RESIDUAL LIFE ESTIMATION OF A THERMAL POWER PLANT COMPONENT – THE HIGH-PRESSURE TURBINE HOUSING CASE

by

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This study focuses on the estimation of residual life of damaged thermal power plant components. The high-pressure turbine housing was chosen as an example of thermal power plant component where, during the years of exploitation, damage appeared in the form of dominant crack. Residual life estimation procedure, based upon experimental and numerical methods has been introduced and applied. Material properties were determined experimentally both at room and operating temperature, while all necessary calculations were performed by the special finite element method, so-called X-FEM. The residual life estimation of the damaged high-pressure turbine housing was performed by applying the Paris's law for crack growth analysis.

Key words: *residual life estimation, damage, X-FEM, thermal power plant component, high-pressure turbine housing, paris law*

Introduction

The high-pressure turbine housing is a highly responsible component of any thermal power plant. To maintain the reliability of such a component it is required to evaluate its residual life especially if damage appears during its exploitation. In this study, crack-like damage in the high-pressure turbine housing of thermal power plant Kolubara, has been analysed. Damage, observed during standard maintenance (fig. 1), was caused by thermo-mechanical stress, including sudden changes in the working regime.

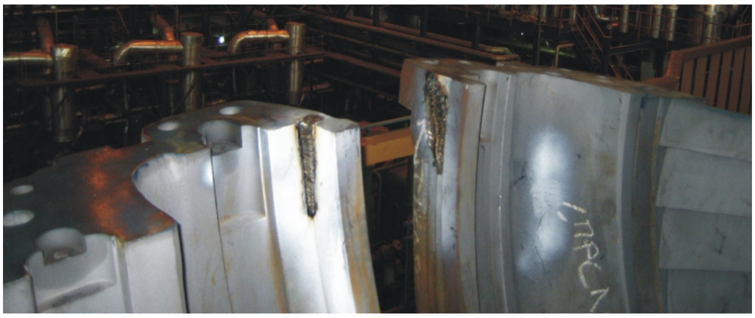

Figure 1. Example of detected and repaired cracked part of turbine housing

The procedure for residual life estimation of a damaged component involves several stages:

- monitoring of the construction during scheduled or non-scheduled maintenance (repairs),
- location of the damage as well as measurement of its dimensions,
- sampling of material from the damaged zone,
- experimental evaluation of material properties,
- numerical modeling of damaged component,
- numerical evaluation of mechanics fracture parameters – stress intensity factor, and
- estimation of residual life by applying the Paris law.

For the numerical calculation of strain and stress in a cracked body, the X-FEM (eXtended finite element method) method was used. The X-FEM methodology is becoming more and more accepted and widely used in various areas: the modeling of fluid-solid contact phenomena, including the phase transformation, the modeling of material properties of functionally graded materials, as well as for modeling of two-dimensional static and quasi-static crack growth [1-4].

From the standpoint of practical estimation of the residual life of the highest importance are the laws of fatigue crack growth [5-7]. To apply these laws, one needs the experimental data for parameters such as C and m, as defined by the standard procedure and applied here using the test specimen made from the turbine housing [8, 9].

The estimation procedure for turbine housing residual life

In structural elements with observed damages, in which there are regular changes of the load during the exploitation, the residual life is estimated by applying fatigue crack growth law in a period of the initial crack length up to the critical crack length as defined by the fracture toughness value, K_{Ic}, or some other criterion for brittle fracture [10-12].

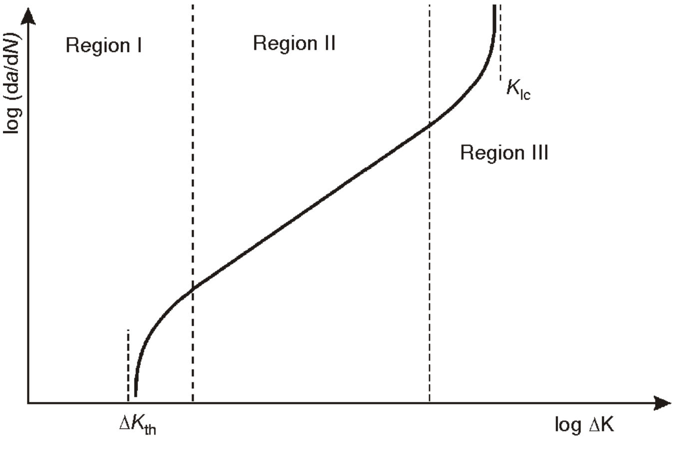

Figure 2. The fatigue-crack-growth rate, d*a*/d*N*, *vs.* the stress intensity factor amplitude, Δ*K*

