ORIGINAL PAPER

ASSESSMENT OF DELAYED HYDRIDE CRACKING IN CANDU PRESSURE TUBE USING THE PROCESS ZONE WITH CREEP EQUATION FROM ARTIFICIAL NEURAL NETWORK MODELLING

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Manuscript received: 15.03.2024; Accepted paper: 11.09.2024;
Published online: 30.09.2024.

Abstract. *The pressure tubes of the CANDU 600 nuclear power plant at CNE Cernavoda Romania are made of Zr-2.5%Nb alloy, which is susceptible to hydrogen accumulation during normal operation. As part of the work, structural integrity analyses will be performed regarding the initiation of the Delayed Hydride Cracking (DHC) phenomenon at the complex flaws in the pressure tubes, which can be detected by the periodic inspections performed on the fuel channels. These flaws are described by the Canadian standard CAN/CSA N285.8 as a combination of a Bearing Pad Fretting Flaw (BPFF) with a Debris Fretting Flaw (DFF). The analysis of the mechanical stresses and strains field is obtained by finite element analysis (FEA) in the process zone of the flaws, that are located on the inner surface of the CANDU pressure tube. The work develops a method based on FEA, regarding the evaluation of the phenomenon of mechanical stress relaxation by creep in the process zone of flaws for the time interval between two periodic inspections of the CANDU fuel channels. This method allows obtaining the relaxation of mechanical stresses, by inserting the explicit function of the radial strain rate of the CANDU pressure tube (Zr-2.5%Nb alloy) into the algorithm for obtaining iterative numerical solutions in creep. The explicit function was obtained by the Multilayer Feedforward Neural Network (MFNN) method under the conditions of irradiation in-service specific to the CANDU fuel channels. The results of the work are used in the assessment of structural integrity by analysing the prevention of DHC initiation in the pressure tubes of a CANDU plant.*

Keywords: *CANDU pressure tube, DHC phenomenon, process zone, creep, stress relaxation, artificial neural network.*

1. INTRODUCTION

Units U1 and U2 from CNE Cernavoda Romania contain CANDU pressure tubes in the fuel channels, which are made of Zr-2.5%Nb alloy. The fuel bundles and the heavy water coolant are housed in the pressure tubes. From the experience of operating CANDU-type plants, it is known that for pressure tubes there is a notable probability that certain defects/flaws are initiated during their normal operation. It should be noticed that this occurs against the background of corrosion produced by the interaction of the heavy water coolant (D_2O) with the inner surface of the pressure tube. Normally, these defects/flaws are assumed to occur mostly during normal operation and refuelling. Thus, during these operations, specific defects may occur on the inner surface of the pressure tube due to possible debris captured between the pads of the fuel elements and the inner surface of the pressure tube, and

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https://doi.org/10.46939/J.Sci.Arts-24.3-c02

they are called debris-fretting flaws (DFF). Also, defects only due to friction between the element fuel pads with the pressure tube are called Bearing Pad Fretting Flaws (BPFF).

The initiation of these volumetric flaws produces localised spots with high mechanical stresses. By combining them with deuterium absorption and exceeding the solubility limits of hydrogen in the Zr-2.5%Nb alloy (about 20-50 ppm), at normal operating temperatures in the reactor, fragile precipitates of zirconium hydride $ZrH_{1.6}$ can be generated, so-called hydride platelets. The hydride platelets, which previously also underwent a phenomenon of reorientation in the radial direction of the pressure tube at the tip of the complex flaw (a combination of BPFF and DFF-type flaws) can generate the phenomenon of slow cracking in the hydride state under mechanical stress - Delayed Hydride Cracking. This is briefly referred to in the literature as the DHC phenomenon [1-4]. Canadian Standard CAN/CSA N285.8 [5] sets out "Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors". Pressure tubes in CANDU nuclear power plants are inspected following CAN/CSA N285.4 [6], entitled "Periodic Inspection of CANDU Nuclear Power Plant Components". When a flaw is detected during periodic inspections and the indication does not meet the acceptance criteria by examination, or when contact between the pressure tube and the calandria tube is detected or predicted, Clause 12 of CAN/CSA N285.4 allows an evaluation of the fitness-for-service.

