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ANALYTICAL EVALUATION OF CRACK PROPAGATION FOR BULB HYDRAULIC TURBINES SHAFTS

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Rezumat. *Centralele hidroelectrice utilizează energia regenerabilă a cursurilor de apă. Turbinele hidraulice Bulb funcţionând la căderi reduse reprezintă surse excelente de energii alternative. Arborii turbinelor Bulb sunt piese masive, de formă cilindrică realizate din oţel slab aliat. Lucrarea analizează fisurile de oboseală ce au apărut în zona de racordare dintre arbore şi flanşa turbinei. Starea de tensiune din această zonă a fost analizată cu programele ANSIS şi AFGROW. Ca rezultat final, a fost stabilit numărul orelor de funcţionare până la străpungerea completă a peretelui arborelui.*

Abstract. *The Hydroelectric Power Plants uses the regenerating energy of rivers. The hydraulic Bulb turbines running with low heads are excellent alternative energy sources. The shafts of these units present themselves as massive pieces, with cylindrical shape, manufactured from low-alloyed steels. The paper analyses the fatigue cracks occurring at some turbines in the neighbourhood of the connection zone between the shaft and the turbine runner flange. To obtain the tension state in this zone ANSIS and AFGROW computing programs were used. The number of running hours until the piercing of the shaft wall is established as a useful result.*

Keywords: bulb turbines, horizontal shafts, fatigue cracks, crack propagation

1. Introduction

The horizontal shafts are more exposed to fatigue cracks than the vertical ones as a result of the variable stresses occurring at each turn. From constructive reasons, the great majority of the Power Stations have the hydro aggregates vertically oriented and the fatigue fracture is an unusual event. The exception are the station endowed with Bulb turbines, Pelton turbines with a reduced number of injection nozzles as well as the aggregates with small and very small output. For the Pelton turbine case, the shaft is permanently wetted because of jets in the turbine chamber. In this situation, at variable stresses, the Wöhler curve does not present an asymptotic tendency limit, so after a certain number of running hours, the fatigue fracture occurs. This phenomenon is known as corrosive fatigue. Many years ago, through oral reports, I have heard about an extremely interesting breakdown of the horizontal

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shaft of a Pelton turbine. The runner was overhang disposed and the shaft was working in small corrosion conditions (permanent dense fog but also droplets or even small water jets washed continuously the shaft). When the fluctuating stresses have great values, a tendency of multiple crack inceptions appear. For the shaft in discussion, in the same cross section there were simultaneously, without being observed, three fatigue cracks disposed approximately at 120° (see Figure 1). After the extension of these cracks, the shaft was fractured and the aggregate suffered severe damages.

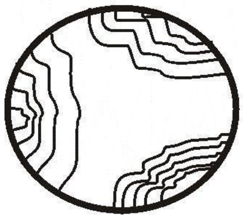

Fig. 1. Pelton turbine shaft fatigue fracture.

While for Bulb turbines, the shaft is placed into a case, well sealed off and heated by the electric generator, it is considered that the fluctuating stresses take place in the absence of corrosion, the material has “fatigue limit” and fatigue failure has very reduced probabilities. Our observations show that this opinion is not in conformity with the facts and for bulb turbines it appear simultaneously both corrosion and variable stresses and the material do not have a fatigue limit, failure being possible.

2. Turbine parameters, geometry and shaft manufacturing procedure

During the year 2008 we examined some turbines shafts, with the service and constructive parameters presented in Tables 1 and 2. For some aggregates, there were effected refurbishing works (HA3- 2006 + 2007; HA4-2005 and HA5-2008). During the refurbishing operations, the shaft was completely replaced. Next, we present the principal differences between the initial shafts and those refurbished. Those consist exclusively into a new manufacturing procedure.