Typical fatigue crack growth curve is presented in fig. 2. From the engineering point of view, region II, *i. e.*, region of stable crack growth is important. There are many different empirical equations describing the fatigue crack growth curve [6]. The most frequently used is Paris law:

$$\frac{\mathrm{d}a}{\mathrm{d}N} \quad C(\Delta K) \qquad (1)$$

where ΔK is the stress intensity factor amplitude which corresponds to the minimum and maximum loading stress, C and m – the fatigue parameters which are determined experimentally, da/dN – the crack growth rate, a – the crack length, and N – the number of cycles.

The estimation procedure basically requires precise stress distribution, especially around crack tip, which is provided here by applying the X-FEM, and experimental determination of fatigue parameters for the material used in the analysis. In both cases, temperature plays important role due to its effect on materials properties, which has to taken into account.

Experimental determination of fatigue parameters for the turbine housing material

Specimens for experimental testing are directly taken from the high-pressure turbine housing (HPTH) of thermal power plant A4 TE Kolubara. Experiments were carried out at standard temperature $T = 20$ °C and at operating temperature $T = 550$ °C, in order to observe temperature influence on the crack growth rate. Testing was done according to the ASTM Standard E647, using standard Charpy specimens on the resonance high-frequency Cracktronic system in the load level control [8]. Foils RUMUL RMF A-5 with measuring length 5 mm were bonded on specimens, enabling monitoring of crack growth (fig. 3) on Fractomat system and by using "Schenk Treibel" equipment with the thermal chamber. The only difference in the testing procedure at 20 and 550 °C is that in second case the resistant and stable glue up to 700 °C was used.

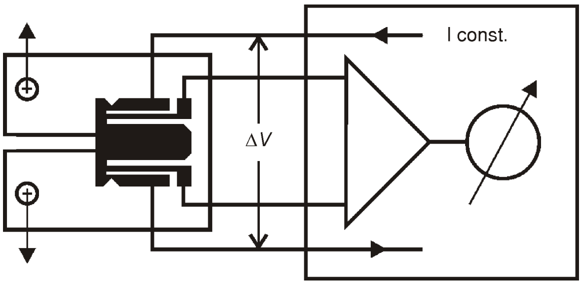

Figure 3. Strain gage system for crack growth measurement

The stress intensity factor amplitude ΔK is determined by the following formula:

$$\Delta K \quad \frac{\Delta P \ L}{B\sqrt{w^3}} f \quad \frac{a}{w} \tag{2}$$

where a is the crack length, w – the width of the specimen, ΔP – the amplitude of force used in the experiment, – $f(a/w)$ the form factor, and L – the length of specimen. The form factor $f(a/w)$ for Charpy specimen is given by the formula:

$$f \quad \frac{a}{w} \quad \frac{3\sqrt{\frac{a}{w}}}{2 \ 1 \ \ 2\frac{a}{w}\sqrt{1 \quad \frac{a}{w}}^{\,3}} \ 1.99 \quad \frac{a}{w} \ 1 \quad \frac{a}{w} \quad 2.12 \quad 3.93\frac{a}{w} \quad 2.7 \quad \frac{a}{w}^{\,2} \tag{3}$$

Based on the experimental data, functions log(da/dN) – logΔK were calculated. In figs. 4 and 5, the typical fatigue crack growth rates as a function of stress intensity factor amplitude are shown. The specimen denoted by EPR-1s was tested at 20 °C while specimen EPR-1p

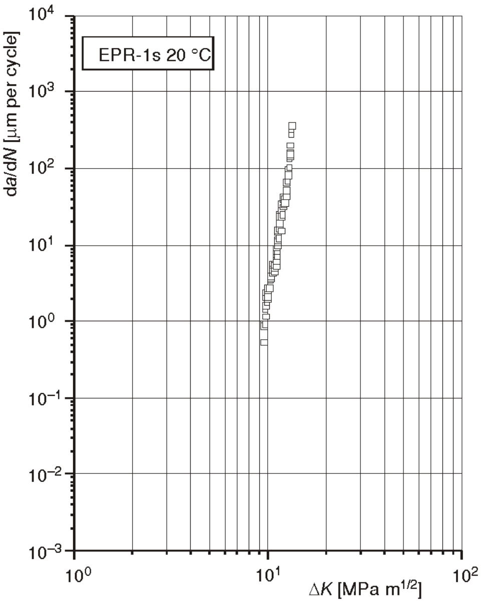

Figure 4. Fatigue crack growth rate *vs.* stress intensity factor amplitude (d*a*/d*N*-Δ*K*) for *T* = 20 °C

