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Time-dependent Analysis and Creep Life Prediction of Rotating Hollow Cylinders Using Theta Projection Concept and Larson Miller Parameter

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ABSTRACT: In this work, stresses, strains, creep damage and remnant life for a rotating thick-walled hollow cylinder made of alloy steel using the theta projection concept and the Larson Miller parameter are investigated. Loading is composed of internal and external pressures, a distributed temperature field and a centrifugal body force. Using stress-strain, strain-displacement and equilibrium relations a second-order non-homogenous differential equation containing creep strains for radial displacement is obtained. Ignoring creep strains, a thermo-elastic solution at zero time is acquired. With considered creep strains in mentioned differential equation and differentiating with respect to a time, a differential equation consist of radial and circumferential creep strain rates for radial displacement rate is obtained. By combining theta projection model and Prandtl-Reuss relations and substituting instead strain rates in last differential equation and then numerically solving that, radial displacement rate and stresses are calculated. Using the Larson Miller parameter and Robinson's rule, creep damage and remnant life redistributions along the thickness of cylinder are obtained. It has been found that the maximum and minimum creep damage occur at the inner and outer surfaces of the cylinder respectively.

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1- Introduction

Creep phenomenon is a time dependent transformation which happens slowly and steadily over time under the effect of fixed load. In high tech industries there are some structures that for a long period of time are subjected to stress and high temperature.

For the design of these advanced structures, in addition to the normal relationships used in the design of structures, the creep relations also have a special place. For instance, gas and steam turbines in the electricity, petrochemicals, aerospace and marine industries are designed to operate in harsh working conditions for a long time under high temperature and stress. Nowadays analysis of time dependent creep, checking creep damages and the remaining life of industries and the equipment that deals with creep phenomenon have a special importance [1-5]. Some researchers in different geometries and loadings have conducted researches and studies in order to have designs and timely plannings to deal with this destructive phenomenon. Hosseini et al. [6] presented an exact solution for thick-walled rotating cylinders based on the Prandtl–Reuss relation. They assumed that the cylinder is pressurized from the inside and outside. They also considered Norton structural equation for their creep solution. After that by assuming plane strain they checked the effects of the angular velocity changes on the redistribution of radial, tangential and effective stresses. In this paper they tried to investigate the redistribution of stresses and creep strains by the method of calculation of stress rates with the help of structural equation of theta range. After that, by using the Larson-Millers fracture structural equation they have checked the creep damage and he remaining life of rotating cylinder based on the Robinson design model.

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2- Numerical Method

In order to calculate all available spots in cylinder thickness for all considered times, cylinder thickness is divided into a number of equal m components and it will be denoted by index j.

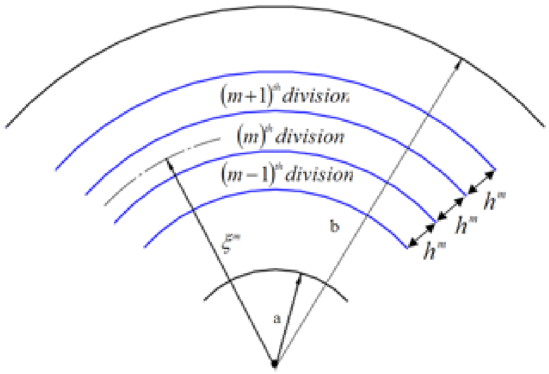

Figure 1. Division of cylinder thickness

Then at the moment [t=0] the resolution of the thermo elastic issue will be discussed and then the values of radial stress, tangential stress and effective stress by using the von Mises equation will be calculated.

Next a proper time range will be selected and total time will be the total of time components during which the creep process takes place. In other words time for (i) stage will be defined as Eq. (1).

$$t_i = \sum_{k=0}^{i} \Delta t_k \tag{1}$$

With the help of Eq. (2) and (3) radial and tangential creep strain rates will be specified in each section.

$$\dot{\varepsilon}^c_{r_{ij}} = -\frac{\sqrt{3}}{2}\left(\theta_1\theta_2 e^{-\theta_2 t_{ij}} + \theta_3\theta_4 e^{\theta_4 t_{ij}}\right) \tag{2}$$

$$\dot{\varepsilon}^c_{\theta_{ij}} = \frac{\sqrt{3}}{2}\left(\theta_1\theta_2 e^{-\theta_2 t_{ij}} + \theta_3\theta_4 e^{\theta_4 t_{ij}}\right) \tag{3}$$

After that stress rate amounts will be calculated in every stage.

