CIP - Каталогизација у публикацији
Народна и универзитетска библиотека
Републике Српске, Бања Лука

621.3(082)(086.76)
621(082)(086.76)

МЕЂУНАРОДНА конференција о достигнућима у машинству и индустријском инжењерству (16 ; 2023 ; Бања Лука)
Proceedings [Електронски извор] : DEMI 2023 / [16th international conference on accomplishments in mechanical and industrial engineering, Banja Luka, Jun 2023 ; editor in chief Petar Gvero]. - El. zbornik. - Banja Luka : Faculty of Mechanical Engineering, 2023. - 1 електронски оптички диск (CD-ROM) : слика ; 12 cm

Систематски захтјеви: нису наведени. - Насл. са насл. екрана. - Ел. публикација у ПДФ формату опсега 533 стр. - Опис извора дана 7. 06. 2023. - Библиографија уз сваки рад.

ISBN 978-99976-11-04-8

COBISS.RS-ID 138545409

University of Banja Luka
Faculty of Mechanical Engineering

PROCEEDINGS

DEMI 2023

Banja Luka, Jun 2023

16TH INTERNATIONAL CONFERENCE ON ACCOMPLISHMENTS IN MECHANICAL AND INDUSTRIAL ENGINEERING

DEMI 2023

Supported by:
MINISTRY FOR SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENT, HIGHER
EDUCATION AND INFORMATION SOCIETY
OF THE REPUBLIC OF SRPSKA

Organizer and publisher:
FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF BANJA
LUKA

Co-organizer:
FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF NIŠ,
SERBIA

FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF
PODGORICA, MONTENEGRO

FACULTY OF ENGINEERING HUNEDOARA
UNIVERSITY POLITEHNICA TIMIŞOARA, ROMANIA REYKJAVIK

UNIVERSITY, ICELAND

For publisher:
Full Prof. Aleksandar Milašinović, PhD

Editor of chief:
Full Prof. Petar Gvero, PhD

Executive editor:
Biljana Prochaska, PhD
Milivoj Stipanović, BsC

ORGANIZING COMMITTEE

Prof. Petar Gvero, PhD
Chairman of Organizing and Scientific Committee
Faculty of Mechanical Engineering, University of Banja Luka

Prof. Aleksandar Milašinović,
PhD Prof. Zorana Tanasić, PhD
Assoc. Prof. Stevo Borojević, PhD
Assoc. Prof. Goran Janjić, PhD
Assist. Prof. Dejan Branković, PhD
Prof. Uroš Karadžić, PhD
(Faculty of Mechanical Engineering, Podgorica)
Assoc. Prof. Dejan Mitrović, PhD
(Faculty of Mechanical Engineering, Niš)
Assoc. Prof. Sorin Ioan Deaconu, PhD
(Faculty of Engineering Hunedoara, Romania)
Assist. Prof. David C. Finger, PhD
School of Science and Engineering University of Reykjavik, Iceland
Goran Jotić, Senior Assistant, MSc
Saša Tešić, Assistant, MSc
Gordana Tošić, Assistant, MSc
Ivana Savković, Assistant, MSc
Dijana Đeorđić, Assistant, MSc
Biljana Prochaska, PhD
Sanja Maglov, MA+
Boro Marić, BA Law
Nedeljka Sladojević Putnik, BA Economics
Milivoj Stipanović, BSc
Zoran Grahovac, Assistant, MSc
Milisav Marković, Senior Assistant, MSc

SCIENTIFIC COMMITTEE

Prof. Darko Knežević, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Radivoje Mitrović, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Vlastimir Nikolić, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Nenad T. Pavlović, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Igor Vušanović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Gelu Ovidiu Tirian, PhD University
Politehnica Timisoara Romania

Prof. Dejan Lukić, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Saša Živanović, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Mijodrag Milošević, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Aleksandar Milašinović, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Milan Tica, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Izet Bjelonja, PhD
Faculty of Mechanical Engineering
University of Sarajevo

Prof. Milan Zeljković, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Slobodan Tabaković, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Franci Pušavec, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Miodrag Manić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Milenko Sekulić, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Mileta Janjić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Assist. Prof. Davorin Kramar, PhD University
of Ljubljana, Slovenia

