INFLUENCE OF LOADING REGIMES AND OPERATIONAL ENVIRONMENT ON FATIGUE STATE OF COMPONENTS OF TURBINE AND HYDROMECHANICAL EQUIPMENT AT HYDROPOWER PLANTS

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Abstract: Horizontal Kaplan turbines, were installed in 10 generating sets units at „DJERDAP 2“. After 163.411 hours of operation, the fracture of the hydro-electric generating set A6 turbine shaft in the area of high stress concentration occurred, at the transition radius between the flange and the runner hub. In this paper the results of the analytical calculation regarding the strength of the turbine shaft are presented and influence of the corrosive environment, as well as tests regarding the fatigue. Tensile tests under constant amplitude loading were carried out on smooth specimens in order to determine fatigue properties of the base material, as well as bending tests on notched specimens in order to determine fracture mechanics parameters, or correlation between the crack growth rate da/dN and the stress intensity factor ΔK. It has been established that stress values were higher than allowable values, which led to the occurence of many cracks due to fatigue corrosion. One of those cracks caused the fracture.

Key words: turbine shaft, stress concentration, corrosion, fatigue, crack

UTICAJA REŽIMA OPTEREĆENJA I RADNE SREDINE NA ZAMOR DELOVA TURBINSKE I HIDROMEHANIČKE OPREME HIDROELEKTRANA

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Abstract: Na deset agregata „ĐERDAP 2“ ugrađene su horizontalne Kaplan turbine. Posle 163411h rada došlo je do loma vratila turbine agregata A6 u zoni velike koncentracije napona, na mestu prelaznog radijusa između prirubnice i glavčine radnog kola. U radu su dati rezultati analitičkog proračuna čvrstoće vratila turbine pri uticaju korozione sredine i ispitivanja na zamor. Ispitivanja na zamor izvršena su zatezanjem glatkih epruveta sa konstantnom amplitudom opterećenja da bi se utvrdile zamorne osobine osnovnog materijala i ispitivanja savijanjem epruveta sa zarezom u cilju utvrđivanja parametara mehanike loma, odnosno zavisnosti brzine rasta prsline da/dN i opsega delujećeg faktora intenziteta napona ΔK. Utvrđeno je da su vrednosti napona iznad dozvoljenih, što je dovelo do većeg broja prslina usled zamorne korozije pri čemu je jedna od njih izazvala lom vratila.

Ključne reći: vratilo turbine, koncentracija napona, korozija, zamor, prslina

1. INTRODUCTION

Turbine and hydro-mechanical equipment of hydropower plants is subjected to loads that occur during the fabrication of parts and equipment assembly (residual stresses), as well as during the process of performing functional tasks (stationary and non-stationary loading) and during a disturbed process of exploitation (non-stationary dynamic loading). By taking into account the influences of the operational environment and exploitation (corrosion, erosion, cavitation), it is clear that loading of certain components and of the equipment as a whole cannot be expressed by a simple mathematical function, in other words it cannot be fully presented by a model in which the parameters uniformly change with the change of operational conditions. Therefore, only testing of components and structures enables the assessment of their state. That is how necessary data for determination of causes of material degradation and degradation of welded joints, as well as for the assessment of the correlation between individual components and for the determination of functionality and reliability of equipment operation is obtained.

Horizontal Kaplan turbines, made in Russia, were installed in 10 hydro-electric generating units at „DJERDAP 2“, Figure 1 [1]. Nominal power of each is 28 MW.