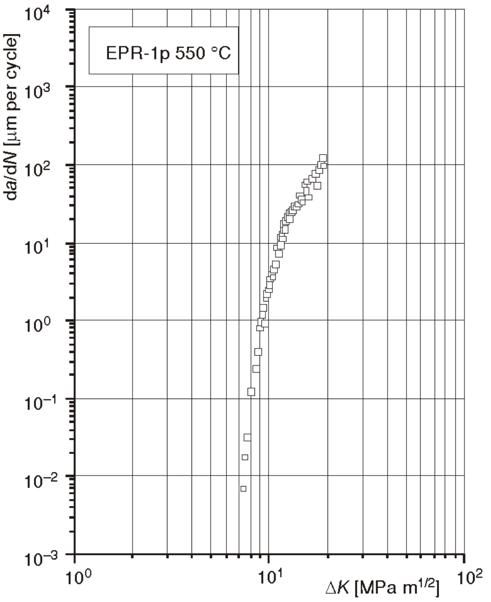

Figure 5. Fatigue crack growth rate *vs.* stress intensity factor amplitude (d*a*/d*N*-Δ*K*) for *T* = 550 °C

Table 1. Experimentally determined parameters *C* and *m*

Specimen	Temperature [°C]	Parameter [*C*]	Parameter [*m*]
EPR-1s	20	$1.51\cdot10^{-13}$	3.80
EPR-1p	550	$3.48\cdot10^{-13}$	3.95

was tested at 550 °C. Based on the obtained results, fatigue parameters *C* and *m* are calculated and presented in tab. 1.

Numerical calculation of strain and stress in cracked body

The strain and stress field in the HPTH with a crack was determined numerically, using the X-FEM formulation. The basic principle of the X-FEM is to incorporate some enrichment functions into the finite element formulation. Singular enrichment functions are used to take into account the non-smooth behavior of the displacement field near the crack tip. The approximation for a vector-valued function $\vec{u}^{h}(x)$ in the X-FEM formulation for crack is:

$$\vec{u}^{h}(x) \qquad \underset{I\ \ N_U}{h_I(x)}\ \ \vec{u}_I \underbrace{H(x)\vec{a}_I}_{I\ \ N_A} \quad \underbrace{\overset{4}{\underset{\alpha\ \ 1}{}}\ F_\alpha(x)\vec{b}_I^{\alpha}}_{I\ \ N_B} \tag{4}$$

where $\vec{u}_I$ is the nodal displacement vector associated with the continuous part of the finite element solution; $\vec{a}_I$ – the nodal enriched degree of freedom vector associated with the Heaviside function; $\vec{b}_I^{\alpha}$ – the nodal enriched degree of freedom vector associated with the elastic asymptotic crack-tip function that has the form of the Westergaard field for the crack tip, h_I, $I = (1, N)$ are the finite element shape functions, $F_\alpha(x)$, $\alpha = (1, M)$ are the near tip enrichment functions; $\vec{x} = (x_1, x_2)$ denotes Cartesian coordinates in 2-D space.

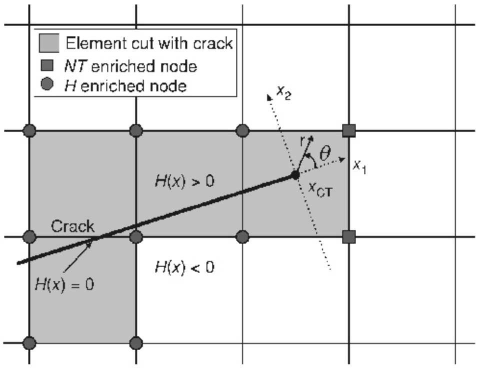

Figure 6. The local enriched nodes of the element which contains the crack and crack tip $\mathbf{x}_{CT}$

The interior of the crack (see fig. 6) is modeled by the generalized Heaviside enrichment function $H(x)$, where $H(x)$ takes the value +1 above the crack and –1 below the crack. More details are given in [1-4].

