UDK 539.3

THE ANALYSIS OF THE CONTINUOUS FRACTURE PROCESS OF THE STEAM-TURBINE ROTOR WITH THE LOCAL DEFECT

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The problem about the determination of the life time value of the steam-turbine rotor with the primary defect regarding growth of the continual fracture zone using the semi-analytical finite element method is considered. The investigation of the damage accumulation process and the evolution of the continual fracture zone is carried out under condition of the creep.
Keywords: semi-analytical finite element method, creep,damage parameter, local defect, heterogeneity of a material.

Introduction. A considerable quantity of responsible elements of spatial structures of a complex form which work in a long-term load condition under an influence of high temperatures. The main factor, that determine the lifetime in such condition are the accumulation of creep deformations and the concomitant accumulation of the material damage. The authors have been dealing with this problem for a long time for various objects of power engineering. Various effects were considered that determine the value of the main resource of these structural elements [1, 2, 3]. The objects that are characterized by the same operating conditions and lifetime exhaustion include steam turbine rotors. Such problems are considering usually in the axisymmetric setting that provides the certain idealization the homogeneity of material propertiesfor example [4]. At the same time the technological processing causes considerable divergences of physical-mechanical properties of the material during the creep consideration [5].

The most susceptible part of the forging rotor is the internal surface because it suffers the smaller impact during the forging. This region during processes of the annealing and the hardening is the most susceptible to the nascence of the anisotropy of material properties the presence of which affects on the working endurance during the operation. The heterogeneity of the material that is caused by the local deterioration of its properties leads to the nascence of the defect that is the concentrator of stresses. Whereas the rotor is the body of the rotation it is rational the using of a semi-analytical finite element method (FEM) [4].

That is why the investigation of the continuous fracture process and the determination of the work lifetime of the steam-turbine rotor considering the local deterioration of material properties and also the determination of the additional rotor lifetime in the presence of the defect on the basis of the modeling of the evolution of the continuous fracture zone are actual.

1. Basic Relations. The description of the elastic deformation of the material is executed using the Hooke's law; the augment of creep strains is determined on the basis of the theory of the strengthening:

$$d\varepsilon_{ij}^{c}=\lambda_c \frac{\partial f_c}{\partial s^{ij}}=\lambda_c s_{ij}\,, \qquad (1)$$

where f_c is the function that determine the creep surface.

To describe the dispersed damages impact on the material strength the function of the damage is applied the value of what changes from 0 to 1 during the operation process: the value $0<\omega_0<1$ corresponds to the existence of primary defects in the material, the value $\omega^*=1$ corresponds to the fracture (loss of bearing capacity) of the material.

The expression of the function of the creep surface f_c in the presence of the continuous fracture is:

$$f_c=\frac{3}{2}s_{ij}s^{ij}-\left[\sigma_i\left(\vartheta_c,\mathrm{T},\xi_c^i,\omega\right)\right]^2=0\,, \qquad (2)$$

where $\sigma_i\left(\vartheta_c,\mathrm{T},\xi_c^i,\omega\right)$ is the fluidity boundary at the pure shear; $\vartheta_c=\int_{\varepsilon_{ij}^c}\sqrt{\frac{2}{3}d\varepsilon_{ij}^c d\varepsilon^{ijc}}$ is the Odkvist's parameter of the strengthening; $\xi_c^i=\frac{\partial\varepsilon_c^i}{\partial t}=\int_{\varepsilon_{ij}^c}\sqrt{\frac{2}{3}d\xi_{ij}^c d\xi^{ijc}}$ is the intensity of the velocity of creep strains.

To describe the deformation of the material under creep condition the expression (2) needs to be supplemented by the equation that describes changes of the damage parameter ω in time. During construction of that equation in general is assumed that the augment of the function $\omega(t)$ during the short period of time t depends on the current state of the material (the value of the parameter of the damage) and loads [6-8]:

$$\frac{d\omega}{dt}=\Phi(\omega,\ p_j)\,, \qquad (3)$$

where $\Phi(\omega,\ p_j)$ is the certain function; p_j is the vector of loads, that defines external force, deformation and temperature impacts.