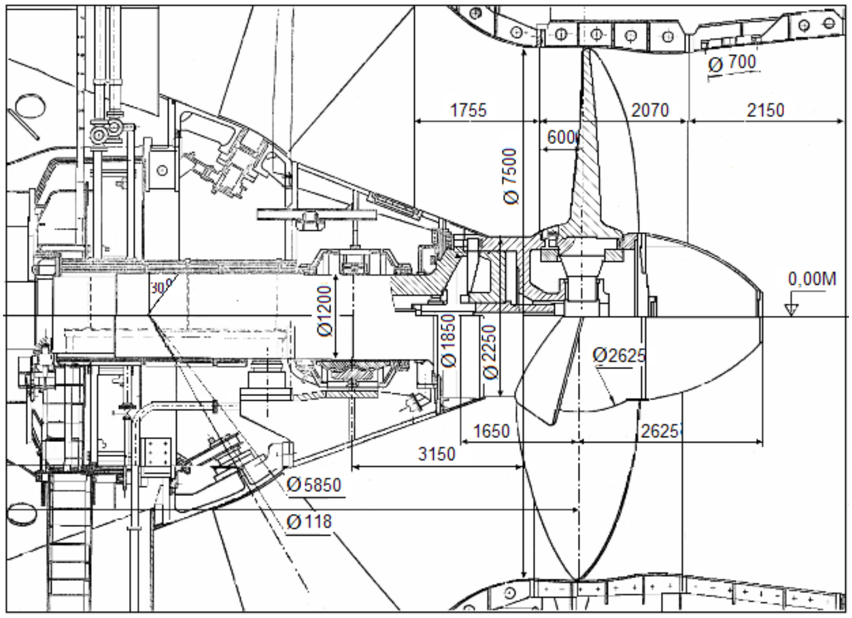


Figure 1. Appearance of the Kaplan turbine, nominal power 28 MW

Taking into account that the fatigue began to occur at many components and structures of turbine and hydromechanical equipment, the researches regarding the influence of the loading regime, operational environment and type of damage on their integrity have been conducted.

These researches have been initiated because of the fracture of the hydroelectric generating set A6 turbine shaft in the area of high stress concentration, at the transition radius R80 between the flange and the runner hub, Figure 2. During the exploitation under high-cycle fatigue loading conditions in the corrosive environment the initial cracks occured that later merged and formed 20-30 mm long cracks, which was being confirmed by the presence of corrosion products at the smooth fracture surface. When the size of the bearing surface of the turbine shaft cross-sectional area, in the zone of crack growth, fell below the critical value, the fracture occurred. That part of the fracture surface is wrinkled and free of corrosion products. Also, cracks were detected on shafts of other turbines, of various lengths and depths, which could be repaired through the use of an adequate procedure for repair welding.

Basic parameters of installed generating sets PL-15/826-G-750 are: maximum strain – 12,75 m, engineering strain - 7,45 m, minimum strain – 5 m, turbine power at the engineering strain – 28 MW, diameter of the runner – 7500 mm, number of revolutions - 62,5 min^{-1}, number of runner blades – 4. Basic components are: GR – generator rotor, GS – generator shaft, TS – turbine shaft, R – runner, R1, R2 and R3 – radial bearings, A – axial bearing, figure 2. Hollow turbine shafts have been assembled by welding together 3 separate parts. Cylindrical parts were made of steel 20GS, while the flange area and flange itself were made of steel 20GSL.

Fatigue is the progressive and localized damage of the material structure that occurs when the material is subjected to variable loading at nominal stresses that cause the failure. Maximum values of stress which cause the occurrence of fatigue are mostly significantly lower than the value of tensile strength, and could as well be lower than the value of yield strength.

Fatigue under corrosive conditions is a process of metal damaging due to the occurrence of initial cracks and their growth caused by variable loading. One of the components could be more influential than the other (fatigue or corrosion), but generally both are significant. Influence of loading frequency is closely connected to dependency of corrosion on time, while the effect of geometric stress concentration should also be taken into account. Corrosive medium reduces the service life in comparison to the situation when the medium is air, because it's not only that the notch acts as a stress concentrator, but the effect of geometric stress concentration is harmful as well.

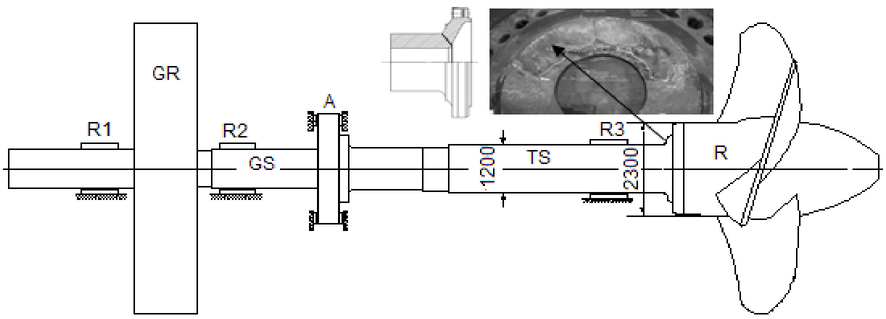


Figure 2. Appearance of basic components of the generating, appearance of the fractured surface