Current values of tension can be calculated with radial and tangential stresses in the previous stage and the thermoplastic state (t=0) based on Eq. (4)

$$\begin{aligned} &\sigma_{rr}^{(i)}(r,t_i) = \\ &\sigma_{rr}^{(i-1)}(r,t_{i-1}) + \dot{\sigma}_{rr}^{(i)}(r,t_i)\Delta t^{(i)} \\ &\sigma_{\theta\theta}^{(i)}(r,t_i) = \\ &\sigma_{\theta\theta}^{(i-1)}(r,t_{i-1}) + \dot{\sigma}_{\theta\theta}^{(i)}(r,t_i)\Delta t^{(i)} \end{aligned} \tag{4}$$

Having the effective stress amounts in every stage and the temperature distribution along cylinder thickness, the Larson–Miller parameter can be calculated at every stage and then the fracture time will be determined at every spot.

Then the damage in all parts in every stage from the solution along the thickness of cylinder can be obtained by using the Robinson model according to Eq. (5)

$$D_{ij} = \Sigma \frac{\Delta t_i}{t_{r_{ij}}} \tag{5}$$

Having damage amounts at every spot and at every stage, the remaining life can be calculated according to Eq. (6)

$$R_{ij} = (1 - D_{ij})\,\mathrm{t}_{r_{ij}} \tag{6}$$

3- Results and Discussion

Fig. 2 shows the history of creep damage along the thickness of the rotating cylinder for long periods of times from the beginning of creep process. As can be seen, over time creep damage will be increased all over the cylinder. Most of creep damage also occurs at the inner edge of the axis. The reason this happens is that the most effective stress happens at the inner edge of the cylinder; also this surface is exposed to the maximum temperature.

Remnant life histories for rotating hollow shaft up to 259200 hours are shown in Figure 3 .As expected minimum remnant lives are located at the inner surface and their maximum values at the outer surface for all three cases.

Dimensionless radial, circumferential and effective stress histories up to 259200 hours are illustrated in figures 4, 5 and 6. Dimensionless radial stress redistribution from its initial elastic solution at zero time up to 259200 hours is illustrated

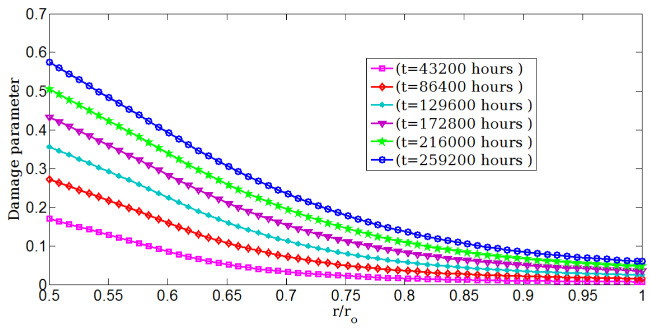

Figure 2. Changes in creep damage along the thickness of cylinder after (259200 hours) from the beginning of creep process.

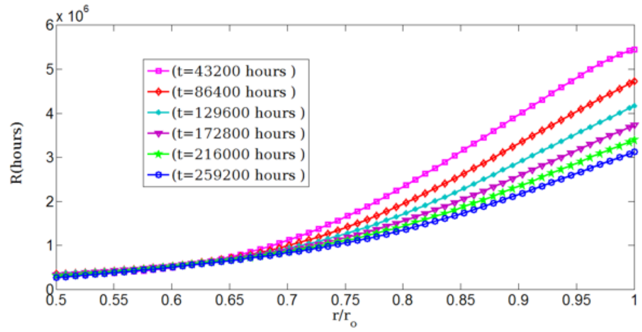

Figure 3. Remnant life histories of rotating hollow shaft from initial elastic up to 259200 hours.