For calculation of the temperature field, the following relation between the rate of heat flux and the temperature gradient is used:

$$q_{\mathrm{x}} \qquad kA\frac{\mathrm{d}T}{\mathrm{d}x} \tag{5}$$

where q_{x} is the rate of heat conduction in the x – direction, k – the thermal conductivity, A – the area normal to x-direction, and T – the temperature. For the heat transfer between a solid and a fluid one can use:

$$q = hA(T_{\mathrm{s}} - T_{\mathrm{f}}) \tag{6}$$

where h is the convective heat transfer coefficient, A – the area, T_{s} – the solid surface temperature, and T_{f} – the surrounding fluid temperature. For the calculation of temperature field, the following data was used: for T = 30 °C, the convective heat transfer coefficient h = 10 [Wm^{-2}°C^{-1}], the insulation thermal conductivity k = 0.04 [Wm^{-1}°C^{-1}]; for T = 550 °C, convective heat transfer coefficient h = 1000 [Wm^{-2}°C^{-1}], thermal conductivity k = 40 [Wm^{-1}°C^{-1}]. Turbine housing is numerically modeled in the 2-D plane strain state [13].

The crack is located in the zones of maximal effective stress occurring due to influence of the maximum pressure, as well as the stress concentration in the vicinity of the sharp edges. During the calculation, the crack growth was simulated in 11 steps, from the initial length of 20 mm up to 70 mm. Within the numerical experiment, monitoring of the stress growth around crack was performed. In figs. 7 and 8, the stress in the crack vicinity is shown,

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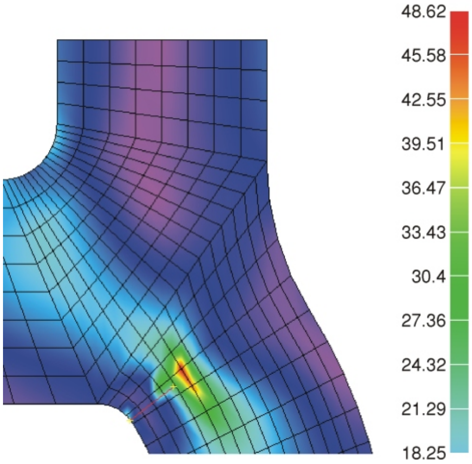

Figure 7. The effective stress area around the crack with the initial length *a* = 20 mm (color image see on our web site)

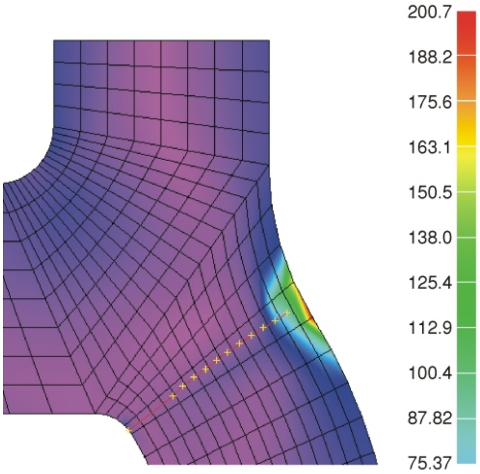

Figure 8. The effective stress area around the crack with the length *a* = 70 mm (color image see on our web site)

ndicating that it concentration moves together with the crack tip, as predicted by the fracture mechanics and the X-FEM methodology, as well. From figs. 7 and 8, one can notice that with the increasing crack length, maximum stress value increases from 50 MPa to 200 MPa which corresponds to yield stress of this material at 500 °C.

Estimation of the residual life

Under the term one cycle, the period from starting up to closing down (in the purpose of the maintenance or repairs) has been defined. In the framework of the residual life assessment, the influence of high temperature is involved through the experimental parameters *C* and *m* measured at the both room and operating temperature.

With the initial values specified, one can use the Paris's law to calculate the increment of the crack growth matching the cycle increment d*N*:

$$\mathrm{d}a = \mathrm{d}NC(\mathrm{d}K)^{\mathrm{m}}$$

The new crack length is given as follows:

$$a_{\mathrm{new}} = a_{\mathrm{old}} + \mathrm{d}a$$

The numerical calculation is carried out until the crack of with given initial length reaches the given final length a_{new} a_{max}, taken here as 20 and 70 mm, respectively, as explained in more details in [13]. The calculation was performed for room and for operating temperature, in order to evaluate the effect of temperature on the residual life. The results are shown in fig. 9, as dependence of the crack length on the number of cycles and fatigue crack growth rate for two different temperatures. As one can see, N = 2807 cycles are needed for crack growth from 20 to 70 mm at T = 20 °C, whereas N = 1130 cycles are needed for the same crack growth at T = 550 °C, reducing the residual life for ~60%.