Table 1. Bulb turbine parameters

Parameter	*Symbol*	*Value*
Net Head	H	7,8 m
Water discharge	Q	475 m^3/s
Effective power	P	32,5 MW
Turbine and Generator rotation sped	n_T	62,5 rpm
Runner diameter	D_1	7,5 m
Position of the runner weight against the shaft flange		1650 mm
Number of blades	Z	4
eight of rotating subsystem (without oil)	G_{rotor}	99,6 To
Position of the runner weight against the shaft flange		1650 mm

Initial shaft (Russian license). The shaft is constituted from three parts assembled through welding. The two half-finished parts placed near the electric generator are manufactured through forging. The half-finished flange for coupling is manufactured through casting. The machine working at final dimensions is done after welding followed by heat treatment and cheek-out. After that, the connecting zones between the flange and the main cylindrical part (zones where occurred cracks during the operation) were bring-up to the final shape through rough turning (Ra = 20 μm).

Table 2. Data regarding shaft geometry

Data	*Value*
Shaft length	7572 mm
Shaft diameter	1200 mm
Flange diameter	1700/2298 mm
Shaft weight	51.170 kg

Table 4. Running hours for the refurbished turbines (hours)

	HA3	*HA4*	*HA5*
Total R	143.647	136.397	157.279
2008	16.257	22.915	7.417

Total R - total running hours till the refurbishing

Table 3. Running hours for not refurbished turbines (hours/state)

HA1	*HA2*	*HA6*	*HA7*	*HA8*	*HA9*	*HA10*
177.560	178.594	158.336	165.563	165.804	108.109	93.908
F	F	F	N	N	F	N

N –Not controlled, F – cracks

Refurbished shaft. The half-finished shaft is manufactured entirely by forging. The employed material, the final dimensions and the machine working operations are identical with those for the initial shaft.

3. Shaft material and corrosion resistance

In Tables 5 and 6 there are presented characteristics of the employed material. From the chemical composition (Table 5) it results, that the material is light manganese alloyed steel. The low proportion of chromium and nickel (especially chromium) is inadequate to confer a good resistance to corrosion, inclusive inter crystalline corrosion. Taking into account the influence of manganese on the crystalline grains, we appreciate that the principal alloying element determines a rough structure of the flange material, especially for casted pieces (great and non-uniform dimension of the grains). Therefore, the corrosion resistance of the material is relatively low.

Table 5. Shaft material mechanical characteristics

Characteristic	*Value*
R_m	470,88 N/mm^2
$R_{p0,2}$	255.05 N/mm^2

Table 6. Shaft material chemical composition

Chemical Element	*Proportion*
C	0,16…0,22%
Mn	1…1,3 %
Si	0,60…0.80%
Cr, Ni, Cu	< 0,3%
S, P	<0.03%

Fig. 2. Spot corrosion (HA 1).

Fig. 3. Corrosion disposed on circumference (HA 8).

4. Cracks detected on turbines shafts

The verbal label „metal fatigue" describe the process of initiation and propagation of cracks because of repetitive loadings, when the value of each individual stresses is insufficient high to produce material failure. The aspects of pieces with endurance failure have the following characteristic features:

- the absence of macroscopic plastic deformations or dimensional deformations (rupture constriction, etc.);
- macroscopic, the rupture surface present two distinct zones, one with relatively smooth aspect (even burnished) characteristic for the slow speed propagation of the crack and the other having the characteristic aspect of the fragile break (coarse surface);
- the smoothed zone may present some unevenness, growing progressively from the crack inception place (the most polished zone is placed in the immediate vicinity of the crack inception); those unevenness are disposed in concentric arcs, similar the surface of a shell valve and are named "stopping lines".

After numerous turbine examinations, we reached to the conclusion that from the point of view cracks aspect, the division in three categories is useful:

- cracks with great depth and extension (see Figure 4);
- multiple but rarely small extension cracks, disposed in parallel planes;
- multiple and abundant small extensions cracks, disposed in parallel planes (see Figure 5).

The most dangerous are the great extension cracks. Figure 4 gives a typical example. Approximately in the same cross section, and at the same time, appeared a few distinct fracture lines.

Fig. 4. Great extensions cracks.