2. The Solution Algorithm of Spatial Creep Problems. The process of the non-linear deformation can be presented as the summation of discrete steps by parameters of external loads and time. Thereby, using the step-by-step algorithm is necessary for solving the problem. In turn, iterative algorithms are used at every step for solving of the system of non-linear equations.

To considerate changes of physical-mechanical properties of the material depending on external loads the possibility of their adjustment is provided at the beginning of every step. Physical-mechanical properties are expected constant in the borders of the step.

The vector of unknown displacements $\{u_l\}_n^m$ of the system of non-linear equations FEM at each iteration n of the step m can be presented as:

$$\{u_l\}_{n+1}^m = \{u_l\}_n^m + \beta\left[K_{ll}\right]^{-1}\left(\{Q_l\}^m - \{R_l\}_n^m\right), \tag{4}$$

where $\{Q_l\}^m$ is the vector of joints loads at the step m; $\{R\}_n^m$ is the vector of joints reactions at the iteration n that is defined depending on values of stresses σ_{ij} changing values of what occurs due to the augment of external loads or time and the corresponding non-linear deformation of the material.

The condition of the coinciding of the iteration process at the step is the inequality:

$$\sum_{l=0}^{L}\left(\{\Delta u\}_l^n\right)^2 \le \xi \sum_{l=0}^{L}\left(\{u\}_l^n\right)^2, \tag{5}$$

where $\xi = 10^{-4}...10^{-6}$ is the correctness parameter of the solving of the system of non-linear equations that can be evaluated on the basis of the investigation of the obtained equation.

At the beginning of each iteration n of the step m components of the tenser of stresses σ_{ij} are defined using the formula:

$$(\sigma_{ij})_n = (\sigma_{ij})_{n-1} + (\Delta\sigma_{ij})_n, \tag{6}$$

where $(\Delta\sigma_{ij})_n$ is the augment of stresses that are determined in accordance with the Hooke's law depending on the value of the augment of total deformations.

Real values of stresses $(\overline{\sigma}_{ij})_n^m$ that are used to define components of the vector of joints reactions $\{R\}_n^m$ are determined using the formula:

$$(\overline{\sigma}_{ij})_n^m = \frac{1}{3}\delta^{ij}(\sigma_{ij})_n^m + (\overline{s}_{ij})_n^m = (\sigma_0)_n^m + (\overline{s}_{ij})_n^m, \tag{7}$$

where $(\overline{s}_{ij})_n^m$ are components of the deviator of stresses that consider the augment of non-linear creep deformations:

$$(\overline{s}_{ij})_n^m = (s^{ij})_n^m - G_1(\Delta\varepsilon_{ij}^c)_n^m, \quad (\Delta\varepsilon_{ij}^c)_n^m = (\xi_{ij}^c)_n^m \Delta t_m, \tag{8}$$

$$G_1 = E/\left(1-2\nu\right),$$

$$(\xi_{ij}^c)_n^m = \frac{3}{2}\left[\xi_i^c\right]_m^n \frac{(s_{ij})_n^m}{(\sigma_i)_m^n},$$

$$\xi_i^c = \frac{d\varepsilon_i^c}{dt} = \xi_i^c\left(\sigma_i, \nu_c, \mathrm{T}, \omega\right),$$

where Δt_m is the value of the step in time.

