ANALYSIS OF CREEP-INDUCED STRAINS AND STRESSES IN THE V NOTCHES PROCESS ZONE FROM THE CANDU PRESSURE TUBES

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Abstract

The paper objective was to study the phenomenon of the mechanical stress relaxation in the vicinity of a V notch (blunt flaw) on the inner surface of the CANDU pressure tube. This kind of notches model the Debris Fretting Flaws found by in-service inspection on the fuel channels. The analyses are done inside of a small zone around the flaw, which is called ″the process zone″. The Neuber's total strain energy density rule is applied to obtain the stress relaxation and the total strain due to the creep phenomenon in the process zone. Further, the paper describes the formalism to obtain the numerical solutions for the stress-strain field in the process zone, where the high stresses are developed due to the flaw tip that play the stress intensifier under tensile stress.

Keywords: *Stress relaxation, Neuber's rule, Process zone, CANDU pressure tubes*

Introduction

In the metallic components, the flaws and notches are mechanical stress intensifiers and this may influence their structural behaviour under operation. Also, the long operation under thermal and mechanical loads, similar those from nuclear reactors, lead to more phenomena like as the stress relaxation and increase of the total localized strain in the vicinity of these stress spots. These are done mainly due to the creep phenomenon that means a continuous deformation under constant mechanical load in the temperature field. Thus, this fact may directly influence the application of the failure criteria, like crack initiation in the CANDU pressure tubes by Delayed Hydride Cracking (DHC), that is based on the maximum equivalent mechanical stress in the defect area.

The assessment of the stress-strain field in a component with flaws or notches, taking into account its evolution in time, is nowadays realized by finite element method within specialized computer codes. However, there are some alternative methods to obtain stress-strain field evolution over the time in a structural component, close to stress intensifiers (flaws, notches, crack-like flaws, etc.). They would be the numerical iterative solutions with respect to the combined problems of creep-plasticity depending on time variable.

The presence of defects on the inner CANDU pressure tube surface, made from Zr-2.5%Nb alloy, leads to high tensile stress occurrence, which could promote DHC phenomenon and finally the failure of respective area. In the meantime, the irradiation and thermal creep under normal operation of CANDU pressure tubes, favours the decreasing of the maximum stress values by means of the stress relaxation process at constant temperature. Therefore, it has to be considered when the structural integrity procedures, described by Canadian CAN/CSA N285.8 [1] for engineering process zone or threshold stress criteria in case of DHC initiation, will be applied.

The paper describes the methodology to analyse the stress relaxation due to the creep phenomenon, for high stress domain, which characterizes adjacent zone of the notch or flaw. The aim was to propose an algorithm for MATLAB environment, intended for obtaining numerical solutions by iterative process both for the stress relaxation and accumulated strain inside of the process zone. The example is focused on the V notch process zone in the CANDU pressure tube wall, made from Zr-2.5%Nb alloy, under thermal creep.

Neuber's rule for stress-strain analyses in the presence of the localized plasticity

The application of the Neuber's rule on the creep analyses has been initially proposed for elastic-plastic body with defects, under shear stress [2-4]. It is based on the hypothesis that stress concentration factor is geometric mean between the elastic-plastic stress concentration factor and those from actual strain:

$$K_t = \sqrt{K_\sigma \cdot K_\varepsilon} \tag{1}$$

It must be mentioned that Eq. (1), known as ″Neuber's rule″ is currently used in the stress-strain analyses in case of the localized plasticity, that take place close to the notch tip, where a small plasticity zone is developed. It could be written in a form which correlates a hypothetic elastic stress σ_{ij}^e, respective elastic strain ε_{ij}^e, with those of the actual components σ_{ij}^0 and ε_{ij}^0:

$$\sigma_{ij}^{e}\varepsilon_{ij}^{e}=\sigma_{ij}^{0}\varepsilon_{ij}^{0} \tag{2}$$

For the plane stress case, the Eq. (2) becomes:

$$\sigma_{22}^{e}\varepsilon_{22}^{e}=\sigma_{22}^{0}\varepsilon_{22}^{0} \tag{3}$$

or simpler

$$\sigma^{e}\varepsilon^{e}=\sigma^{0}\varepsilon^{0} \tag{4}$$

where only load direction is considered. Here: $\sigma_{22}^{e}=\sigma^{e}$ is the elastic stress at notch tip from elastic stress analyses; $\varepsilon_{22}^{e}=\varepsilon^{e}$ is the elastic strain at notch tip from elastic stress analyses; $\sigma_{22}^{0}=\sigma^{0}$ is the actual stress at notch tip from elastic-plastic stress analyses; $\varepsilon_{22}^{0}=\varepsilon^{0}$ is the actual strain at notch tip from elastic-plastic stress analyses.