Prof. Simo Jokanović, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Gordana Globočki-Lakić, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Ardelean Erika, PhD University
Politehnica Timisoara Romania

Prof. Petar Gvero, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Slobodan Lubura, PhD
Faculty of Electrical Engineering University
of East Sarajevo

Prof. Sanda Midžić – Kurtagić, PhD Faculty of
Mechanical Engineering University of
Sarajevo

Assoc. Prof. Srđan Vasković, PhD Faculty of
Mechanical Engineering University of East
Sarajevo

Prof. Bratislav Blagojević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Milan Radovanović, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Dragoslava Stojiljković, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Nebojša Manić, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Milan Lečić, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Neven Duić, PhD
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb

Prof. Vojislav Novaković, PhD NTNU, Norway

Prof. Milan Rackov, PhD Faculty of Technical Sciences University of Novi Sad

Prof. Mirko Blagojević, PhD Faculty of Engineering Sciences University of Kragujevac

Prof. Sanjin Troha, PhD

Faculty of Engineering University of Rijeka, Croatia

Prof. Nebojša Rašović, PhD
Faculty of Mechanical Engineering, Computing and Electrical Engineering,
University of Mostar

Prof. Miroslav Milutinović, PhD Faculty of Mechanical Engineering University of University of East Sarajevo

Prof. Nataša Trišović, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Mladomir Milutinović, PhD Faculty of Technical Science University of Novi Sad

Prof. Dražan Kozak, PhD
University of Josip Juraj Strossmayer in Osijek, Croatia

Prof. Dragan Milčić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Radoslav Tomović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Janko Jovanović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Nebojša Radić, PhD
Faculty of Mechanical Engineering
University of East Sarajevo

Prof. Tomaž Berlec, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Janez Kušar, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Platon Sovilj, PhD Faculty of Technical Sciences University of Novi Sad

Prof. Gordana Stefanović, PhD Faculty of Mechanical Engineering University of Niš

Prof. Miladin Stefanović, PhD Faculty of Engineering Sciences University of Kragujevac

Prof. Vlado Medaković, PhD Faculty of Mechanical Engineering University of East Sarajevo

Prof. Valentina Golubović-Bugarski, PhD, Faculty of Mechanical Engineering, University of Banja Luka

Prof. Strain Posavljak, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Vid Jovišević, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Živko Babić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Atul Bhaskar, PhD University of Southampton United Kingdom

Prof. Socalici Ana, PhD University Politehnica Timisoara Romania

Prof. Milan Banić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Aleksandar Sedmak, PhD Faculty of Mechanical Engineering University of Belgrade

Prof. Branko Blanuša, PhD Faculty of Electrical Engineering University of Banja Luka

Assist. Prof. Srđan Savić, PhD Faculty of Technical Sciences University of Novi Sad

Prof. Dejan Mitrović, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Goran Janevski, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Uroš Karadžić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Deaconu Sorin, PhD University
Politehnica Timisoara Romania

Prof. Bordeasu Ilare, PhD University
Politehnica Timisoara Romania

Assist. Prof. Dejan Branković, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Vinko Babić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Jovanka Lukić, PhD Faculty of
Engineering Sciences University of
Kragujevac

Prof. Goran Petrović, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Radoje Vujadinović, PhD Faculty of
Mechanical Engineering Podgorica,
University of Montenegro

Prof. Snežana Petković, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Miodrag Hadžistević, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Branko Štrbac, PhD, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Bratislav Blagojević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Peđa Milosavljević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Jelena Šaković Jovanović, PhD Faculty
of Mechanical Engineering Podgorica,
University of Montenegro

Prof. Mladen Todić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Milija Krajišnik, PhD
Faculty of Mechanical Engineering
University of East Sarajevo

Prof. Ilija Ćosić, Emeritus Faculty of
Technical Sciences University of Novi Sad

Prof. Zorana Tanasić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Mirko Soković, PhD
University of Ljubljana, Slovenia

Prof. Miroslav Bobrek, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Goran Janjić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Igor Budak, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Tihomir Latinović, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Assist. Prof. Bojan Knežević, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Sead Pašić, PhD
Faculty of Mechanical Engineering, “Džemal
Bijedić”, University in Mostar