Stresses that were obtained using expressions (6), (7), (8) are checked by the condition (5). After the execution of this check the calculation of the augment of creep deformations $(\Delta\varepsilon_{ij}^{c})_m$ and the damage parameter $(\Delta\omega)_m$ is doing using stresses that were obtained at the last iteration of the step and corresponding accumulated values $(\varepsilon_{ij}^{c})_m$ and ω_m :

$$(s_{ij}^{c})_m = (s_{ij}^{c})_{m-1} + (\Delta s_{ij}^{c})_m = (s_{ij}^{c})_{m-1} + (\xi_{ij}^{c})_m \Delta t \, , \tag{9}$$

$$\omega_m = \omega_{m-1} + (\Delta\omega)_m = \omega_{m-1} + \left(\frac{d\omega}{dt}\right)_m \Delta t_m \, . \tag{10}$$

Formulas (6)–(9) are invariant with respect to the concrete form of expressions for ξ_i^c and $\frac{d\omega}{dt}$.

At the end of the step the check of the condition of the local loss of the bearing capacity for all points of the body is performed:

$$\omega \geq \omega^*. \tag{11}$$

where ω* is the critical value of the damage parameter that corresponds to the material fracture moment.

Theoretically ω* =1 [6, 8], but to prevent getting the incertitude in the denominator of expressions for ξ_i^c and $\frac{d\omega}{dt}$ is assuming ω*<1 (ω* =0,9[7], ω* =0,95-0,96 [9], ω* =0,99 [10]).

The moment of time t^* when at least in one of finite element is satisfied the condition (11) is fixed as the moment of the transition from the process of the accumulation of pores and the discontinuity in the material that are considering integrally using the damage parameter to the process of the nascence of macroscopic defects. Modeling of their evolution to the formation of primary cracks can be performed on the basis of correlation of continuum fracture mechanics [9, 10].

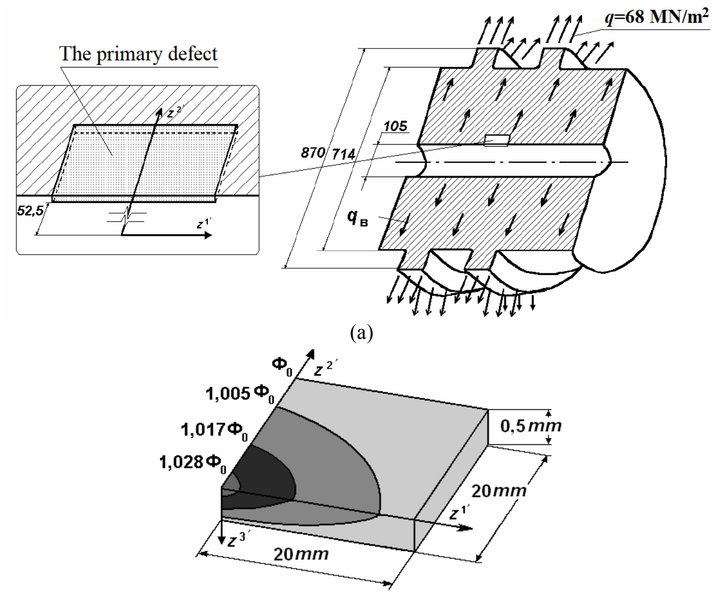
3. Modeling of the evolution process of the fracturezone of the steam-turbine rotor with the defect. The disc of the steam-turbine rotor is the massive axisymmetric body with the central through hole and the rim for fixing the bandage (Fig. 1).

Forces that affect the disc are conditioned by its rotation with the frequency n_0 = 3000 rpm and consist of the uniformly distributed along the plane of the bandage rim S facial load with the intensity 68 *MPa* that models the impact of scapulas and the mass force that are distributed along the volume of the disc.

The mass force dP that acts on the elementary volume of the material dV that rotates around the axis with the frequency n_o and is located at the distance from the axis $R = z^{2'}$ is calculated using the expression:

$$dP = \rho w^2 R dV \, , \tag{12}$$

where ρ = 7850 кg/m^3 is the density of the disc material; $w = \pi n_0 / 30$ is the angular frequency of the disc rotation.