Contemporary concept of determination of service life for components and structures, apart from the knowledge regarding their shape, dimensions, fabriction technology, properties of operational and critical strains, or in other words standard Wöhler curves for the basic dynamic endurance of material and spectres of operational stresses, also requires the knowledge regarding the process of degradation due to fatigue. Process of fatigue degradation is very complex and still insufficiently explored. This multi-step process (submicroscopic, microscopic and macroscopic) unfolds in 3 stages: period until the occurrence of the initial crack, crack growth and fracture.

That's why nowadays various hypotheses regarding the fatigue process are being used for the practical calculations that refer to the assessment of service life, which are based on the assumptions and on the calculation of damage accumulation.

These hypotheses in a simplest way define the following:

- rate of damage progression during one cycle of alteration of the operating stress with the specified amplitude,
- measure of damage accumulation, being caused by a certain number of alterations of operating stresses with various amplitude levels.

On the basis of monitoring of damage progression, all hypotheses could be divided into 2 categories:

- hypotheses based on the fatigue damage accumulation,
- hypotheses based on laws of crack growth rate.

Damage accumulation hypotheses could be divided into fundamental and phenomenal. Fundamental hypotheses embrace the whole fatigue process in a complex way, and on the basis of established criteria regarding the fatigue mechanism predict the dependency of stress on the number of cycles, $\sigma = \sigma$ (N), for components subjected to variable loading. Phenomenal (cumulative) hypotheses are not deeply rooted in physics, and are based on fatigue line for the specific component and on the measure of damage (D). Fatigue line is being obtained through the correction of a great number of geometric, technological, exploitational and other parameters.

Phenomenal hypotheses take into account the initial crack that already exists and define the process of material damaging through crack growth. Expressions for the crack length (a) and its critical value when the fracture occurs (a_k) are based on fracture mechanics theory. Nevertheless, the crack growth rate depends on the crack growth increment per one stress cycle (*da/dN*). This rate is being obtained on the basis of experimental data gathered during the monitoring of the fatigue process.

2. ANALYTICAL AND NUMERICAL CALCULATION OF STRESS STATE OF THE TURBINE SHAFT

Turbine shaft, shown in Figure 3 (F-flange), 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 tend to 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.

Cyclic loads, to which the turbine shaft is subjected, in combination with the corrosive environment (leakage of water through the seal, poor execution and non-renewal of the corrosion protection) caused the occurence 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) [2].

2.1 Load Analysis for the Critical Cross-Section of the Turbine Shaft

Calculation regarding the critical cross-section of the shaft (positioned at the end of the cylindrical part of the shaft) has been carried out through the use of the Theory of Elasticity and data provided by the manufacturer (LMZ, Saint Petersburg, Russia).

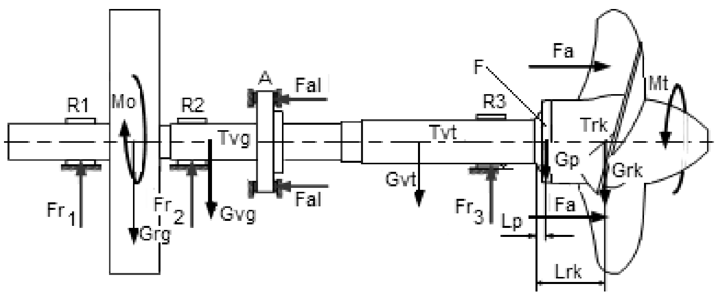


Figure 3. Turbine shaft with loads that occur on the hydro-electric generating set

Critical cross-section of the turbine shaft is subjected to [2]: axial hydraulic force $F_a = 5{,}5426 \cdot 10^6$ N, according to the data provided by the turbine manufacturer, moment of torsion $M_t = 4{,}278 \cdot 10^6$ Nm, bending moment that 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

$M_b = 3{,}3777 \cdot 10^5$ Nm, according to the data provided by the turbine manufacturer and bending moment that occurs due to the weight of the runner and weight of the part of the flange as far as the critical cross-section $M_b = 1{,}9649 \cdot 10^6$ Nm.