Prof. Borut Kosec, PhD
Faculty of Natural Sciences and Engineering,
University of Ljubljana

Prof. Darko Bajić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Dragoslav Dobraš, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Senior Scient. Eng. Milica Grahovac, PhD,
Lawrence Berkeley National Laboratory,
USA

Prof. Doina Frunzaverde, PhD Faculty of
Engineering Resita Babeș-Bolyai University

Prof. Mihajlo Stojčić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Assist. Prof. Esad Tombarević, PhD Faculty
of Mechanical Engineering Podgorica,
University of Montenegro

Assist. Prof. Boško Matović, PhD Faculty of
Mechanical Engineering Podgorica,
University of Montenegro

DEMI 2023

16th International Conference on Accomplishments in Mechanical and Industrial Engineering

www.demi.mf.unibl.org

Banja Luka
1–2 Jun 2023.

Occurrence of cracks due to inadequate turbine shaft construction

Srđan Bulatović[a], Vujadin Aleksić[a], Bojana Zečević[b], Biljana Prochaska[c]

[a] *Institute for Testing of Materials (IMS Institute), Bulevar vojvode Mišića 43, Belgrade, Serbia*
[b] *University of Belgrade, Innovation Centre of Faculty of Technology and Metallurgy, Karnegijeva 4, Belgrade, Serbia*
[c] University of Banja Luka, Faculty of Mechanical Engineering, Bulevar vojvode Stepe Stepanovica 71, Banja Luka, Bosnia and Hercegovina

Abstract *After several decades of constant exploitation of the horizontal bulb turbine, which is an integral part of the hydroelectric power unit, empirically, the formation of a crack occurs in the turbine shaft due to the influence of corrosion, erosion and cavitation.*

Through experimental tests and calculations it has been determined that values of bending stresses of the turbine, which occur due to the action of fatigue and corrosion, as well as stress concentration, are bigger than 25 MPa for flanges exposed to water, and in other case bigger than 40 MPa for flanges exposed to `corrosive water` and can cause the occurrence of surface cracks on the transition radius between the cylindrical part of the shaft and the flange. It has been determined that stress values in the zone under the influence of bending stresses were bigger than allowable values, which led to the occurrence of many cracks due to fatigue corrosion. One of those cracks caused the failure of the shaft and of the whole turbine.

Keywords *fatigue, crack, turbine shaft, stress concentration*

1. INTRODUCTION

Turbine loads originate during the production of components and equipment assembling (residual stresses), during the process of performing functional requirements in exploitation (stationary and dynamic loads) and during the disturbed process of exploitation (non-stationary dynamic loads). It`s clear that component and equipment loads can`t be expressed by a simple mathematical function knowing that unpredictable influence of corrosion, erosion and cavitation during exploitation should be taken into account. That`s the reason why extensive researches, tests and inspections of hydropower plant equipment have been undertaken [1 - 7].

Turbine shaft was assembled by welding the cylindrical body of the hollow shaft (outer diameter 1200 mm, internal diameter 600 mm) to the flange, made of 20GSL steel. During welding heat-affected zone has been created, which overlapped the transition diameter. Residual stresses were accumulated at the external surface of the transition area from the shaft to the flange. Anti-corrosive protection in the shaft flange area has been exposed to water.

After several hundred thousand hours of use, a huge loss of oil from the regulating system of hydroelectric generating set was noticed. After the exclusion of the hydroelectric generating set from the service and visual inspection of all suspicious locations a crack, 2100 mm long, was detected, through which the turbine oil from the servo motor leaked, on the transition radius

Corresponding author

Phd Srđan Bulatović, Research Associate
srdjan.bulatovic@institutims.rs
Institute for testing of materials-IMS Institute
Bulevar vojvode Mišića 43
Belgrade, Serbia

R80 from the cylindrical part of the shaft toward the runner hub.

2. ASSESSMENT AND ANALYSIS OF STRENGTH AND FRACTURE OF THE TURBINE SHAFT RADIUS

Turbine shaft is subjected to tensile stress due to the effect of the hydraulic force on turbine runner.

Pressure of oil in the servo motor of the runner in the closing stroke and axial hydraulic force load subject the flange to bending. The weight of the runner and of the shaft itself subject the shaft to cyclic bending. Due to the transfer of the force the shaft is subjected to torsion as well.

