Integrity and life estimation of turbine runner cover in a hydro power plant

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ABSTRACT. This paper presents integrity and life estimation of turbine runner cover in a vertical pipe turbines, Kaplan 200 MW nominal output power, produced in Russia, and built in six hydro-generation units of hydroelectric power plant „Đerdap 1" in Serbia. Fatigue and corrosion-fatigue interaction have been taken into account using experimentally obtained material properties, as well as analytical and numerical calculations of stress state, to estimate appropriate safety factors. Fatigue crack growth rate, da/dN, was also calculated, indicated that internal defects of circular or elliptical shape, found out by ultrasonic testing, do not affect reliable operation of runner cover.

KEYWORDS. Hydro power plant; Runner cover; Fatigue; Corrosion.

INTRODUCTION

Designing, construction and running hydro power plants is a complex task. Due to limited possibilities of periodic inspections, hydro turbines and their components are designed for at least 40 years of operation. Therefore, extensive researches and testing of hydro power plant equipment have been carried out all over the world. Turbine and hydromechanical equipment testing has been introduced recently in Serbia as well. Special attention has been given to the problem of reduced material plasticity, as explained below.

Along with experimental tests carried out on the cover, made of cast steel 20GSL (GOST), tests were performed in order to determine mechanical properties and fracture mechanics parameters. Test results indicated large dispersion of material plasticity, i.e. elongation (A5) and contraction (Z), [1,2]. Namely two specimens met the demands of the standard (A_5 =

23% and 27%), while two other had significantly lower values of elongation (A_5 = 8% and 9%). Obtained values of fracture mechanics parameters (critical stress intensity factor - K_{Ic}, critical fatigue crack length - a_c, fatigue threshold - ΔK_{th}, coefficient in Paris equation - C, exponent in Paris equation - m_p, fatigue crack growth rate - da/dN) are presented in Tab. 1, as shown also in [1,2].

Specimen	K_{Ic} [MPa√m]	a_c [mm]	ΔK_{th} [MPa√m]	C	m_p	da/dN [m/cycle]
With reduced plasticity	46.3	9.3	7.4	$5.7 \cdot 10^{-11}$	3.15	$6.36 \cdot 10^{-08}$
With adequate plasticity	50.4	8.7	3.0	$3.0 \cdot 10^{-11}$	3.02	$5.11 \cdot 10^{-08}$
Minimum allowed value of K_{Ic} for 20GSL at temperature below 0°C is K_{Ic} = 41 - 44 MPa·m$^{1/2}$						

Table 1: Fracture mechanics parameters at 23°C, for the stress intensity factor range ΔK = 10 MPa√m.

STRESS STATE

Turbine runner cover at the hydro power plant "Djerdap 1" is presented in Fig. 1.
Loading is defined for normal operation conditions, comprising combined action of pressure, axial force and torsion moment, as explained in [1]. Finite element mesh for axisymmertic model is shown in Fig. 2. The results, indicating max. stress 81.1 MPa, is shown in Fig. 3.
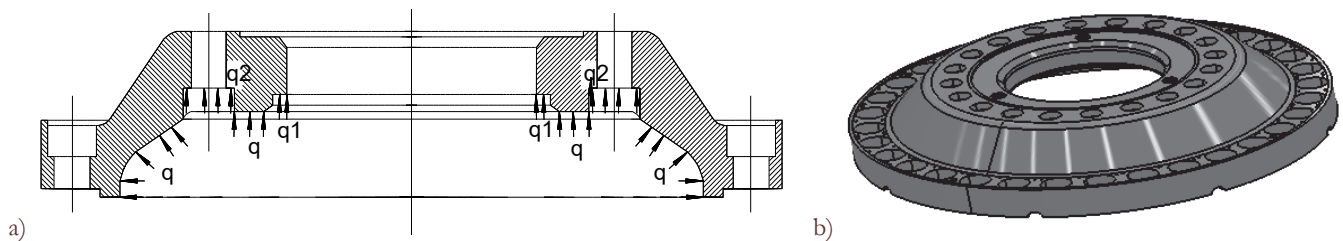