Eq. (3) is directly derived from original Neuber's rule, and could be seen as an equivalent of total strain energy density. In the literature is shown that the total strain energy density at notch tip is approximately constant:

$$\Omega=\sigma_{22}^{e}\varepsilon_{22}^{e} \tag{5}$$

This is valid as long as plastic deformation is localized near to the notch tip, which is a stress intensifier. Moreover, this fact is valid even when it takes place a stress relaxation due to the creep. In other words, the Neuber's rule could be extended directly to stress and strain analyses time dependent as follows:

$$\Omega=\sigma_{22}^{e}\varepsilon_{22}^{e}=\sigma_{22}^{0}\varepsilon_{22}^{0}=\sigma_{22}^{t}\varepsilon_{22}^{t} \tag{6}$$

The last term in Eq. (6) represents total strain energy density at a certain point of time under constant stress and temperature.

The main features of the numerical approach in formulating the localized creep are shown below. It is considered a structural component heaving a stress concentrator (volumetric flaw) under constant mechanical loading for a long time. Because the creep mechanism is localized in this situation, since the high stresses arise only near to the notch, it can be assumed accordingly to the Neuber's theory the following relationship:

$$\sigma_{22}^{0}\varepsilon_{22}^{0}=\sigma_{22}^{t}\varepsilon_{22}^{t} \tag{7}$$

The time dependence of deformation can be decomposed in three terms: elastic part ε_{22}^{et}, plastic part ε_{22}^{p0} and those came from creep ε_{22}^{ct}:

$$\varepsilon_{22}^{t}=\varepsilon_{22}^{et}+\varepsilon_{22}^{p0}+\varepsilon_{22}^{ct} \tag{8}$$

The induced plastic component, ε_{22}^{p0}, could be considered as constant during long period of time under constant loading, since it is the plastic deformation at the initial moment *t*=0.0. This suggests that there is a compromise between elastic unloading and creep deformation. By introducing Eq.(8) in Eq.(7) and differentiating, we get:

$$\sigma_{22}^{0}\varepsilon_{22}^{0}=\sigma_{22}^{t}\varepsilon_{22}^{et}+\sigma_{22}^{t}\varepsilon_{22}^{p0}+\sigma_{22}^{t}\varepsilon_{22}^{ct} \tag{9}$$

$$0.0=\sigma_{22}^{t}\dot{\varepsilon}_{22}^{et}+\dot{\sigma}_{22}^{t}\varepsilon_{22}^{et}+\dot{\sigma}_{22}^{t}\varepsilon_{22}^{p0}+\sigma_{22}^{t}\dot{\varepsilon}_{22}^{ct}+\dot{\sigma}_{22}^{t}\varepsilon_{22}^{ct} \tag{10}$$

For the uniaxial stress state, the elastic strain is:

$$\varepsilon_{22}^{et}=\frac{\sigma_{22}^{t}}{E} \tag{11}$$

with E – Young modulus. The deformation rate becomes:

$$\dot{\varepsilon}_{22}^{et}=\frac{\dot{\sigma}_{22}^{t}}{E} \tag{12}$$

and Eq. (10) is written as:

$$0.0=\frac{2}{E}\sigma_{22}^{t}\dot{\sigma}_{22}^{t}+\dot{\sigma}_{22}^{t}\varepsilon_{22}^{p0}+\sigma_{22}^{t}\dot{\varepsilon}_{22}^{ct}+\dot{\sigma}_{22}^{t}\varepsilon_{22}^{ct} \tag{13}$$