Combination of cyclic loads and corrosive environment (leakage of water through the seal, poor execution and non-renewal of the corrosion protection) led to the occurrence of the corrosion fatigue on the transition radius (location where value of the stress concentration factor is 3). Corrosion fatigue damages, as far as stress concentration is concerned, act like cracks (stress concentration value is ranging from 3 to 6).

High-cycle fatigue conditions in a corrosive environment the initiation of cracks occurred, and their joining led to the formation of 20-30 mm long cracks, which was confirmed by the existence of corrosion products on the smooth fracture surface. When the load bearing area of the turbine shaft, under low-cycle fatigue conditions, fell under the critical value in the crack growth area the fracture occurred. That segment of the area is embossed and deprived of corrosion products.

Calculation regarding the critical cross-section of the shaft has been carried out through the use of the Theory of Elasticity and data provided by the manufacturer. Taking into account the fact that the fracture is irregularly shaped, it has been adopted that the critical cross-section is positioned at the end of the cylindrical part of the shaft.

Critical cross-section of the turbine shaft is subjected to [7]:

- Axial hydraulic force F_a=5.5426·106 N,
- Moment of torsion M_t=4.278·10^6 Nm,
(P=28000 kW-turbine power and n=1.04166 s^{-1} - turbine shaft number of revolutions)
- Bending moment M_o=337768 Nm (occurs due to the action of the axial hydraulic force and force that occurs due to the oil pressure in the cylinder of the servo motor of the runner),
- Bending moment M_o=1964943 Nm (occurs due to the weight of the runner and weight of the part of the flange as far as the critical cross-section):
- Tensile stress due to the action of the axial hydraulic force:

$$\sigma_z = \alpha_z \frac{F_a}{A_k} = 14{,}3\ MPa \tag{1}$$

where: α_z=2.19-stress concentration factor during tension and A_k critical cross-section area.

- Bending stress due to the action of the axial force and force that occurs due to the pressure in the servo motor of the runner

$$\sigma_o = \frac{M_o}{W_o} = \frac{M_o}{h^2/6} = 22{,}52 MPa \tag{2}$$

where: W_o-moment of resistance per length unit of the critical cross-section.

- Torsional stress:

$$\tau = \alpha_t \frac{M_t}{W_t} = \alpha_t \frac{M_t}{\frac{\pi \cdot D^3}{16}\left[1-\left(\frac{D}{d}\right)^4\right]} = 20{,}85 MPa \tag{3}$$

where: W_t-polar moment of resistance per length unit of the critical cross-section, α_t = 1.55 - stress concentration factor during torsion for

$$\frac{D_p}{D} = \frac{2300}{1200} = 1{,}916 \quad \frac{R}{D} = \frac{80}{1200} = 0{,}066 \tag{4}$$

-Equivalent static stress at the critical cross-section:

$$\sigma_m = \sqrt{(\sigma_z + \sigma_o) + 4\tau^2} = \sqrt{(14{,}3 + 22{,}52)^2 + 4 \cdot 20{,}85^2} = 55{,}6 MPa \tag{5}$$

Cyclic stress at the critical cross-section occurs due to the bending moment caused by weights of the runner and of the part of the flange as far as the critical cross-section:

$$\sigma_a = \alpha_s \frac{M_s}{W_s} = \alpha_s \frac{M_s}{\frac{\pi \cdot D^3}{32}\left[1-\left(\frac{D}{d}\right)^4\right]} = 24{,}46 MPa \tag{6}$$

where: W_s-moment of resistance per length unit of the critical cross-section, α_s=1.98-stress concentration factor during bending for

$$\frac{D_p}{D}=\frac{2300}{1200}=1{,}916 \quad \frac{R}{D}=\frac{80}{1200}=0{,}066 \tag{7}$$

2.1 Corrosion fatigue factor of safety

Factor of safety of the turbine shaft, in relation to corrosion fatigue and in conditions of cyclic loading of amplitude σ_a=24.4 MPa and corrosion is obtained through the use of the following equation:

$$S_\sigma=\frac{\sigma_{-1}-\psi_\sigma\cdot(\sigma_m+\sigma_{MO})}{\sigma_a} \tag{8}$$

where: σ_{-1} = 26.5 MPa-permanent corrosion fatigue strength of steel 20GSL during the action of the alternating changeable load in the corrosive environment, ψ_σ-coefficient that takes into account the asymmetry of the cycle and is equal to the ratio of the corrosion fatigue strength σ_{-1} and tensile strength R_m.