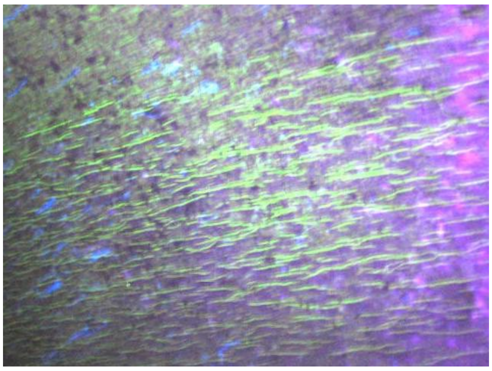

Fig. 5. Numerous small extension cracks.

In Figure 4, there are three such fissures. In time, all the fracture lines grow on both circumference and depth. The two fissures on the right side of the figure progressed very much in the depth (the thick line of the penetrated liquid) before establishing a small connecting way between them and the fracture line in the left side of the figure. Because the great depth of the fracture lines the repair work is difficult, expensive and does not give sufficient assurance. From case to case, the shaft replacement is advisable. The manner of forming and evolution of those cracks is proper to the pieces having structural faults (chromium carbides, great and heterogeneous crystalline grains) and incorrectly machined (too great roughness). From the loading point of view the variable stress amplitudes is great relatively to the mean stresses. In the continuation, only the great and deep fracture lines will be treated.

5. Crack analyses

Table 7 gives information of the fissures obtained by the UCMR specialists during the non-destructive control of the turbine shafts (two of them are presented in Figures 4 and 5). Analysing the data from Table 7, we reach to the following conclusions:

- for HA1, HA2 and HA9 the fracture length is approximately 4…5 times greater than the depth, while for HA 6 this value varies in great limits from a fissure to other;
- from the obtained ratio 2c/d, we appreciate that the crack must have an elliptic shape.

For the following computations, it is compulsory to work with a unique value for the rate d/c. The measurements undertook until now for HA1, HA2 and HA9 show values between 0.4 and 0.5 for the rate in discussion. For a depth of 7 mm at HA6 were obtained various lengths "c" between 5 and 30 mm, giving a mean of 17.5 and the ratio 0.4, close the other values. It is possible that in the critical zone the ratio between the crack depth and length to have modifications from one zone to another as result of composition and structure unevenness. A graphic representation of the disposable data is given in Figure 6 and is difficult to explain. In the future, the beneficiary must demand, in this direction, information that is more detailed.

Table 7. Results of non-destructive control

	HA1	*HA2*	*HA6*	*HA9*
Running duration, N [hours]	167105	168626	148396	101199
Crack depth, d [mm]	16.8	5	7	12
Crack length, 2c [mm]	80	20	10 - 60	60
2c/d	4,76	4	1,43-8,57	5
d/c	0.42	0.5	1.4-0.233	0.4

HA - hydro aggregate

In the following computation we adopted an elliptical fissure having the semi axes ratio of a/b= 0.5. The maximum possible depth of the fracture line is of maximum 300 mm. Even if a crack attain this depth there will not exist dramatic damages (the shaft will not break apart), but the incident will lead to massive oil leakage (for the oil commanding the blade servomotor) and in this situation the turbine must be stopped and the shaft changed.

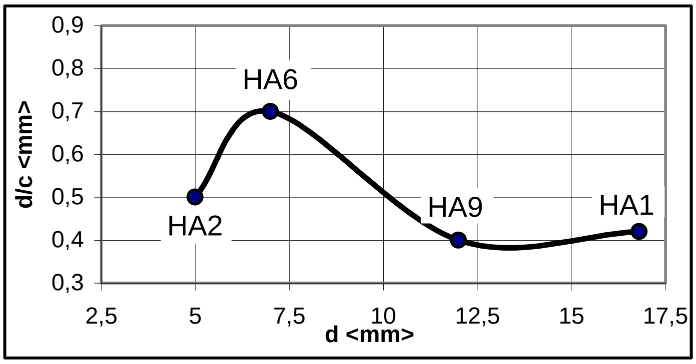

Fig. 6. Dependence of measured d/c against d.