The present study describes the assessment of the structural integrity of a pressure tube by evaluating a complex flaw, namely a BPFF, where a DFF is found, by the process zone engineering method mentioned in Canadian standard CAN/CSA N285.8-21. In this method, an important role is played by the principal maximum stresses at the tip of the analysed flaw. The flaw is analysed for a while equal to the interval between two periodic inspections, during which the pressure tubes are subjected to in-service creep due to temperature and irradiation. The creep phenomenon produces a relaxation of the mechanical stresses at the tip of the analysed flaw, so it must be considered in the methodology of the process zone regarding the initiation of the DHC cracking mechanism [7]. Also, as it was mentioned in [8] if plasticity at the blunt flaw is not taken into account, then DHC initiation predictions can be too conservative. To obtain the relaxation of mechanical stresses through creep, a numerical method was implemented that uses the creep equation obtained by the method of artificial neural networks within the works that constituted the support of the Project "Prediction of Axial and Radial Creep in CANDU 6 Pressure Tubes", No. 17519/R0, by the IAEA [9]. The explicit function obtained considers the evaluation of the radial deformation rate of the CANDU pressure tube (Zr-2.5%Nb alloy) under the specific creep conditions to the CANDU fuel channels from Cernavoda NPP Units.

Chapter 2 presents the method of obtaining relaxation due to the creep in the flaw process zone of mechanical stresses, which were derived by finite element analysis with the software VisualFEA [10]. This is obtained by inserting the explicit function of the radial strain rate of the CANDU pressure tube (alloy Zr-2.5%Nb) into the algorithm for obtaining iterative numerical solutions in creep [11-14]. This explicit function was obtained by the method of artificial neural networks of the Multilayer Feedforward Neural Network (MFNN) type under the conditions of creep under specific irradiation to the CANDU fuel channel [9]. Chapter 3 describes, in short, the work stages regarding the assessment of DHC crack initiation prevention through the process zone methodology, stipulated by the Canadian standard CAN/CSA N285.8-21. In Chapter 4, an application of the method described in the paper is presented, for the evaluation of a complex BPFF-DFF, using the material properties of the Zr-2.5%Nb alloy, under the conditions of accumulating an equivalent hydrogen concentration specific to the end-of-life.

2. THE STRESS RELAXATION THROUGH CREEP IN THE FLAW PROCESS ZONE

Flaws and discontinuities in a metallic component constitute the mechanical stress concentrators that influence its structural behaviour. At the same time, long-term operation under thermo-mechanical stresses such as those in the nuclear reactor, leads to the appearance of additional phenomena near these concentrators, such as the relaxation of mechanical stresses through creep, respectively the increase of localised deformation. This directly influences the application of various failure criteria, including the initiation of cracking by the DHC mechanism in the CANDU pressure tube.

An evaluation of the stresses and deformations field carried out by the finite element method, for the situations in which they depend on time (the case of thermal creep and creep under irradiation) is carried out, as a rule, with high accuracy with specialized calculation codes in this sense. In the present study, the relaxation of the mechanical stresses at the flaw tip, due to the phenomenon of localized creep, can be done by obtaining some iterative numerical solutions, which combine the phenomena of creep and time-dependent plasticity. The method obtained by iterative numerical solutions is based on the results obtained by the finite element method, for the stresses and strains field in the flaw process zone on the pressure tube. In this way, the values of the mechanical stresses can be obtained after their relaxation due to the phenomenon of in-operation creep, for various periods, values that will then be used in the procedure of the DHC initiation evaluation process zone.