$$\psi_\sigma=\frac{\sigma_{-1}}{R_m}=\frac{26{,}5}{480}=0{,}0552 \tag{9}$$

σ_m–maximum value of static exploitation stresses at the calculated cross-section, eq. (5).
σ_a –amplitude of cyclic stresses, eq. (6).
σ_{MO}–residual stresses present after casting and heat treatment have not been taken into account (σ_{MO}=0 MPa) because there were no exact values available.

Permanent corrosion fatigue strength is being determined experimentally by testing the samples in the water and correcting the obtained results through the use of dimensional factors. Factor of safety is less than S_σ=1.5, the value predicted by the manufacturer's designation.

2.2 Effect of Stress Concentration and Corrosion on Fatigue Strength

At locations of sudden changes of shape of loaded structural components local increase of stress (stress concentration) occurs. Level of stress increase is defined by the ratio of the maximum local (σ_{max}) and nominal (σ_{nom}) stress, which is being called the theoretical stress concentration factor [6]:

$$K_t=\frac{\sigma_{max}}{\sigma_{nom}} \tag{10}$$

Fatigue strength due to the action of the corrosive environment is defined by the following factor:

$$k_{kor}=\frac{\sigma_{max(-1)kor}}{\sigma_{max(-1)}} \tag{11}$$

where: $\sigma_{max(-1)kor}$, $\sigma_{max(-1)}$-fatigue strengths of smooth specimens in the corrosive environment and in the air atmosphere, respectively.

Fatigue strength in the corrosive environment depends on the number of cycles, but also on the length of exposure period of elements to the corrosive environment.

The joint effect of corrosion and stress concentration can be expressed by the following coefficient:

$$K_{fkor}=K_f+\frac{1}{k_{kor}}-1 \tag{12}$$

where: K_f =1.98-effective stress concentration factor for testing in the air atmosphere, k_{kor}=0.5 (for R_m=480 MPa) - coefficient of the effect of corrosion for smooth specimens. As far as the turbine shaft is concerned, value of stress concentration coefficient, including the effect of corrosion, is K_{fkor}=2.98.

Corrosion fatigue analysis of asymmetric cycle it has been determined that mean tensile stress unfavorably affects, or in other words significantly decreases the dynamic durability amplitude. Mean pressure stresses favorably affect the resistance to corrosion fatigue.

Decrease of fatigue strength of an element with respect to fatigue strength of the smooth specimen is calculated through the use of the overall fatigue strength reduction factor:

$$K_D=\left(\frac{K_f}{k_3}+\frac{1}{k_{kor}}-1\right)\frac{1}{k_{po}k_A} \tag{13}$$

K_f=1.98-stress concentration coefficient,
k_3=0.6 - cross-section coefficient,
k_{po}=1-coefficient that takes into account technological methods of surface strengthening,

k_A=1-coefficient of anisotropy for steel castings, k_{kor}=0.5-corrosion coefficient.

At the end, K_D=4.28 for the turbine shaft. Factor K_D can be used in formulas for determination of the factor of safety.

2.3 Analysis of fracture mechanics parameters

To assess material behaviour and structural integrity in the presence of cracks, fracture mechanics parameters are used. Also, fracture mechanics parameters are used for better determine the tendency to crack growth, critical conditions for fracture development, material resistance to rapid crack propagation.

During 1961, Paris, Gomey, and Anderson have first proposed that the crack growth rate, da/dN, might be correlated with the stress intensity factor range, *ΔK*, when the material is exposed to variable loading of constant amplitude.

Paris–Erdogan equation according to Paris' law [8,9] is the fatigue crack growth rate, which is defined as a function of the stress intensity factor range *ΔK*:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{14}$$

where *C* and *m* are material parameters. These constants are related to the fatigue properties, material microstructure, stress, frequency, cyclic loading, and applied temperature. The constant m is usually between 2 and 4, near 4 for metallic materials. For materials with low static fracture toughness, the value of material parameter *m* can be as high as 10.