Using the circle equations $X^2+Y^2=R^2$ and the ellipse one $\frac{X^2}{b^2}+\frac{y^2}{a^2}=1$, for arbitrary chosen abscissa we obtain the ordinate values for the circles R and r:

$$Y=\sqrt{R^2-X^2}\ ,\ Y=\sqrt{r^2-X^2} \qquad (1)$$

as well as the ordinate for the ellipses:

$$y=\frac{a}{b}\sqrt{b^2-X^2} \qquad (2)$$

The Y- ordinates of the ellipse which realize the crack „d” in relation to the origin O(XY) are:

$$Y = \left[R + (a - d)\right] - \frac{a}{b}\sqrt{b^2 - X^2} \tag{3}$$

Notations:

r ($D_i = 2\,r$) – radius/diameter of the inner circle of the shaft (300/600 mm);

R ($D_e = 2\,R$) – radius/diameter of the outer circle of the shaft in the analysed cross section (600/1200 mm);

a – ellipse minor semi-axis;

b – ellipse major semi-axis;

d – depth of the fissure;

c – length of the fissure measured on the circle periphery;

X – abscissa;

Y – ordinate measured from the origin O;

y – ordinate measured from the origin O_1;

α – angle between the radius of point (X_1, Y_1) and the ordinate.

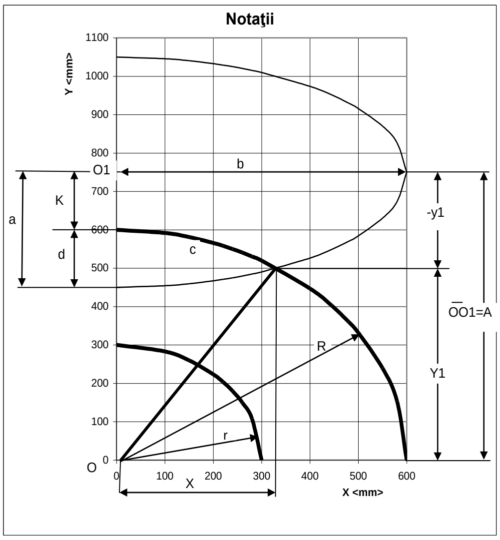

Fig. 7. Notations

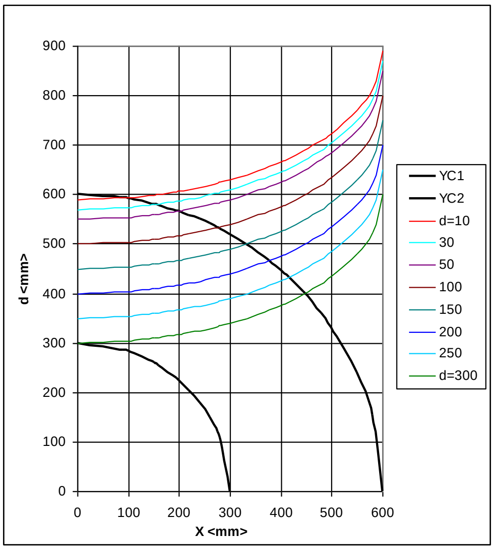

Fig. 8. Intersection shaft/cracks

To determine the crack semi-length "c" is needed the angle α (in circular measure) made by the radius, which goes through the crack end and the ordinate axis (see Figure 7). The equations are:

$$tg\alpha = \frac{X}{Y} \quad and \quad c = R\alpha \tag{4}$$

In Figure 8 is presented the ellipses family with the same value *a/b* = 0.5 for different depths "*d*", for a quarter of the shaft. The lines representing the external and internal circles of the shaft were notated with YC1 and YC2. With the obtained