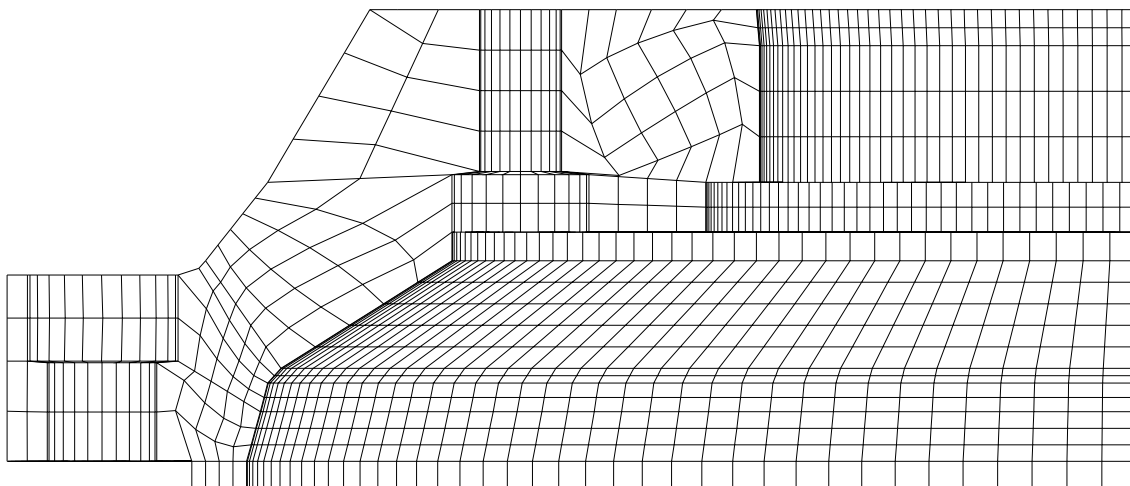Figure 1: Vertical Kaplan turbine, with nominal output power of 200 MW.
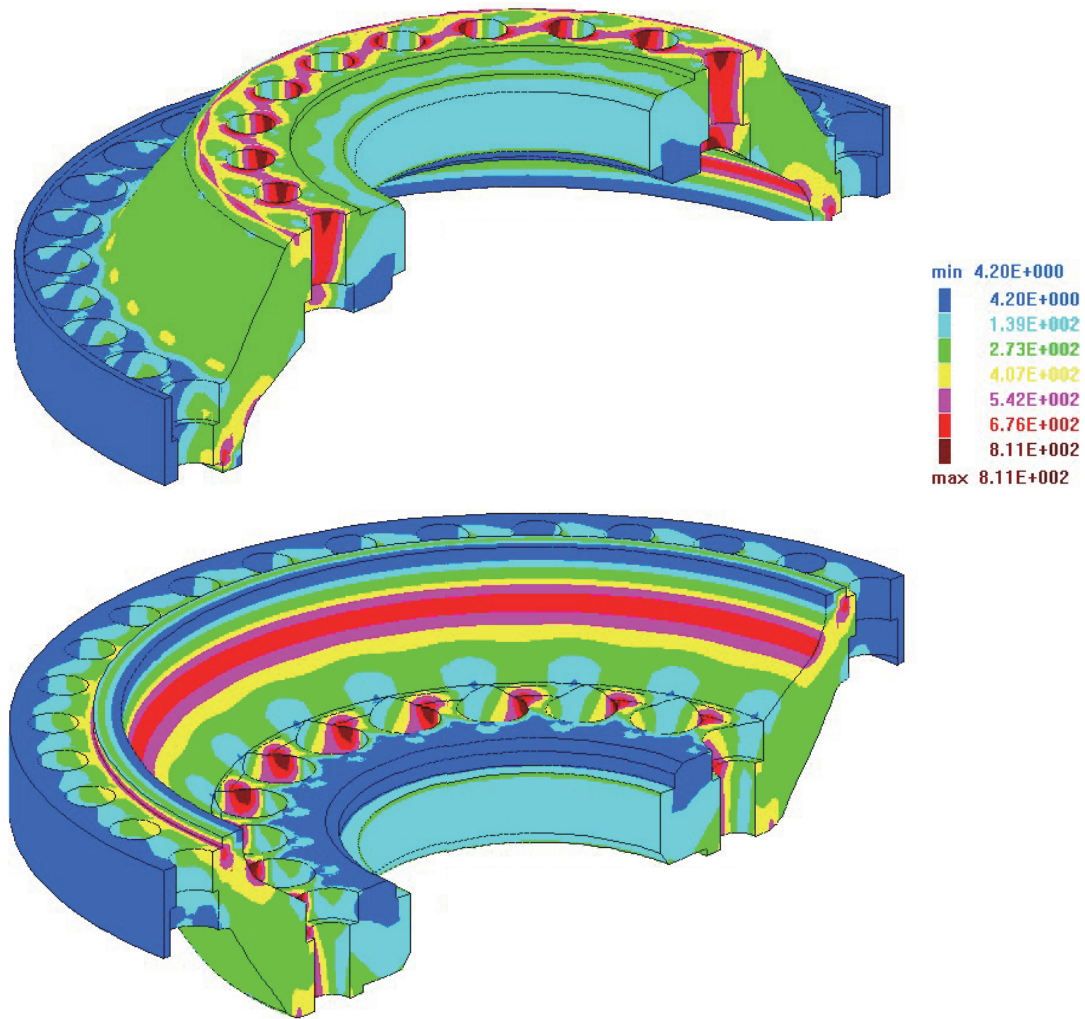