The diagram in Fig. 1 shows three different regimes of crack growth. The fatigue life can be divided into two parts: crack initiation phase (regime A) and propagation phase (regime B). Fatigue crack propagation behaviour is typically described in terms of crack growth rate or crack length extension per cycle of loading (*da/dN*) plotted against the stress intensity factor range or the change in stress intensity factor from the maximum to the minimum load [10].

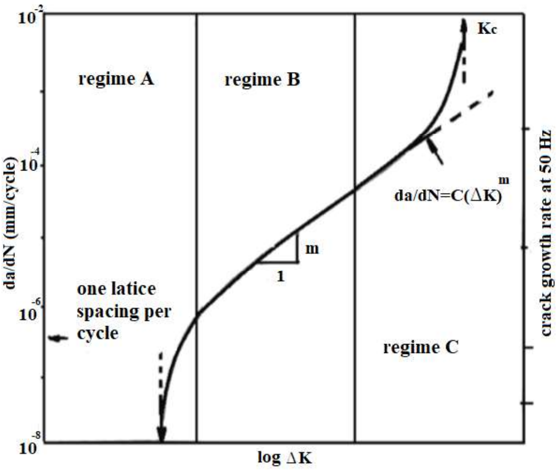

Fig. 1. Different regimes of stable fatigue crack propagation [11]

Using CRACKTRONIC pulsator, in load control conditions [12, 13], the fatigue crack growth rate *da/dN* and fatigue threshold ΔK_{th} are performed.

Crack growth is monitored by measuring potential drop by strain gauge RUMUL RMF A-5, measuring 5 mm length, located on the specimen face surface, Fig. 2.

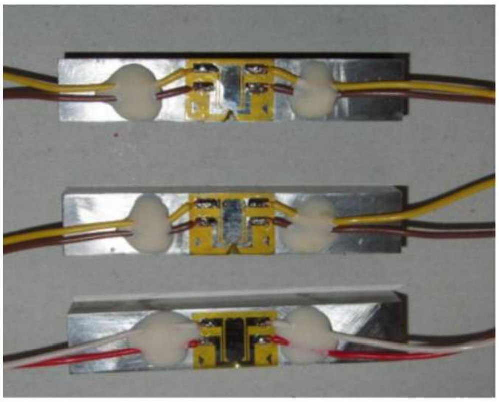

Fig. 2. Strain gauge RUMUL RMF A-5 located on the Charpy specimen (dimensions: 55x10x10 mm) face surface

Strain gauges RUMUL RMF A-5 of 5 mm length are cemented on machined specimens, allowing crack growth monitoring by FRACTOMAT device, based on electrical potential of gauge and connected with instrumentation, Fig. 3. The measuring gauge, a thin resistant measuring foil, is cemented on the specimens in the same way as classical strain gauges. As the crack grows under the measuring foil causing it to rip, it traces the fatigue crack tip, changing foil electrical resistance linearly with the crack length [14].

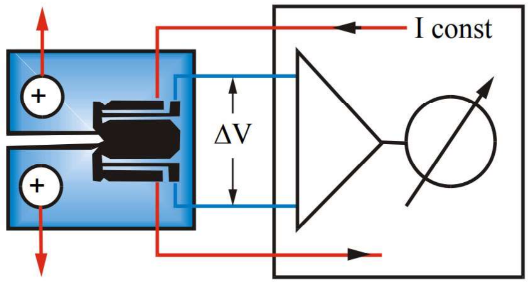

Fig. 3. Scheme of measurement foil and crack growth detection

By reducing the relationship between the fatigue crack growth rate per cycle da/dN and the range of stress intensity factor ΔK is determined the coefficient C and the exponent m. ΔK, which depends on the geometry of the specimen, the length of the crack, and on the range of variable force, ΔP, should be added to the fatigue crack growth rate for current crack length a [12].

Table 1 shows values of the fatigue threshold ΔK_{th} and material parameters-coefficient C and exponent m for fatigue crack growth, according the standard ASTM E647 [15] for determining the stress intensity factor range.