Table 8. Determination of the half crack length

d	50	100	150	200	250	300
X	195	275	332	377	415	445
Y	566	533	500	467	433	399
tg alfa	0,344523	0,515947	0,664	0,807281	0,95843	1,115288
atg alfa	0,331795	0,476324	0,586154	0,679165	0,764175	0,839847
c	199	286	352	407	459	504
d/c	0,2512	0,3499	0,4265	0,4908	0,5453	0,5953

data were computed the semi-cracks length (Table 8). The variation of the ratio d/c against d is shown in Figure 9 together with the equation and the square value of the correlation coefficient. For the determination of the values d/c for small crack depth (around the measured values) was used the regression equation (given in Figure 9). The comparison between the measured crack length and those obtained through computation is given in Table 9. From the comparison a these values it results that taking the ratio *a/b* = 0.5 for the ellipse semi-axis offer covering results,

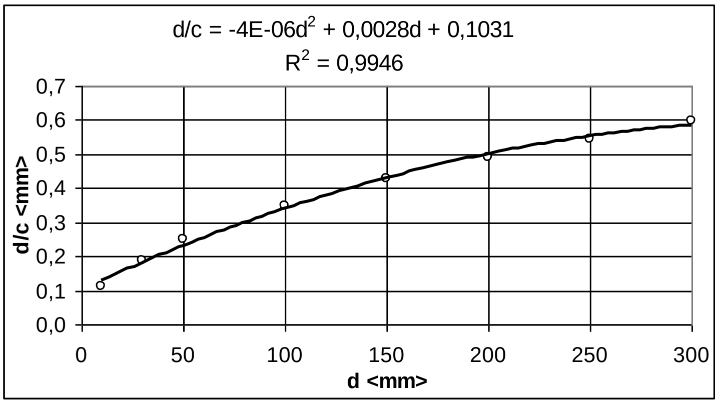

Fig. 9. Variation of d/c for the considered ellipses family.

while the computed values give greater length of the cracks than those appearing in the reality. The refinement of the computation is possible only through obtaining from the non-destructive controls data that are more precise.

Table 9. Comparison of the cracks length

d	*5*	*7*	*12*	*16,8*
d/c	0,117	0,123	0,136	0,149
c (computed)	42,735	57,141	88,155	112,743
c (real)	10	30	30	40

6. Estimation of the mean stress state in the turbine shaft

The geometric modelling of the shaft was done with the help of the program INVENTOR, imported in the FEM program ANSYS v11. The model contains 177,344 tetrahedral elements connected in 290,848 knots. In the neighbourhood of the connection zone between the flange and main shaft it was used a refined mesh. In the ANSYS program, there were successively determined: total deformation, displacements along the axis x, y, z, the nominal stresses after the same axis, the tangential stress τ_{max} and the equivalent von Mises stress.