Figure 2: Finite element mesh for axisymmetric model.

Figure 3: Equivalent stresses for combined loading (pressure, axial force, torsion).

FATIGUE AND FATIGUE-CORROSION ESTIMATION

Fatigue and fatigue-corrosion interaction are the most important aspects of turbine cover life and integrity estimation. Here, this combined effect of fatigue and corrosion is estimated by using the equation for safety factor, [3]:

$$n_\sigma = \frac{\sigma_{-1} - \psi_\sigma \cdot (\sigma_m + \sigma_{M0})}{\sigma_a}$$

where σ_{-1} is the fatigue strength, obtained by standard testing, in conditions simulating the real, i.e. in water, ψ_σ coefficient of loading asymmetry, equal to ratio of maximum fatigue strength to the maximum static strength (470 MPa in this case); σ_m mean cycling stress; σ_{mo} residual stress – in this case $\sigma_{mo} = 60$ MPa, [1]; σ_a amplitude of cycling stress.

Fatigue strength depends on number of cycles and can be evaluated by using logarithm curve, obtained from Weller's curve:

$$\lg \sigma_{-1} = A - B \cdot \lg N$$

In the case of new material:

lg (σ_{-1}) = 2.787 − 0.155 × lg (N).

Taking into account 1,000 cycles per year (shut down - start up) and 40 years of designed life, one should use 40×10^3 as relevant number for fatigue strength estimation for material with adequate plasticity:

lg σ_{-1} = 2.787-0.155·lg N = 2.787 - 0.155·lg($40 \cdot 10^3$) = 2.073,

σ_{-1} = 118.5 MPa;

For the turbine under consideration the maximum stress at shut down and start up is σ_{max} = 81.1 MPa, thus the amplitude stress σ_a=40.55 MPa.
Coefficient of sensitivity to cycle asymmetry is

$$\psi_\sigma = \frac{\sigma_{-1}}{\sigma_{\hat{a}}} = \frac{118.5}{470} = 0.25$$

whereas the corrosion-fatigue safety coefficient is:

$$n_\sigma = \frac{\sigma_{-1} - \psi_\sigma \cdot (\sigma_m + \sigma_{MO})}{\sigma_a} = \frac{118.5 - 0.25 \cdot (40.55 + 60)}{40.55} = 2.30$$

Taking into account 5% of the amplitude as the usual value for corrosion fatigue, one gets:

$$\sigma_m = 81.1\,MPa$$
$$\sigma_a = 0.025 \cdot 81.1 = 2.03\,MPa$$

For the number of cycles one can get:

N = n_n·60·7000·40 = 71.43·60·7000·40 = $1.2 \cdot 10^9$ cycles,

where n_H – number of rotation/min, (n_H = 71.43 min^{-1}); 60 – minutes in an hour; 7000 – number of operating hours per year; 40 – designed life (years). Now, one can get:

lg σ_{-1} = 2.787 - 0.155·lg N = 2.787 - 0.155·lg($1.2 \cdot 10^9$) = 1.379,

σ_{-1} = 23.9 MPa;