(a)

(b)

Fig. 1. The steam-turbine rotor with the primary defect (a) – general view, (b) – model of defect

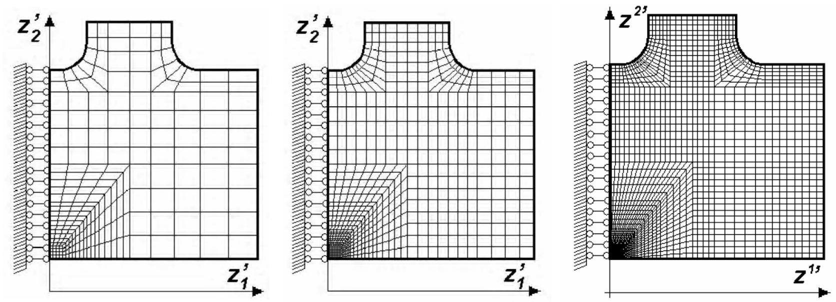
We consider the impact of the initial defect (a local variance of the mechanical properties of the material taking place within this defect) on the rotor design life-time value. The defect is shaped as parallelepiped with dimensions $40\times20\times0.5$ mm placed in plane of the meridional section, (Fig. 1). The variance of mechanical properties under creep is discribed by the change of the degree index ф in (13) in a cross-sectional plane and by a circular coordinate by nonlinear law. The numerical values is illustrated with isolines within local defect area are shown in Fig. 1 (b). The maximum constant deviation from the nominal value is observed near the axis of rotation of the rotor, outside the constant defect value is equal to nominal.

The equation that describes the body deformation in the creep circumstances considering the material damage accumulation:

$$\xi_i^c = A\left(\frac{\sigma_i}{1-c\omega}\right)^n t^m, \quad \frac{d\omega}{dt} = B\left[\frac{(1-\alpha)\sigma_i+\alpha\sigma_1}{1-\omega}\right]^{\phi}, \qquad (13)$$

where A = 3.523·10 –21 MPa–n hour–m–1; B = 6.555·10–19 MPa– ф hour–1; c = 0.7; n = 5.51; m = –0.47; α = 0.7; ф =4.23 – material constants.

To perform the research of the coinciding depending on the quantity of nodes$N$ in finite element model in the cross-section some discrete models are considered:$N = 235$ (Fig. 2 (a)), $N = 731$ (Fig. 2 (b)) and$N = 2047$ (Fig. 2 (c)). The structure of discrete models is oriented to the description of stress-strain state features around the defect and further modeling of the evolution of the continuous fracture zone.



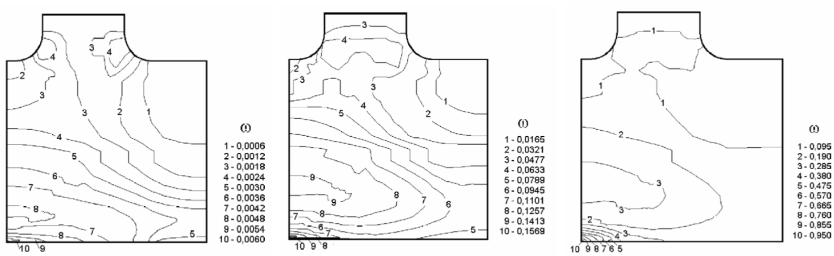
(a) (b) (c)

Fig. 2. Finite-element models of the rotor cross-section

The concentration of the finite-element model leads to obtaining of more exact results. Using of the thicker discrete model (Fig. 2 (b)) allows to clarify the rotor basic lifetime value on 2%. But using the next more thicker discrete model at $N = 2047$ (Fig. 2 (c)) allows to clarify the rotor basic lifetime value less than on 1%. Considering the significant volume of computing costs the further increasing of the joints quantity more than 731 is inexpedient.

Considering conducted researches of the coinciding depending on the quantity of harmonicas that were performed using the finite-element model with $N = 731$ the rotor basic lifetime value in the presence of the defect is near of 104000 hours that is less by 15% than in the case of the defect absence [4].