2.2 Analytical Calculation of Static Stresses in the Critical Cross-Section of the Turbine Shaft

On the basis of loads in the critical cross-section [2], the following stresses were obtained: tensile stress due to the action of the axial hydraulic force $\sigma_t = 14{,}3$ MPa, 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 $\sigma_b = 22.52$ MPa, torsional stress $\tau = 20.85$ MPa and equivalent static stress at the critical cross-section $\sigma_{es} = 55{,}6$ MPa.

2.3 Numerical Calculation of the Stress State in the Critical Cross-Section of the Turbine Shaft

Calculation of stress state for the turbine shaft with the transition radius R80 between the cylindrical and flange area of the shaft has been carried out by turbine manufacturer LMZ (Russia), UCM Resita (Romania), Institute for Materials Testing (Serbia), LOLA Institute (Serbia) and Faculty of Mechanical Engineering, University of Belgrade (Serbia). All calculations showed that the values of bending stresses, which occur due to the action of the load and corrosion fatigue, including stress concentration factors, are higher than 25 MPa for flanges subjected to "corrosive water" and can cause the occurence of surface cracks at the transition radius between the cylindrical and flange area of the shaft.

3. FATIGUE UNDER CYCLIC LOADING WITH VARIABLE AMPLITUDES

3.1 Fatigue Tests Performed on Specimens by Tensioning with the Constant Loading Amplitude

Fatigue tests that refer to the base material of the turbine shaft have been carried out through the use of the high-frequency pulsator „AMSLER”, in accordance with standard GOST 25.502/79. Test results that refer to residual dynamic strength (σ_{-1}), for the variable load with the coefficient of asymmetry $R = \sigma_{min}/\sigma_{max} = -1$ and boundary number of cycles $N = 2x10^6$, are shown in Figure 4.

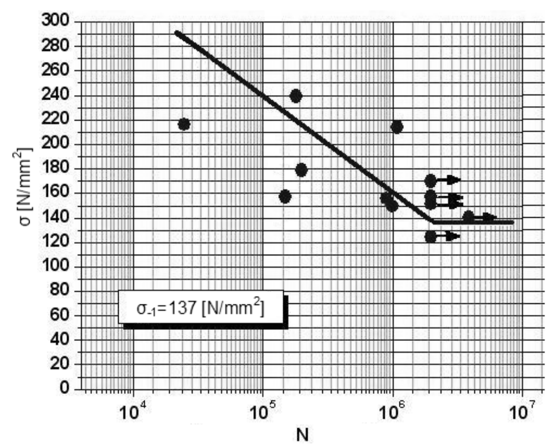


Figure 4. Dependency of fatigue strength σ on the number of cycles N (Wöhler’s curve)

3.2. Calculation of the Cyclic Stress at the Critical Cross-Section

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:

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

where: W_r - moment of resistance per length unit of the critical cross-section, D – outer diameter of the shaft, d – inner diameter of the shaft, α_b = 1,98 - stress concentration factor during bending for

$$\frac{D_f}{D} = \frac{2300}{1200} = 1,916 \text{ and } \frac{R}{D} = \frac{80}{1200} = 0,066 \tag{2}$$

where: D_f – diameter of the flange

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:

$$S_\sigma = \frac{\sigma_{-1} - \psi_\sigma \cdot \left(\sigma_m + \sigma_{R_0}\right)}{\sigma_a} \tag{3}$$

where: σ_{-1} = 26,5 MPa - residual corrosion fatigue strength of steel 20GSL during the action of the alternating variable load in the corrosive environment, ψ_σ - coefficient that represents the ratio of the fatigue strength σ_{-1} and tensile strength R_t, σ_m – maximum value of static exploitation stresses at the calculated cross-section, σ_a – amplitude of cyclic stresses, σ_{RO} - residual stresses present after casting and heat treatment have not been taken into account (σ_{RO} = 0 MPa) because there were no exact values available.

$$\psi_\sigma = \frac{\sigma_{-1}}{R_t} = \frac{26,5}{480} = 0,0552 \tag{4}$$

Residual corrosion fatigue strength is being determined experimentally by inspecting the samples in the water and correcting the obtained results through the use of dimensional factors. For this analysis experimental results regarding the testing of 20GSL material during the calculation process for the cover of the runner for HPP „ĐERDAP 1“ [3] have been used. Obtained equation contains the correction factors:

$$\log\sigma_{-1} = A - B \cdot \log N$$
$$\log\sigma_{-1} = 2.787 - 0,155 \cdot \log N \tag{5}$$

where: N – true number of loading cycles.