To obtain the iterative numerical solutions in creep, one starts from the application of the Neuber theory which was originally proposed for elastic-plastic bodies with defects, these being subjected to mechanical stress of pure shear [11-13]. The Neuber theory is since the elastic stress concentration factor, K_t is equal to the geometric mean of the elastoplastic stress concentration factor, K_σ and that of the current strain, K_ε:

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

It should be mentioned that relation (1), known as "Neuber's rule" is currently used for stress-strain analyses in the presence of localized plasticity, i.e., at the tip of a defect where a small plastic zone is formed. The Neuber rule can also be written in a form that correlates a hypothetical elastic stress σ_{ij}^e , respectively the elastic deformation ε_{ij}^e with the σ_{ij}^0 component of the current elastoplastic stress and the ε_{ij}^0 component of the respective deformation in the form:

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

In such situations, equation (2) is reduced in the case of plane mechanical stress to the equation:

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

or simpler:

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

where only the direction of mechanical stress is considered.

Here:

- $\sigma_{22}^e = \sigma^e$ represents the elastic stress at the tip of the defect, resulting from the linear elastic stress analysis.
- $\varepsilon_{22}^e = \varepsilon^e$ represents the elastic strain at the tip of the defect, resulting from the linear elastic stress analysis.

- $\sigma_{22}^{0} = \sigma^{0}$ the current stress at the tip of the defect resulting from the elastoplastic stress analysis.
- $\varepsilon_{22}^{0} = \varepsilon^{0}$ the component of the actual strain at the tip of the defect resulting from the elastoplastic analysis.

Equation (4) follows directly from the original Neuber rule and can be interpreted as an equivalence of the total strain elegy density.

In the reference [11, 12] it was shown that the energy density of the total deformation at the tip of a defect remains almost constant:

$$\Omega = \sigma^{e} \varepsilon^{e} \tag{5}$$

This is true as long as the plastic deformation remains localized near the tip of the defect, which constitutes a mechanical stress intensifier. Furthermore, this is true even when there is a relaxation of the mechanical stresses through the phenomenon of creep. In other words, Neuber's rule can be directly extended to the analysis of time-dependent stresses and strains, considering only the direction of mechanical stress [11, 12], thus:

$$\Omega = \sigma^{e} \varepsilon^{e} = \sigma^{0} \varepsilon^{0} = \sigma^{t} \varepsilon^{t} \tag{6}$$

In relation (6) the last term represents the total strain energy density at a certain instant of time, t, under constant mechanical stress and constant temperature. Some of the main characteristics of the numerical approach in the formulation of localized creep taken from [11-14] are described below and will be specifically adapted for an algorithm implemented in the MATLAB programming environment.

It is considered a structural component having a mechanical stress concentrator (volumetric flaw) subjected to constant mechanical stress for a long time. Since the creep mechanism can be considered localized in this situation, given that the stresses are high only near the defect, the following relationship can be assumed according to the Neuber theory [11, 12]:

$$\sigma^{0} \varepsilon^{0} = \sigma^{t} \varepsilon^{t} \tag{7}$$

The time-dependent deformation can be decomposed into three terms, namely the elastic part ε^{et}, the mechanically induced plastic component ε^{po} and the creep contribution ε^{ct}:

$$\varepsilon^{t} = \varepsilon^{et} + \varepsilon^{po} + \varepsilon^{ct} \tag{8}$$

The mechanically induced plastic strain component, ε^{po}, can be considered constant during the time under mechanical stress since it represents the permanent plastic strain at time $t = 0.0$. This hypothesis suggests that during time-constant mechanical stress, there is a trade-off between elastic unloading and creep strain.

Following the proof from [11, 12], the elementary variation $\Delta\sigma^{t_n}$, which occurs in the time interval Δt_n is given by:

$$\Delta\sigma^{t_n} = \frac{-\sigma^{t_{n-1}} \cdot \Delta\varepsilon^{c_n}}{\frac{2}{E} \cdot \sigma^{t_{n-1}} + \varepsilon^{p0} + \varepsilon^{c_n}} \tag{9}$$

Here E is Young's modulus of elasticity, and ε^{p0} is the plastic strain at time $t = 0$.