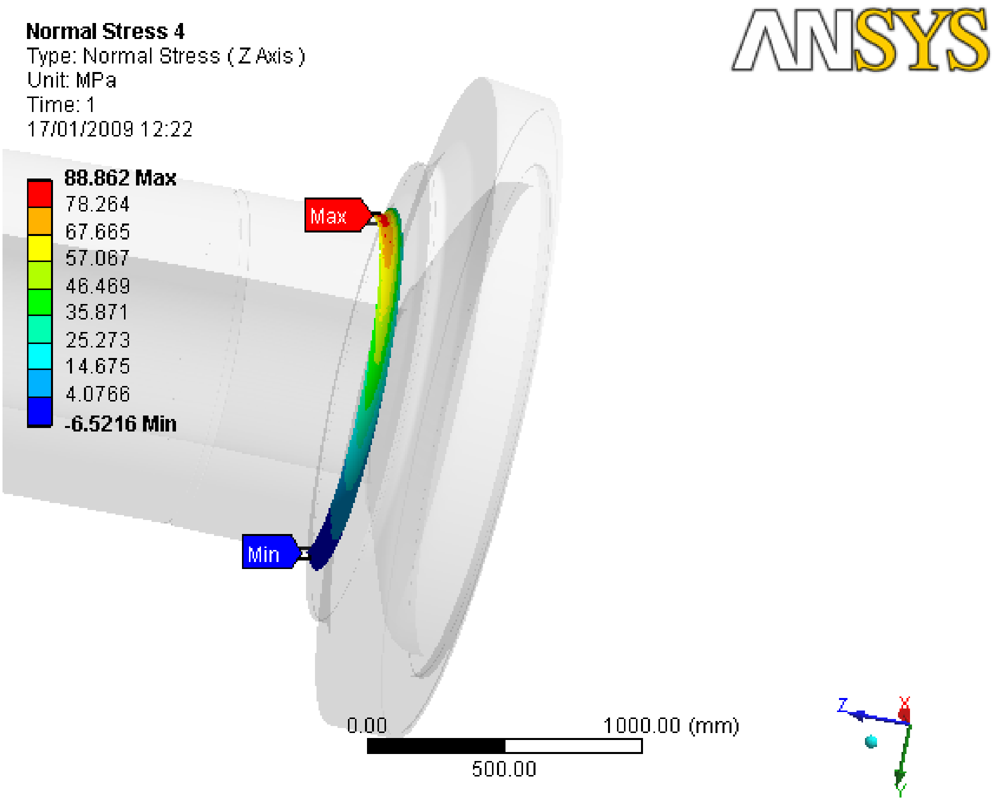

Fig. 11. Normal stress σ_z distribution.

The obtained results indicate the presence of the stress concentration at the connection between the flange and the main shaft body. The maximum equivalent stress being of 105.98 MPa is smaller than the admitted stress of 150 MPa. We consider that from the point of view of "Material strength" the design was correct. The coefficient of stress concentration in the connection zone flange-shaft, determined for the equivalent stress is:

$$k_t = \frac{\sigma_{ech,\max}}{\sigma_{ech,nom}} = \frac{105,98}{33,38} = 3,17 \quad (5)$$

7. Fatigue computations

a. Estimation of the crack initiation time through fatigue

The fatigue computation was done for the z stress component, produced through the superposition of the bending and tension. The characteristics of the loading cycle in the connection zone, resulted from the strength computations [1], using the ASNYS program are: σ_{max} = 88.86 MPa, σ_{min} = - 6.52 MPa and $R = \sigma_{min}/\sigma_{max}$ = -0.07.

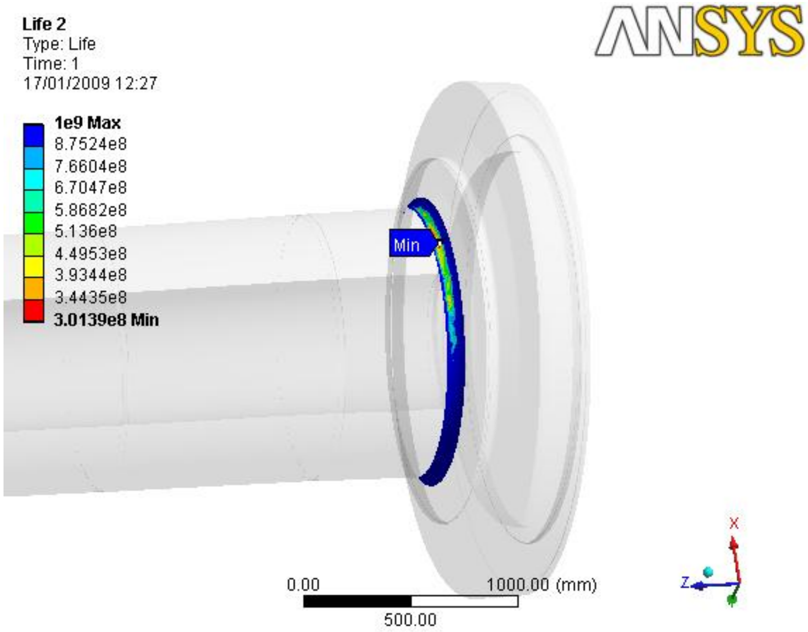

Fig. 12. Cycles number until crack initiation.

