0,000000008 | 9,04135937192 | 5 |
| 450000 | 0,005173606 | 0,000000010 | 9,24632473889 | 5 |
| 475000 | 0,005465515 | 0,000000012 | 9,49333804702 | 5 |
| 500000 | 0,005827870 | 0,000000016 | 9,79886003758 | 6 |
| 525000 | 0,006286809 | 0,000000020 | 10,1876744517 | 6 |
| 550000 | 0,006890081 | 0,000000027 | 10,7097690737 | 6 |
| 575000 | 0,007728524 | 0,000000040 | 11,4770782129 | 7 |
| 600000 | 0,009023644 | 0,000000067 | 12,8413361524 | 7 |
| 625000 | 0,011882966 | 0,000000230 | 17,9588072597 | 7 |

## CONCLUSION

When it comes to experimental research, primary attention is focused on determining low cyclic fatigue behaviour characteristics of materials, which are necessary for assessing the century tower. Complete low cyclic fatigue (LCF) properties are experimentally determined for the tower material, structural steel S355 JR.

In addition, LCF for these two materials have been experimentally determined and also the dynamic behavioural characteristics (*C*, *m*), which are used in the conventional crack propagation laws as the Paris, Forman and other. Experiments have defined certain dynamic characteristics of the material, and the fracture toughness of the material.

Two different computational estimates of residual life are compared in the problem of a representative structural element, a plate with a hole and a crack in the area of stress concentration with constant amplitude cyclic loading.

The proposed methods for estimating residual life of tower structures are real and contribute to streamlining the application procedure in condition monitoring and maintenance, both in terms of technical performance, and in terms of optimization, preventative maintenance and cost reduction at all. Universal methodology (procedures) to estimate residual life of the tower plant structure for oil and gas exploration can also be applied to other structures.

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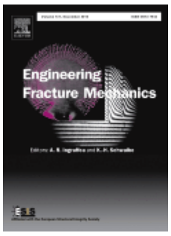
* * *



## ESIS special issues in 2013-14

| Journal | Title | Source | Editor | Status |
|---|---|---|---|---|
| Int J Fatigue | Recent Progress in the Understanding of Fatigue Crack Propagation | ECF 18 | H.J. Christ,<br>D. Klingbeil | IJF 57, 2013 |
| Eng Fract Mech | Fracture of Polymers, Composites and Adhesives | 6th Int. ESIS TC4 conference | B.R.K. Blackman,<br>J.G. Williams | EFM 101, 2013 |
| Int J Fatigue | Thermomechanical Fatigue | 2nd Int. Workshop on Thermo-mechanical fatigue, May 2011, BAM, Berlin, Germany / TC 11 | H. Klingelhöffer | IJF 53, Aug. 2013 |
| Eng Fract Mech | Micromechanisms of Deformation and Fracture | TC 2 Meetings in Berlin and Oxford | J. Pokluda,<br>T.J. Marrow | EFM 110, Sept. 2013 |
| Eng Fract Mech | Crack Paths 2012 | 4th Int. Conf. on Crack Paths (CP 2012) / TC3 | R. Brighenti,<br>A. Carpinteri,<br>F. Iacoviello,<br>L.P. Pook | EFM 108, 2013 |
| Int J Fatigue | New Advances in VHCF | VHCF-5 | C. Berger,<br>B. Pyttel | IJF 60C, March 2014 |
| Int J Fatigue | Fatigue Crack Paths 2012 | 4th Int. Conf. on Crack Paths (CP 2012) / TC3 | A. Carpinteri,<br>L.P. Pook,<br>L. Susmel,<br>S. Vantadori | IJF 58, 2014 |
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| Int J Fatigue | Failure Analysis of Structure Components Undergone Stress Corrosion, Fatigue and Neutron Irradiation | ECF 19 | R. Goldstein,<br>V. Shlyannikov | in preparation |