Using the distribution of isolines of the damage parameter within the rotor cross-section that includes the defect (Fig. 3, a,b,c) can be traced the evolution of the fracture process and the character of the defect impact on the nascence of the crack initiation region. The maximum value of ω can be observed on isolines (Fig. 3, a) right nearby the defect at the moment of time 2200 hours already and the difference between maximum values of the damage parameter for the rotor with the defect and hereunto is 30% that increases over time and at the moment of time 103000 hours reaches 70%.

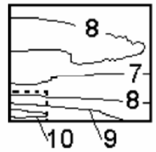


(a) (b) (c)

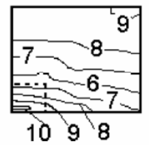
Fig. 3. The distribution of the damage parameter in the cross-section of the rotor with the defect at the moment of time: (a) – t = 2200 h, (b) – t = 60400 h, (c) – t = 103650 h

Scilicet the presence of the defect influences the fracture process at the initial stage already. At the moment of time 103650 hours it can be observed that the distribution of maximum values of ω occurs in two directions within the plane of the rotor cross-section. It can be seen in the Fig. 3, c that the presence of the defect the contour of which is described by the dashed line has already the local character.

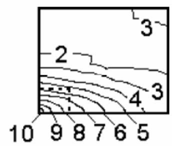
The impact of the heterogeneity of the material on the distribution of the damage parameter around the primary defect in more details is shown in the Fig. 4. The accumulation of the damage along the axis of the rotation occurs faster than by the radius.



(a)



(b)



(c)

Fig. 4. The distribution of the damage parameter around the primary defect at the moment of time: (a) – t = 2200 h, (b) – t = 60400 h, (c) – t = 103650 h

At the moment of time 104000 hours that corresponds to the rotor basic lifetime value it's too early to talk about the form of the continuous fracturezone. But the accumulation region of the maximum values of ω increases in both directions of the rotor cross-section over time in such way that the augment of the maximum values of the damage parameter occurs more intensively in the rotation axis direction. At the moment of time 107000 hours the correlation between characteristic dimensions of the region in axes directions $z^{1'}$ and $z^{2'}$ is 2/3. The qualitative character of this correlation is preserved in the future and at the moment of time 110000 hours the correlation between dimensions of the continuous fracture region in the plane of the rotor cross-section is about 1/2. Thus the rotor additional lifetime value is 6000 hours.

Herewith the value of the damage parameter in finite elements those border with the fracture region doesn't exceed 0,3 scilicet the accumulation of the damage has the pronounced local character.

Conclusion. In this paper the problem about the determination of the basic lifetime value of the steam-turbine rotor with the defect on the basis of the semi-analytical finite element method is considered. Obtained results allow analyzing the evolution of the rotor fracture process at different progress stages of the accumulation of the damage parameter value and show the character of the heterogeneity presence impact on the lifetime value. The presence of divergences of material physical-mechanical properties affects on the region location in which the process of the accumulation of the damage parameter occurs faster and the fracture begins earlier. Continuous fracturezone increase time to the crack-like formation is 6000 hours. The continuous fracturezone extends within the rotor cross-section and takes the form of semi-elliptical crack with correlation between semi-axes 1/2.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ РОЗВИТКУ КОНТИНУАЛЬНОГО РУЙНУВАННЯ РОТОРА ПАРОВОЇ ТУРБІНИ З ЛОКАЛЬНИМ ДЕФЕКТОМ