Eq. (13) is a differential equation, and together with the creep law, forms the mathematical set necessary to solve the problem. The analytical solution for these coupled equations is difficult to obtain, especially when the creep model is complex. Thus, in the literature [3] a method for numerical integration has been proposed. It was suggested to divide the integration period of time in a number of steps, each of size by Δt_n, and inside of each to generate a solution for the next step. Based on this approach, derived in relation to time is in an elementary form:

$$\dot{\sigma}_{22}^{t}=\frac{d\sigma_{22}^{t}}{dt}\simeq\frac{\Delta\sigma_{22}^{t_n}}{\Delta t_n}=\frac{\sigma_{22}^{t_n}-\sigma_{22}^{t_{n-1}}}{t_n-t_{n-1}} \tag{14}$$

$$\dot{\varepsilon}_{22}^{ct}=\frac{d\varepsilon_{22}^{ct}}{dt}\simeq\frac{\Delta\varepsilon_{22}^{c_n}}{\Delta t_n}=\frac{\varepsilon_{22}^{c_n}-\varepsilon_{22}^{c_{n-1}}}{t_n-t_{n-1}} \tag{15}$$

By introducing Eqs. (14) and (15) into Eq. (13), the following form is obtained:

$$0.0=\frac{2}{E}\frac{\Delta\sigma_{22}^{t_n}}{\Delta t_n}\sigma_{22}^{t_{n-1}}+\frac{\Delta\sigma_{22}^{t_n}}{\Delta t_n}\varepsilon_{22}^{p0}+\frac{\Delta\sigma_{22}^{t_n}}{\Delta t_n}\varepsilon_{22}^{c_n}+\sigma_{22}^{t_{n-1}}\frac{\Delta\varepsilon_{22}^{c_n}}{\Delta t_n} \tag{16}$$

Inside of step Δt_n, the elementary solution $\Delta\sigma_{22}^{t_n}$ is:

$$\Delta\sigma_{22}^{t_n}=\frac{-\sigma_{22}^{t_{n-1}}\Delta\varepsilon_{22}^{c_n}}{\frac{2}{E}\sigma_{22}^{t_{n-1}}+\varepsilon_{22}^{p0}+\varepsilon_{22}^{c_n}} \tag{17}$$

where ε_{22}^{p0} is the plastic strain at moment *t=0*.

As expected, the elementary variation $\Delta\sigma_{22}^{t_n}$ is negative, that means the stress relaxation at the notch tip. Also, the elementary variation of strain, $\Delta\varepsilon_{22}^{c_n}$ is directly obtained from the creep law:

$$\dot{\varepsilon}_{22}^{c}(\sigma;t)=f(\sigma)\cdot g(t) \tag{18}$$

Usually, the creep law is written as Norton law:

$$\dot{\varepsilon}_{22}^{c}(\sigma;t)=A\cdot\sigma^{\alpha}\cdot t^{\beta} \tag{19}$$

Here *A, α, β* are material constants for a specific temperature. In the paper we use the elementary form:

$$\Delta\varepsilon_{22}^{c_n} = \Delta t_n \cdot \dot{\varepsilon}_{22}^{c}(\sigma;t) \tag{20}$$

Further, the elementary form from Eq. (20) is used in the Eq. (17) to numerically obtain the elementary variation of the stress $\Delta\sigma_{22}^{t_n}$ at each current step of time Δt_n.

Ramberg-Osgood material law and the creep law used in the process zone

To obtain the actual stress at notch tip, we used both Neuber's rule and Ramberg-Osgood equation in the following equation set:

$$\sigma^e \cdot \varepsilon^e = \sigma \cdot \varepsilon \tag{21}$$

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \cdot \left(\frac{\sigma}{\sigma_0}\right)^n \tag{22}$$

with: σ_0 = reference stress that we consider as yield stress $\sigma_{0.2}$; ε_0 = reference train corresponding to yield stress as $\varepsilon_{0.2}$; n = work hardening exponent; α = Ramberg-Osgood coefficient.

Usually, n and α constant are derived from the tensile stress-strain curves for the temperature of interest in analysis.