After using the fatigue module (FATIGUE TOOL) of the ANSYS v.11 program [2] resulted a minimum duration, until the fissures initiation, of $N_i = 3.0139\times10^8$ cycles, equalling 80370 running hours.

b. Number of cycles estimation for the propagation of a crack for variable stresses with constant amplitude

It must be underlined, that the final break zone is characterized through high velocities of the crack propagation. The service life, expressed through the number of cycles needed for the extension of a fissure, can be obtained from:

$$\int_{N_d}^{N_f} dN = N_f - N_d = N_r = \int_{a_d}^{a_{cr}} \frac{da}{f(\Delta K, R)} \quad (6)$$

The relation (6) was used to calculate the number of cycles N_r needed for the extension of a fissure from the detectable length a_d corresponding to N_d cycles to the critical length a_{cr} which is reached after N_f cycles. The computation can be done graphically, analytically or numerically. The analytical method is suited for a limited number of situations in which the intensity factor can be correlated with the crack length and the geometrical factors remain unchanged in the integral limits. In present, there are specialized programs for computing automatically the life duration. One of these programs is AFGROW developed by Hartner at WRIGHT-PATTERSON AIR FORCE BASE for estimating the durability of attack aircrafts components. For the fracture line propagation it was considered a piece having ring cross- section with an elliptical crack disposed on circle, Figure 8. For such geometry, Raju and Newman (1984) proposed for the stress intensity factor a solution, under the form [3]:

$$K_I = \left(\sigma_t + H\sigma_b\right)\sqrt{\pi \frac{d}{Q} F\left(d, c, D_i, D_e, \Phi\right)} \tag{7}$$

where:

- σ_t represent the tension stress applied to the shaft;

- σ_b is the bending stress;

- *H* and *F* are functions depending on the crack geometry (the crack depth and length), the thickness of the shaft wall and the frontal position of the fissure while Q is obtained from (8):

$$Q = 1 + 1{,}1464\left(\frac{d}{c}\right)^{1.65} \quad for \quad \frac{d}{c} \leq 1 \tag{8}$$

The simulation was done with AFGROW [4]. The initial crack depth d = 1 mm and crack length c = 2 mm are reached after 80370 hours in conformity with the study of fissure initiation. For the study of crack propagation, it was taken into consideration a composite loading bending plus tension, with the condition that the static load is superposed over bending resulting a pulsating cycle with σ_{max} = 88,9 MPa, σ_{min}= - 6,5 MPa , R = - 0,07; the loading amplitude remaining constant. The material constants are those of the American steel AISI 1020 comprised in the data base of the AFGROW program (C= $1.447\text{x}10^{-12}$, n = 3.6, m = 1; the breaking tenacity corresponding for the plane state of tension K_C=110 MPa $m^{1/2}$, respective for the plane state of deformation K_{IC} 77 MPa $m^{1/2}$, yield strength σ_C = 262 MPa, elastic modulus E = 206843 MPa, the Poisson's number ν = 0.3, the limit value of the intensity factor variation under which the fissure does not propagate ΔK=1,5 MPa $m^{1/2}$).

The number of hours for the fracture line propagation was added to the initiation number of hours. With the previous conditions, the crack increase until d = 16 mm, 2c = 64 mm is obtained after 153,243 hours. It is important to know that after only 159,737 service hours the crack pierces completely the shaft wall (the curve d= 300 in Figure 8 is reached).

Conclusions

1. The Bulb turbines shaft work in condition of corrosive fatigue. The atmosphere loaded with fog and water vapors is due to minor deficiencies of the sealing devices as well as to the water.
2. The crack results from fatigue phenomenon induced by the variable loads.
3. The evolution of crack propagation was obtained using the Fracture Mechanics concepts, in the linear elastic domain, in the case of bending plus tension with a pulsating cycle.
4. Using the fatigue module ANSYS v.11, we obtained a minimum duration until the initiation of fissures in the connection zone of N_i = 3.0136 10^8 cycles, equivalent with 80,370 service hours.
5. The simulation for crack increase until d = 16 mm (depth) and 2 c = 64 mm (length) lead to a service duration of approximately 153.243 hours and approximately 159737 hours until the piercing of the shaft wall, which implies the shaft replacement.
6. The obtained results are of deep interest for establishing the inspection periods for the Bulb units in the Power Station Iron Gates II.

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