The elementary variation $\Delta\sigma^{t_n}$ is negative which signifies the relaxation of mechanical stresses by creep at the tip of the flaw.

The elementary variation of the creep strain $\Delta\varepsilon^{c_n}$ can be obtained directly from the creep law, and in this paper, we will work with the equation of the deformation creep rate obtained in the framework of modelling the deformation of the tubes from U1 CNE Cernavoda with the method of artificial neural networks [9].

Artificial neural network technology makes it possible to describe very complex correlations between the input and target parameters [15, 16]. The Multilayer Feedforward Neural Network (MFNN) is a network architecture used in nonlinear neural model in function approximation. Each unit in this kind of network receives the input data as a weighted sum and runs this activation level via a transfer function. Input data is processed through a one-way network, "forward", passing through successive layers. Fig. 1 shows a simplified flow chart used for a two-layer *tansig/purelin* MFNN network. After going through several layers, input data is processed via a one-way network that is "forward".

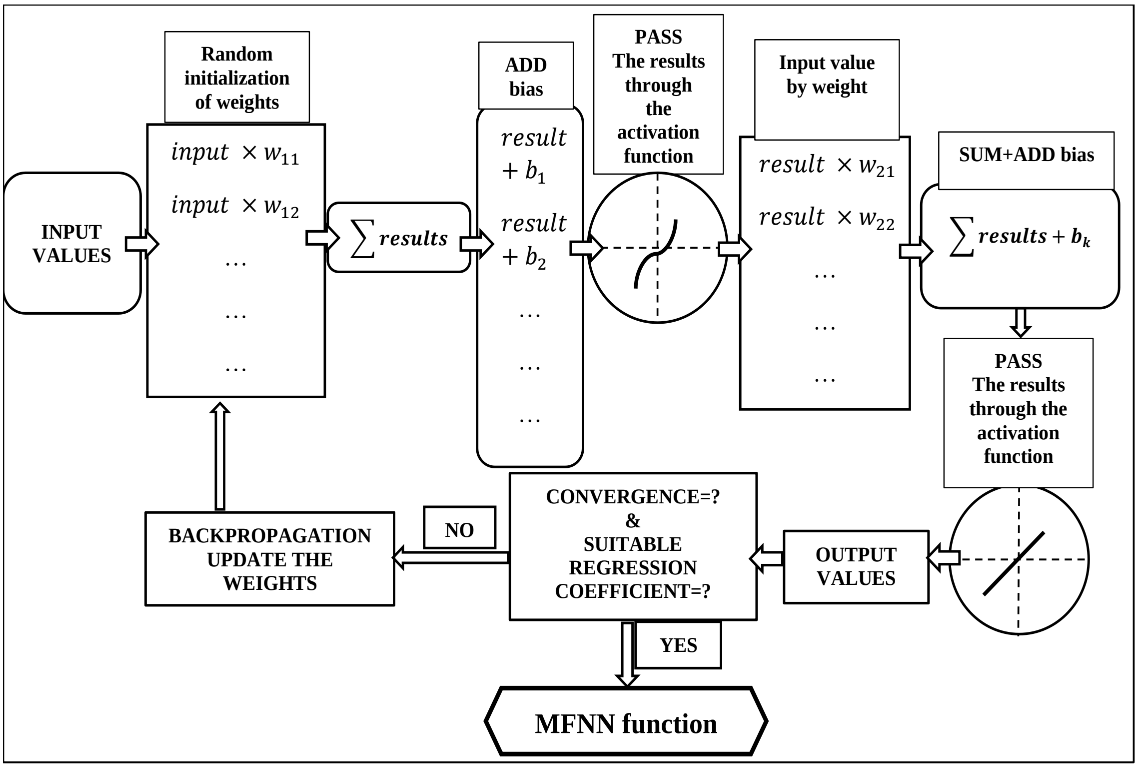

Figure 1. Flaw chart of two-layer tansig/purelin MFNN network [17].