Having in mind coefficient of sensitivity to cycle asymmetry:

$$\psi_\sigma = \frac{\sigma_{-1}}{\sigma_{\hat{a}}} = \frac{23.9}{470} = 0.05$$

safety coefficient for corrosion-fatigue strength is then:

$$n_\sigma = \frac{\sigma_{-1} - \psi_\sigma \cdot (\sigma_m + \sigma_{\hat{u}})}{\sigma_a} = \frac{23.9 - 0.05 \cdot (81.1 + 60)}{2.02} = 8.34$$

Influence of internal defects on fatigue of cast steel 20GSL is an important issue and should be carefully evaluated. Toward this aim the mechanisms of microcrack initiation and conditions of propagation of microcracks to macrocracks have been established, [2,3]. Based on test results establishment of the following empirical relation has been established:

$$\sigma_{-1}^{*} = \frac{\sigma_{-1}}{\left(1 + \beta \cdot d_{\max}\right)^{1/2}}$$

where: σ_{-1} - lower limit of fatigue strength dispersion; β – material coefficient, dmax - maximum size of the defect in cast material.

For the cast steels with defects (material with reduced plasticity), the following equation for fatigue strength holds:

$$lg\ \sigma_{-1} = 2.69 - 0.155 \cdot lg\ N$$

Based on this equation, one can conclude that defect sizes up 0.5 mm do not influence fatigue strength, whereas the maximum acceptable defect size (d = 1.5 mm) reduces fatigue strength σ_{-1} from 118.5 MPa to 91.15 MPa. Anyhow, the corrosion-fatigue safety factor is still satisfactory, $S_\sigma = 1.63$.

ESTIMATION OF SERVICE LIFE OF THE RUNNER COVER THROUGH THE USE OF FRACTURE MECHANICS

Estimation of runner cover service life through the use of fracture mechanics has been carried out according to methodology presented in paper [3]. In the area of stable crack growth, Paris' equation describes the behaviour of the material with sufficient accuracy:

$$\frac{da}{dN} = C \cdot \left(\Delta K\right)^{m_p}$$

where ΔK is the stress intensity factor range, defined by $\Delta K = M \Delta \sigma \sqrt{a}$, $M = 1.21 \pi Q$, defect shape parameter. In the case of an internal defect, measuring 6 mm in diameter, detected by ultrasonic inspection, Q=1.65, [4].
If the critical crack length is calculated for $\sigma_{max} = 81.1 + 60 = 141.1$ MPa,

$$a_{cr} = \frac{1}{M}\left(\frac{K_{Ic}}{\sigma_{\max}}\right)^2 = \frac{1}{2.38}\left(\frac{46.3}{141.1}\right)^2 = 45.2\ mm$$

number of cycles until reaching the critical size of the internal defect within the turbine runner cover, made of cast steel 20GSL with reduced plasticity (m_p=3.15, c_p=5.7·10⁻¹¹), can be calculated by the integration of Paris' equation:

$$N = \frac{2}{\left(m_p - 2\right) \cdot C_p \cdot M^{\frac{m_p}{2}} \cdot \Delta\sigma^{m_p}}\left(\frac{1}{a_0^{\frac{m_p-2}{2}}} - \frac{1}{a_{cr}^{\frac{m_p-2}{2}}}\right) = 2.35 \cdot 10^{10}$$

for $\Delta\sigma$=4.055 MPa, a_0=6 mm, a_{cr}= 45.2 mm. Taking into account number of load cycles per year period ($N_u = n_b \cdot 60 \cdot 7000$ = 71,43·60·7000 = 3·10⁷ cycles), one can estimate service life of the turbine runner cover with reduced plasticity as N/Nu=783 years.

CONCLUSIONS

Results of fatigue strength tests carried out on large specimens, as well as obtained values of fracture mechanics parameters, enabled the estimation of service life of turbine runner cover with reduced plasticity. Defects up to 0.5 mm have no influence on fatigue strength, whereas defects with acceptable value (1.5 mm) reduce fatigue strength from 118.5 to 91.15 MPa, still enabling reliable operation of the cove.

Finally, internal defect with size of 6 mm, as recorded by NDT, does not jeopardize integrity of turbine cover, since predicted fatigue life is more than 783 years.

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