Combining the Eq. (21) and (22) results in a nonlinear equation to infer the actual stress value at notch tip:

$$\frac{\sigma^e \cdot \varepsilon^e}{\sigma \cdot \varepsilon_{0.2}} = \frac{\sigma}{\sigma_{0.2}} + \alpha \cdot \left(\frac{\sigma}{\sigma_{0.2}}\right)^n \tag{23}$$

Taking into account the elastic strain given by:

$$\varepsilon^e = \frac{\sigma^e}{E} \tag{24}$$

the Eq. (23) becomes:

$$\frac{\left(\sigma^e\right)^2}{\sigma \cdot E \cdot \varepsilon_{0.2}} = \frac{\sigma}{\sigma_{0.2}} + \alpha \cdot \left(\frac{\sigma}{\sigma_{0.2}}\right)^n \tag{25}$$

The elastic value of stress is obtained with finite element method computer code and Ramberg-Osgood parameters from the experimental data. Finally, the solution of Eq. (25) gives values of actual stress in the elastic-plastic regime σ_{22}^0. Further, the plastic strain ε_{22}^{p0} at the initial moment *t=0.0* is obtained from the equation:

$$\varepsilon_{22}^{p0} = \varepsilon_{0.2} \cdot \frac{\sigma_{22}^0}{\sigma_{0.2}} + \alpha \cdot \varepsilon_{0.2} \cdot \left(\frac{\sigma_{22}^0}{\sigma_{0.2}}\right)^n \tag{26}$$

After obtaining the solutions of Eqs. (25) and (26), it can move on to the iterative calculation of the stress relaxation at the notch tip, based on the adequate creep law and on the specific period of time.

The stress relaxation due to the creep is approached by "time stress hardening", and the creep strain rate is given by [5-7]:

$$\dot{\varepsilon}_{22}^{c}(\sigma;t) = A \cdot \sigma^{\alpha} \cdot t^{\beta} \tag{27}$$

with: $\dot{\varepsilon}_{22}^{c}$ - the creep strain rate; A - a constant dependent on the temperature; σ - the applied stress; t - the time under loading; α, β - material constants.

Results

Note that the creeps under high stresses have different constants in the creep equations, different from those for normal stresses. In present paper, the coefficients are taken over from "small punch tests" [8]:

$$A = 1.54 \cdot 10^{-43.5}\left(\frac{1}{h}\right) \quad \alpha = 13.16 \quad \beta = 0.0 \tag{28}$$

For time exponent, β=0 is chosen because during the iterations, the time step is small (order of hours). For the CANDU pressure tube, a V notch (according to CAN/CSA N285.8-05) is analysed by finite element method with VisualFEA computer code [9] for the initial stress-strain state in the elastic domain.

The defect's characteristics are, as follows: depth a=0.5 mm, tip root ρ=0.1 mm. The loading in elastic domain is characterized by: internal pressure in the tube P=10 MPa, and nominal hoop stress σ_n=140.8 MPa.

The results of the elastic analysis by finite element method are displayed in Fig. 1. One may see that maximum value of the principal stress is σ_{p1}=784 MPa, that will be used in the analyses as σ^e=784 MPa at t=0.0. From Ramberg-Osgood equation the following values are obtained: σ_{22}^0 =522 MPa and $\varepsilon_{22}^{p0} = 0.0119$.

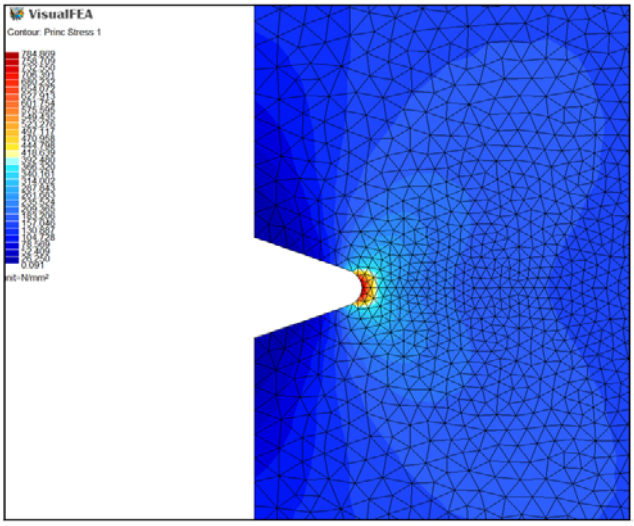


Fig.1. Aspect of mesh and maximum principal stress field by VisualFEA for V notch in the CANDU pressure tube