The mathematics behind the artificial neural network fitting tool is quite complex and it is not the subject of the present study. For data processing, the Neural Network Toolbox from MATLAB program [16] was used in the present paper.

The elementary creep-induced strain variation used in the paper has the form:

$$\Delta\varepsilon^{c_n} = \Delta t_n \cdot \dot{\varepsilon}_{\mathrm{MFNN}}(T, \Phi, \sigma) \quad (10)$$

In reference [9], Radu employed a Multilayer Feedforward Neural Network (MFNN) framework with a transverse strain rate model, $\dot{\varepsilon}_{\mathrm{MFNN}}$, to estimate the in-service deformation of Zr-2.5%Nb pressure tubes. Also, Stoica used a Multilayer Feedforward Neural Network (MFNN) model in reference [17], with a good result. The measured data from Cernavoda NPP Unit 1 have been used for the MFNN training. Ultimately, the explicit standalone function for the transverse strain rate was achieved by employing 15 neurons in the hidden layer of the MFNN model [9] following training and validation stages:

$$\dot{\varepsilon}_{\mathrm{MFNN}}(T,\Phi,\sigma)=0.24829964347448125+ + \frac{0.30962913932017166}{\left(1+\exp\left(722.9530387591496-0.4454020093813524\cdot \mathrm{T}+0.42687205931199607\cdot \Phi-3.409121142520387\cdot \sigma\right)\right)} + \cdots 15\ terms \tag{11}$$

Here, the parameters are:

- $\dot{\varepsilon}_{\mathrm{MFNN}}(\mathrm{T},\Phi,\sigma)$= transverse strain rate (units of $10^{-6}\ h^{-1}$)
- T = temperature (K).
- Φ=Fluence (units of $10^{25} n/m^2$).
- σ= mechanical hoop stress (MPa).

The complete form of equation (11) can be found in reference [9].

The elementary law which is given by the creep rate equation $\dot{\varepsilon}_{\mathrm{MFNN}}(T,\Phi,\sigma)$ will be used in equation (10) to numerically obtain the elementary variation $\Delta\varepsilon^{c_n}$, which will be used to obtain $\Delta\sigma^{t_n}$ at each current time step Δt_n. The algorithm is implemented for this paper in the MATLAB programming environment to generate the solution containing the stress relaxation by creep at the flaw tip and the corresponding accumulated strain. The finite element method's initial stress-strain state serves as its starting point.

3. THE ASSESSMENT OF THE DHC INITIATION IN THE CANDU PRESSURE TUBES

The Canadian standard CAN/CSA N285.8-21 [5] mentions that the Process Zone Engineering Procedure is based on the cubic polynomial representation of the principal stress distribution at the tip of the volumetric flaw as a function of the distance measured in the radial direction from the tip of the flaw. The singular entity, which is also called the process zone, can be considered as a very narrow two-dimensional strip, emanating from the tip of the defect. Inside this process zone the tensile mechanical stress is idealized and considered to have a constant value p_H, while the relative displacement along the zone from the tip of the surface defect is equal to v_T [5]. Considering the expansion associated with the precipitation of hydrides, it can be argued that as the number of hydrides increases, the stress p_H decreases while v_T increases. It is assumed that the loss of cohesion at the edge of the process zone subjected to tensile stress at the surface flaws, which would correspond to the initiation of DHC occurs when v_T reaches a critical value v_C.

The work steps in the engineering procedure are mentioned in reference [5]. After the v_T and v_C parameters have been calculated, the DHC initiation prevention evaluation will be done using the process zone engineering method. A value of the displacement factor of the process zone denoted C_V is:

- when the stress analysis at the tip of the defect was based on the elastic behaviour of the material, it will be considered $C_V = 1.0$;
- when a cubic polynomial distribution is used at the tip of the defect in the process zone, and plasticity or creep is also considered, then the value $C_V = 1.15$;
- other values can be taken for C_V, with appropriate justification, but its value must not be less than 1.0.