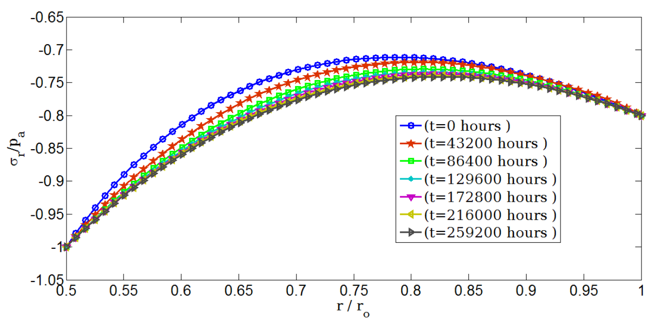

Figure 4. Dimensionless radial stress redistribution of rotating hollow shaft from its initial elastic up to 259200 hours.

in Figure 4. The boundary conditions of internal pressure and outer free surface are satisfied. Radial stress at most outer part of the rotating shaft is tensile which is due to centrifugal body force however it is compressive at the inner part of the shaft which has to satisfy the internal pressure boundary condition. Radial stresses are finally converged to steady state condition after 259200 hours. History of dimensionless circumferential stresses is shown in Figure 5. Maximum value of initial elastic circumferential stress is located at the inner surface of the shaft at zero time. Later in the life of the shaft due to creep stress redistribution this maximum value is decreasing at the inner surface while the minimum value of the initial circumferential stress at the outer surface is slightly increasing. Physically high tensile stresses at the inner surface are relaxing with time because of creep phenomenon while loading condition is constant in the presence of high temperature environment. Dimensionless effective stress history up to 259200 hours is shown Figure 6. It is similar

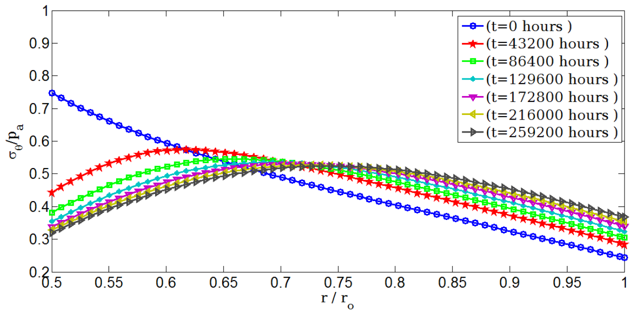

Figure 5. Dimensionless circumferential stress redistribution of rotating hollow shaft from its initial elastic up to 259200 hours.

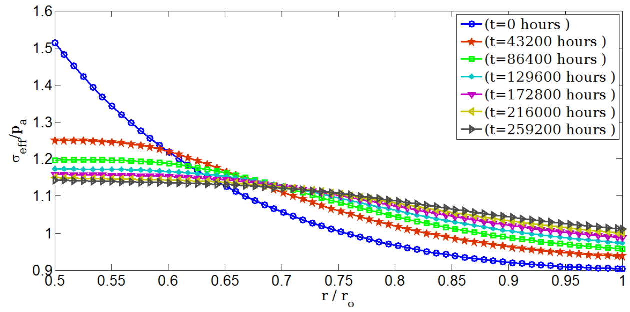

Figure 6. Dimensionless effective stress redistribution of rotating hollow shaft from its initial elastic up to 259200 hours.

to circumferential stress history due to dominancy of high tensile circumferential stresses.

4- Conclusions

In this work the redistribution of stresses, strains and also creep damages and the remaining life for a period of 30 years after the beginning of the creep process was checked by the structural equation of theta range and the fracture parameter of Larson-Miller. The acquired results showed that the most effective stress and also creep damage happens at the inner edge and the least at the outer edge, whereas the remaining life shows exactly the opposite behavior. Over time effective stress decreases at the inner surface and increase a little bit at the outer edge, but likewise the inner edge is exposed to the highest creep damage.

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