An iterative loop has been implemented in Matlab with the implementing of described methodology, for a time period of 10^5 Effective Full Power Hours (EFPH). The algorithm followed in this paper to obtain the effects of the stress relaxation in the V notch process zone area is given below:

1. the finite element analyses in the elastic domain is performed by using VisualFEA computer code for a CANDU pressure tube specimen in the V notch area;
2. maximum value of the elastic principal stress σ^e is obtained, and by using the Neuber's rule and Ramberg-Osgood law the actual value of stress σ_{22}^0 is inferred;
3. at *t=0.0* the plastic deformation is obtained ε_{22}^{p0} ;
4. start the creep analyses and at each time step Δt_n , the creep strain increase $\Delta\dot{\varepsilon}_{22}^{c_n}$ is obtained based on the defined creep law;
5. decrement of the stress $\Delta\sigma_{22}^{t_n}$ is obtained based on the previous creep strain $\Delta\dot{\varepsilon}_{22}^{c_n}$;
6. total deformation is calculated until current step time;
7. steps 4 to 6 are reloaded until the specified time period is reached for the creep analyses;
8. time dependence $\sigma = F_1(t)$ and $\varepsilon = F_2(t)$ are obtained.

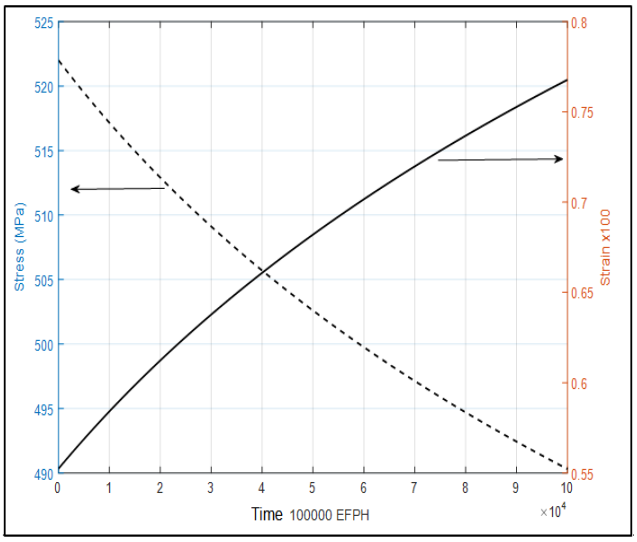


Fig.2. The stress relaxation and increased strain in the V notch process zone for the CANDU pressure tube

In Fig. 2 the results of the stress and strain in a V notch process zone of a pressure tube after 10^5 EFPH are displayed. One may see the stress relaxation and increased strain in the V notch process zone for the CANDU pressure tube. Table 1 presents the relative variation for the two mechanical parameters analysed.

Table 1. Analyses results

Relative variation	***Time***	***Relative variation***
$\frac{\Delta\sigma}{\sigma}$	10000	- 6.13
$\frac{\Delta\varepsilon}{\varepsilon}$	10000	40.0

From the analysis of the results for a time period of 10^5 EFPH we may conclude that:
- the relative decrease stress due to the stress relaxation phenomenon during the creep is about -6.13%;
- relative increase of the accumulated strain is 40%.

Conclusions

The paper develops a methodology for numerical analyses of the stress relaxation and strain accumulation in a V notch process zone due to the thermal creep with the following steps:
- the Neuber's total strain energy density rule is applied to obtain the stress relaxation and the total strain due to the creep phenomenon in the process zone;
- the numerical approach has been described for the localized creep in the process zone;
- by using the VisualFEA computer code, the stress-strain field for the initial state is obtained in the elastic domain, and with Ramberg – Osgood law, the actual stress and strain is inferred;
- an algorithm implemented in Matlab environment is applied and the results of the stress relaxation and accumulated strain in a V notch process zone are obtained;
- for near future works, more complex flaws are foreseen in order to use the results in the framework of CANDU fuel channels structural assessments from Cernavoda NPP.

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