$N = n \cdot T = 62,5 \cdot 60 \cdot 163411 = 0,63 \cdot 10^9$ ciklusa
(6)

where: n = 62,5min^{-1} - number of revolutions per minute of the shaft, T = 163411 h - service lifetime of the hydro-electric generating set until the breakdown.

After placing adequate values into the equation the following is obtained:

$$\log\sigma_{-1} = 2.787 - 0,155 \cdot \log\left(0,63 \cdot 10^9\right)$$
$$\log\sigma_{-1} = 1,423 \tag{7}$$
$$\sigma_{-1} = 26,5 MPa$$

Factor of safety is less than S_σ = 1,1, the value predicted by the manufacturer's designation, a factor of safety in relation to corrosion fatigue:

$$S_\sigma = \frac{\sigma_{-1} - \psi_\sigma \cdot \left(\sigma_m + \sigma_{R_0}\right)}{\sigma_a} = 0,96 \tag{8}$$

3.3 Possibility of Assessment of Service Life for the Turbine Shaft Based on Linear Damage Accumulation Hypothesis

Operating regimes vary during the exploitation, and for each one of them service life and value of static and dynamic stresses on the turbine shaft should be determined. Fatigue tests based on stress spectrum are extremely expensive, due to the price of the equipment and duration of the experiment. When there are no possibilities available for the conduction of an experiment, the hypotheses based on fatigue damage accumulation are being used, which have nothing but Wöhler's curve as a starting point. The most frequently used hypotheses that refer to damage accumulation, through the use of which the service life of structures is being calculated, are the initial linear damage accumulation hypothesis by Palmgren – Miner and modified linear damage accumulation hypotheses by Corten – Dolan, Heibach, Sorensen – Kogaev, which were attempting to increase the precision of the equation for determination of the overall number of loading cycles until the fatigue fracture occurs, Figure 5 [4].

According to the Palmgren–Miner hypothesis that refers to linear damage accumulation, the fracture occurs when:

$$\sum_{i=1}^{i=j} \frac{n_i}{N_i} = 1 \tag{9}$$

where: i – load level, j – number of levels of amplitude stresses σ_{ai} in the spectrum, with amplitudes higher or equal to the amplitude of residual fatigue strength, n_i – number of applied load cycles of type i, N_i – number of cycles of stress changes until the occurrence of the fracture according to the fatigue curve for an adequate operating stress amplitude σ_{ai}, which is being obtained from Wöhler's curve:

$$N_i = N_{-1}\left(\frac{\sigma_{-1}}{\sigma_{ai}}\right)^m \tag{10}$$

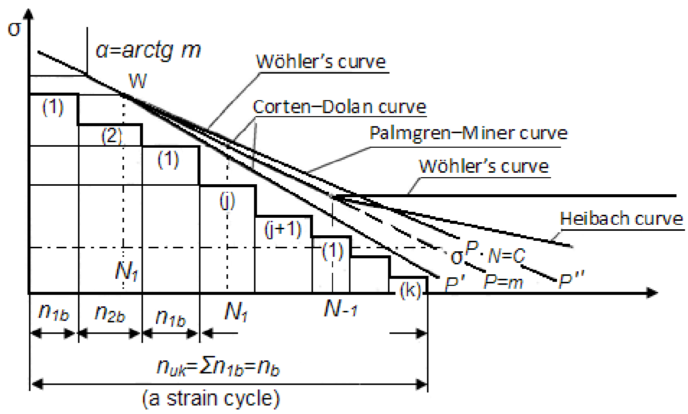


Figure 5. Spectrum of operating stresses the illustration of linear hypothese

From the above mentioned it is evident that, for the assessment of service life (N_i) for an equipment part or a component of a structure, it is sufficient to know only one stress level and number of cycles in the spectrum, while for the rest of stress levels numbers of cycles N_i are being taken from

Wöhler's curve. Mean value of residual fatigue strength for steels could be taken with a boundary number of loading cycles $N = 10^6 - 10^7$ and value of parameter $m = 6 - 9$.