Найголовнішими факторами, що визначають ресурс роботи роторів парових турбін, які працюють в умовах тривалого навантаження під дією високих температур, є накопичення деформацій повзучості і супутнє накопичення пошкодженості матеріалу. Неоднорідність матеріалу призводить до виникнення дефекту, який є концентратором напружень. Для опису впливу розсіяних пошкоджень на міцність матеріалу конструкції застосовується функція пошкодженості, значення якої змінюється в процесі експлуатації. Для проведення дослідження розглядаються дискретні моделі при N = 235, N = 731 та N = 2047. Використання густіших дискретних моделей дозволяє уточнити величину основного ресурсу ротора на 2% та 1% відповідно. Для скінченноелеметної моделі при N = 731, величина основного ресурсу роботи ротора при наявності дефекту становить 104000 годин, що на 15% менше, ніж при відсутності дефекту. Величина додаткового ресурсу роботи ротора складає 6000 годин. На ізолініях у межах поперечного перерізу ротора в момент часу 2200 годин можна спостерігати найбільші значення параметра пошкодженості поблизу дефекту, а різниця максимальних значень параметра пошкодженості для ротора з дефектом та без нього складає 30%, яка з часом збільшується до 70%. Після 104000 годин область накопичення максимальних значень ω збільшується в обох напрямках поперечного перерізу ротора таким чином, що в напрямку осі обертання приріст максимальних значень параметра пошкодженості відбувається інтенсивніше. В момент часу 107000 годин співвідношення між характерними розмірами зони континуального руйнування в напрямках осей становить 2/3, а в моменту часу 110000 годин становить приблизно 1/2. Значення параметра пошкодженості у скінчених елементах, що межують із зоною руйнування не перевищує 0,3, тобто накопичення пошкодженості є локальним.

Ключові слова: напіваналітичний метод скінченних елементів, повзучість, параметр пошкодженості, локальний дефект, неоднорідність матеріалу.

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THE ANALYSIS OF THE CONTINUOUS FRACTUREPROCESS OF THE STEAM-TURBINE ROTOR WITH THE LOCAL DEFECT

Main factors that determine the steam-turbine rotors work lifetime which work in a long-term load circumstances under an influence of high temperatures are the accumulation of creep deformations and the concomitant accumulation of the damage of the material. The heterogeneity of the material leads to the nascence of the defect that is the concentrator of stresses. To describe the dispersed damages impact on the construction material strength the function of the damage is applied the value of what changes during the operation process. To perform the research discrete models with N = 235, N = 731 and N = 2047 are considered. Using thicker discrete models allows clarifying the rotor basic lifetime value on 2% and 1% respectively. For the finite-element model with N = 731 the rotor basic lifetime value in the presence of the defect is 104000 hours that is less by 15% than in the absence of the defect. The rotor additional lifetime value is 6000 hours. The maximum value of the damage parameter can be observed on isolines nearby the defect at the moment of time 2200 hours and the difference between maximum values of the damage parameter for the rotor with the defect and hereunto is 30% that increases over time to 70%. After 104000 hours the accumulation region of the maximum values of the damage parameter increases in both directions of the rotor cross-section over time in such way that the augment of the maximum values of the damage parameter occurs more intensively in the rotation axis direction. At the moment of time 107000 hours the correlation between dimensions of the continuous fracture region in axes directions is 2/3 and to the moment of time 110000 hours is about 1/2. The value of the damage parameter in finite elements those border with the fracture region doesn’t exceed 0,3 scilicet the accumulation of the damage is local.

Keywords: semi-analytical finite element method, creep,a parameter of a damage, local defect, heterogeneity of a material.

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Пискунов С.О., Остапенко Р.М., Кара І.Д. **Дослідження процесу розвитку континуального руйнування ротора парової турбіни з локальним дефектом** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2022. – Вип. 109. – С. 203-212.
Розглядається задача про визначення величини основного і додаткового ресурсу ротора парової турбіни з початковим дефектом з використанням напіваналітичного методу скінчених елементів.
Іл. 4. Бібліогр. 10 назв.

UDK 539.3
Pyskunov S.O., Ostapenko R.M., Kara I.D. **The Analysis of the Continuous FractureProcess of the Steam-Turbine Rotor with the Local Defect** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles – Kyiv: KNUBA, 2022. – Issue 109. – P. 203-212.
The problem about the determination of the basic and additional lifetime value of the steam-turbine rotor with the primary defect using the semi-analytical finite element method is considered.
Fig. 4. Ref. 10.

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