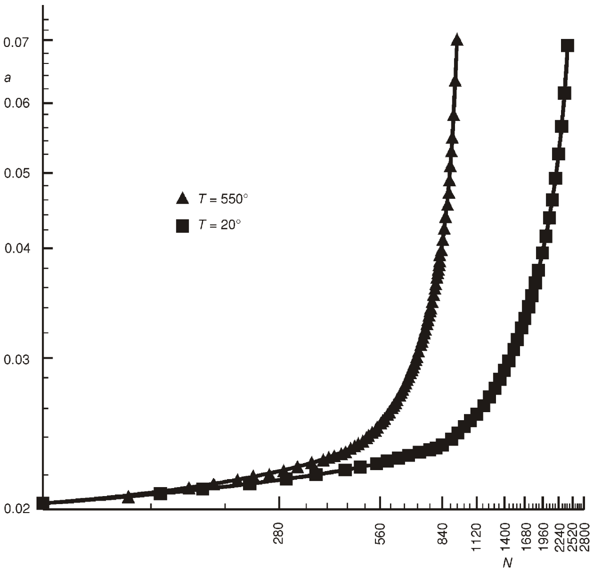

Figure 9. Dependence the crack length from the number of cycles

Conclusions

In this study the procedure for the evaluation of the residual life of damaged turbine housing has been introduced and applied. The procedure is based on the application of the X-FEM and the fatigue parameters for the analysis of the crack growth in the turbine housing. For the estimation of the residual life of turbine housing with the initial crack, test specimens were taken from the turbine housing. The procedure used was as simple as possible in order to enable wide engineering application. Thus, some limitations were inevitable, like not taking into account creep effects and reducing loading to dominant components only, as described in more details in [13]. Possible creep effects can be taken into account in different ways, some of them described in [10, 11, 14].

The focus of this analysis was to estimate the effect of temperature on the residual life of the turbine housing. As shown in fig. 9, high operating temperature, $T = 550$ °C, reduces residual life for ~60% comparing to the room temperature, clearly indicating the need for detailed and precise knowledge about the temperature effects.

Nomenclature

a – crack length, [mm]
$\vec{a}_I$ – the nodal enriched degree of freedom vector associated with the Heavisade function, $I = (1, 4)$
$\vec{b}_I^{\alpha}$ – the nodal enriched degree of freedom vector associated with CT functions $F_\alpha(x)$, $\alpha = (1, M)$
C – dynamic factors for fatigue, $[\mathrm{m^7M^{-1}N^4}]$
$\mathrm{d}a/\mathrm{d}N$ – crack growth rate, [mm cycle]
$F_\alpha(x)$ – $=[F_1, F_2, F_3, F_4]$, $\alpha = (1, M)$ – the near tip enrichment functions
$f(a/w)$ – form function of the crack, [–]
$H(x)$ – Heavisade (discontinuous) function, [–]
h – heat transfer coefficient, $[\mathrm{Wm^{-2}{}^\circ C^{-1}}]$
h_I – finite element shape functions, $I = (1, n)$ n – number of nodes in a finite element
K – stress intensity factor, $[\mathrm{MPam^{1/2}}]$
K_{IC} – fracture toughness, $[\mathrm{MPam^{1/2}}]$
ΔK – $(= K_2 - K_1)$ stress intensity factor amplitude, $[\mathrm{MPam^{1/2}}]$
k – thermal conductivity, $[\mathrm{Wm^{-1}{}^\circ C^{-1}}]$
L – length of specimen, [mm]
m – exponent in Paris law, [–]
N – number of cycles, [–]
ΔP – force amplitude $(= P_{\max} - P_{\min})$, [kN]
q_x – rate of heat conduction transfer in the x-direction
$r(x)$ – axial polar coordinate, [mm]
T – temperature, [°C]
$\vec{u}_I$ – nodal displacement vector associated with the continuous part of the finite element solution, $I = (1, n)$
$\vec{u}_i$ – vector components of the displacement, $i = (1, 2)$
w – width of specimen, [mm]
x – length parameter, [mm]
x (x_1, x_2) – Cartesian coordinates

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