With multi-step loading of turbines in exploitation, amplitudes and mean values of stress could change from cycle to cycle, and that's why such processes can not be described as previously. That fact led to the development of the procedure for the description of irregular changes of loads by stress spectrum, obtained on the basis of statistical processing of random processes.

Operating strength σ_{OS} is the highest value of all variable amplitude stress values in the stress spectrum, which lead to the fracture after N_{OS} changes. All changes are included in the number of changes N_{OS}, large and small, but it should be noted that the relative contribution of certain changes is the same as within the adequate stress spectrum. So, if the structure is subjected to the variable stress σ_1 which causes the fracture after N_1 changes, this stress presents fatigue strength, while if the same stress σ_1 is only the highest of stresses in the stress spectrum, a larger number of cycles is needed for the fracture to occur ($N_{OS} > N_1$). This relation is graphically presented in Figure 6, while equations for the assessment of service life, according to Palmgren – Miner hypothesis which refers to linear damage accumulation, are (11) and (12). Gasner and his collaborators have developed step – shaped stress spectrum in 8 levels, with $0{,}5 \times 10^6$ loading cycles.

$$N_i = N_0 \cdot \left(\frac{\sigma_{OS}}{\sigma_i} \right)^m \tag{11}$$

$$N_{P-M} = \frac{\sum_{i=1}^{j} n_i}{\sum_{i=1}^{j} \frac{n_i}{N_i} \left(\frac{\sigma_i}{\sigma_{OS}} \right)^m} \tag{12}$$

It is evident, taking into account the above mentioned, that tests performed on the turbine shaft regarding the fatigue primarily depend on probability calculation, which requires the following:

- knowledge of the load spectrum for the shaft, in other words knowledge of stress amplitudes for every spectrum level,
- knowledge of the boundary state, expressed in the form of the service life curve or of the strength of the shaft during exploitation,
- possibility of comparing the boundary state with operating stresses, in other words determination of the safety factor.

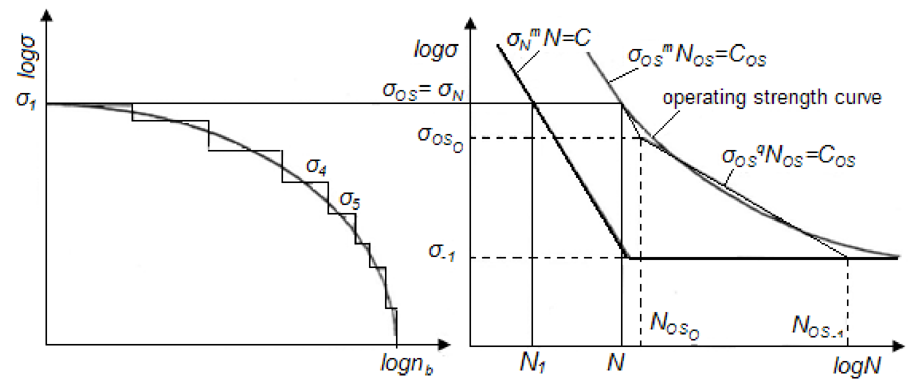


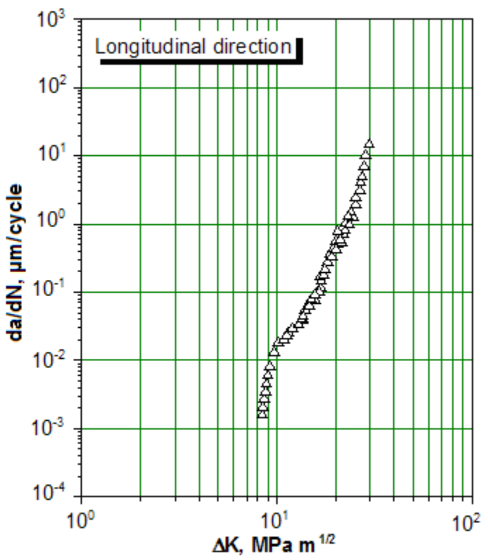
Figure 6. Operating strength curve compared to Wöhler's curve and stress spectrum