Table 1. Fracture mechanics parameters for specimens taken longitudinally and transversally from the casting

Spec.	Fatigue threshold ΔK_{th}, MPa m$^{1/2}$	Coeff. C	Coeff. m	da/dN, m/cycle at $\Delta K=10$ MPa m$^{1/2}$
Longitu-dinal	8,7	$3.0 \cdot 10^{-11}$	2	$5.62 \cdot 10^{-08}$
Transv-ersal	7.4	$3.2 \cdot 10^{-11}$	4	$6.36 \cdot 10^{-08}$

3. CONCLUSION

Calculation of fatigue strength, fracture mechanics parameters and effect of the stress concentration in the corrosive operating environment it can be concluded that cracks and fracture of the turbine shaft before its predicted service lifetime passed occured due to the inadequate construction solution regarding the production of the shaft.

More precisely, the mentioned refers to occurrence of initial cracks in corrosive environment and insufficient moment of resistance in the critical cross-section of the transition radius and shaft operation in the corrosive environment, as well as exposure to the leaking water, which caused the bending stress to grow beyond acceptable values.

Acknowledgements

This research is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract No. 451-03-47/2023-01/ 200012).

REFERENCES

[1] Angehrn, R., Eckert, R. Service Life of Horizontal Shafts in Low Head Turbines under Corrosion Fatigue*, IAHR 15th Symposiym,* 1990, Belgrade.

[2] Ohashi, W. (1991). *Vibration and Oscillation of Hydraulic Machinery*, Ashgate, Farnham.

[3] Vladislavlev. L. A., "Machine Vibration of Hydroelectric Plant", 1972, Moscow.

[4] Pejovic, S., Maricic, T., Karney B.W. (2009). The Guide to Hydropower Mechanical Design, *ASME "Hydro Power Technical Committee",* HCI Publications, New edition planned.

[5] Pejovic S. (1997). Profit Management and Control of Hydropower and Pump Plants, *Proceeding of the International Joint Power Generat*ion Conference, Denver, Colorado, p. 539 –545.

[6] Peterson R.E. (1974) *Stress concentration factor*, John Wiley&Sons, Inc, New York.

[7] Hertzberg R. (1995). *Deformation and fracture mechanics of engineering materials*, John Wiley&Sons, Inc, New York.

[8] Milovic, LJ., Vuherer, T., Radakovic, Z., Petrovski, B., Jankovic, M., Zrilic, M., Danicic, D. (2011). Determination of fatigue crack growth parameters in the welded joint of HSLA steel, *Structural integrity and life*, vol. 11, no. 3, p. 183-187.

[9] Burzic, M., Manjgo, M., Kozak, D., Prokic-Cvetkovic, R. (2013). The effects of dynamic load on behaviour of welded joint a-387 gr. 11 alloyed steel, *Metalurgija*, vol. 52, no. 1, p. 27-31.

[10] Alam, M.S. (2005). *Structural integrity and fatigue crack propagation life assessment of welded and weld-repaired structures*. PhD thesis. Louisiana State University and Agricultural and Mechanical College, Baton Rouge.

[11] Milovic, LJ., Vuherer, T., Radakovic, Z., Petrovski, B., Jankovic, M., Zrilic, M., Danicic, D. (2011). Determination of fatigue crack growth parameters in the welded joint of HSLA steel, *Structural integrity and life*, vol. 11, no.3, p. 183-187.

[12] Burzic, M., Kutin, M., Puharic, M., Adamovic, Z. (2007). An effect of service conditions to the behavior of welded joint of the alloyed steel 13 Cr Mo 4 4 (Č.7400), *Tehnička dijagnostika*, vol. 6, no. 2, p. 19-25.

[13] Popovic, O., Prokic-Cvetkovic, R., Sedmak, A., Buyukyildrim, G., Bukvic, A (2011). The influence of buffer layer on the properties of surface welded joint of high-carbon steel, *Materiali in tehnologije /Materials and technology,* vol. 45, no. 6, p. 579- 584, 2011.

[14] Camagic, I., Burzic Z., Cvetkovic, S. (2008). The usage of the fracture mechanics in determining the growth parameters of the fatigue crack for particular areas of a welded joint, *Welding & Welded structures*, vol. 53, no. 3, p. 97-103.

[15] ASTM E647. (2002). *Standard Test Method for Measurement of Fatigue Crack Growth Rates*, Annual Book of ASTM Standards, ASTM.