3.4 Fatigue Crack Growth Rate Tests, Depending on the Range of the Stress Intensity Factor

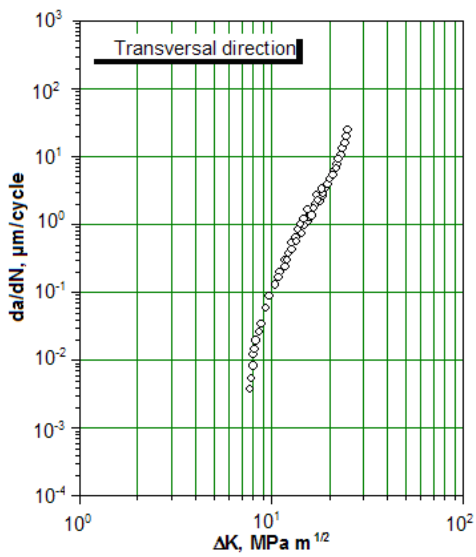
Basic improvement which was introduced by fracture mechanics in the area of fatigue of materials was the analytical separation of the fracture on the period of initiation, during which the crack initiates, and the period of growth or propagation during which the crack length reaches the critical value at which the sudden fracture occurs.

Behaviour of the material subjected to alternating loading in the presence of a crack is defined by the following parameters, which are being determined through fatigue crack growth analysis: fatigue crack growth rate (da/dN) and minimum critical stress intensity factor that causes no crack growth or fatigue threshold (ΔK_{th}). Analysis of stress state and deformations on the tip of a fatigue crack by the use of linear-elastic fracture mechanics for stable crack growth is being shaped by Paris - Erdogan equation, which is applicable for all metals and alloys (eq. 13). Results of tests performed in order to determine crack growth rate (da/dN) in relation to stress intensity factor (ΔK) are shown in Figure 7 and Table 1, [6].

$$da / dN = C \cdot \left(\Delta K \right)^{m} \tag{13}$$



a) Longitudinal direction of the shaft flange casting



b) Transversal direction of the shaft flange casting

Figure 7. Diagram of the dependence between crack growth rate and stress intensity factor range

Table 1. Fracture mechanics parameters for specimens taken in two different direction from the casting

Specimen	Fatigue threshold ΔK_{th}, MPa $m^{1/2}$	Coefficient C, $(m/cycle)/(MPa\sqrt{m})^{m_P}$	Coefficient m_p	da/dN, m/cycle at ΔK=10 MPa $m^{1/2}$
Longitudinal	8,7	$3.0 \cdot 10^{-11}$	3.14	$5.62 \cdot 10^{-08}$
Transversal	7,4	$3.2 \cdot 10^{-11}$	3.10	$6.36 \cdot 10^{-08}$

Obtained results for fatigue threshold ΔK_{th} indicate that the casting of the flange area of the turbine shaft in the longitudinal direction (crack is transversely oriented) is more resistant to the propagation of the existing crack, which confirms the conclusions reached through the analysis of the fracture area of the turbine shaft. Effect of notch orientation on fatigue crack growth rate da/dN is directly related to parameters in the Paris equation, coefficient C and exponent m. For the analysis the stress intensity factor range $\Delta K = 10$ MPa $\cdot$ $m^{1/2}$ has been taken, because that value resides in the area of stable crack growth in da/dN versus ΔK graph, for which the Paris law [5] is applicable.

A comparison of a number of loading cycles until the critical length of the crack was reached, determined on the basis of the dependency between the crack growth rate and the stress intensity factor ($N_k = 2.78 \times 10^6$), as well as on the basis of the number of loading cycles until the occurrence of shaft fracture after 163.411 hours of turbine A6 operation with a frequency of $1,04 s^{-1}$ ($N=63 \times 10^9$), showed that anti-corrosion protection slowed down the process of formation of initial cracks [6].

4. CONCLUSION

On the basis of theoretical considerations, testing results regarding the 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 of the hydro-electric generating set nr. 6 before its expected service life passed occurred due to the inadequate structural solution regarding the fabrication of the shaft, referring to the following:

- high stress concentration on the transition radius of the flange area of the turbine shaft and operating in a corrosive environment, which caused the occurence of initial cracks in that area,
- 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 and other components of stress to grow beyond acceptable values,
- inadequate structural solution concerning the seal caused the exposure of the flange area of the shaft to the corrosive environment (leaking water),
- corrosion protection was poorly executed and not renewed,
- absence of periodic inspections by non-destructive testing methods.

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