Prevention of DHC initiation will be demonstrated if the inequality is satisfied:

$$C_V \cdot \mathrm{v}_T < \mathrm{v}_C \tag{12}$$

The CAN/CSA N285.8-21 standard states that there is no limit on the number of thermal cycles (heating-cooling) in the application of criterion (12). All coefficient values are presented in "Appendix A: Procedures for the evaluation of pressure tube flaws" of document CAN/CSA N285.8-21. The MATLAB programming environment is used to implement the algorithm that is mentioned in reference [5]. Finally, the results regarding the prediction of DHC initiation from the complex flaw considered in the paper will be analysed.

For the calculation of the critical displacement of the process zone, v_C, the following values of the constants were used: $p_C = 450\ MPa$; K_{IH}=4.5 $MPa.m^{1/2}$.

The critical value of the displacement at the process zone tip is:

$$\mathrm{v}_C = 0.38\ \mu m. \tag{13}$$

This value will be used for comparison with displacement at the process zone tip, v_T.

To obtain the displacement value v_T of the process zone under the mentioned conditions, a calculation script was implemented in the MATLAB programming environment, under the steps described in reference [5].

4. APPLICATION FOR DHC ASSESSMENT USING THE MECHANICAL STRESS RELAXATION THROUGH MFNN CREEP

For the operating conditions of the CANDU fuel channels, there are two thermo-mechanical stress transients within which the DHC cracking initiation scenarios are analysed. These are contained in the characteristics of cool-down transients and heat-up transients, depending on certain features of the nuclear power plant unit. In this paper, the temperature and pressure parameters on the pressure tube during a cooling transient will be considered to obtain the input parameters in the modelling with the finite element method.

In the present study, we will consider that the zirconium hydride platelets are precipitated at the tip of the blunt flaw. For the nominal mechanical stress in the wall of the pressure tube, the pressure exerted on the faces of the volumetric defect can also be considered, namely:

$$\sigma_n = P\left(\frac{R_i}{w} + 1\right) \tag{14}$$

If we consider the nominal stress in the tube wall, away from the defect zone, then the calculation relationship will be:

$$\sigma_n = P \cdot \frac{R_i}{w} \tag{15}$$

Here:

P - is the coolant pressure;

R_i – the inner radius of the pressure tube;

w – the wall thickness of the pressure tube.

The input data for the analysis with the finite element method in the present study will be those of the pressure tube at the coolant inlet (inlet, P_{in}). Thus, the following input data will be considered for the modelling of volumetric blunt flaws in the wall of the pressure tube by the finite element method:

- for coolant pressure $P_{in} = 11.3\ MPa$, a conservative value that can appear in operation, for which the values of the nominal stress in the wall of the pressure tube are obtained, $\sigma_{in} = 145\ MPa$;

- for the material properties of the Zr-2.5%Nb alloy, the Young's modulus of elasticity $E = 91.7\ GPa$ and the Poisson's ratio of the zirconium matrix: $\upsilon = 0.4$;
- for the BPFF plus DFF volumetric flaw dimensions, the following geometric characteristics were selected, based on the mentions in the Canadian profile literature [7, 8] (DFF defects with the highest degree of induction of DHC initiation in CANDU pressure tubes):
- a wall thickness of the TP: $w = 4.0\ mm$;
- o the inner diameter of the pressure tube: $D = 103\ mm$;
- the total depth of the defect: $a = 0.8\ mm$;
- the DFF flaw is type V with a tip radius $\rho = 50\ \mu m$;

For the complex defect type BPFF plus DFF type V, the analysis of the initial state of stresses and deformations is carried out in the elastic-plastic field with the finite element method. The material properties were selected from the Canadian standard CAN/CSA N285.8-21 [5], under the conditions of prolonged irradiation ($\emptyset > 1.8 \cdot 10^{24} n/m^2$).

Using the method described by Stoica in reference [18], the Ramberg-Osgood constitutive relationship shown in Fig.2 is obtained.

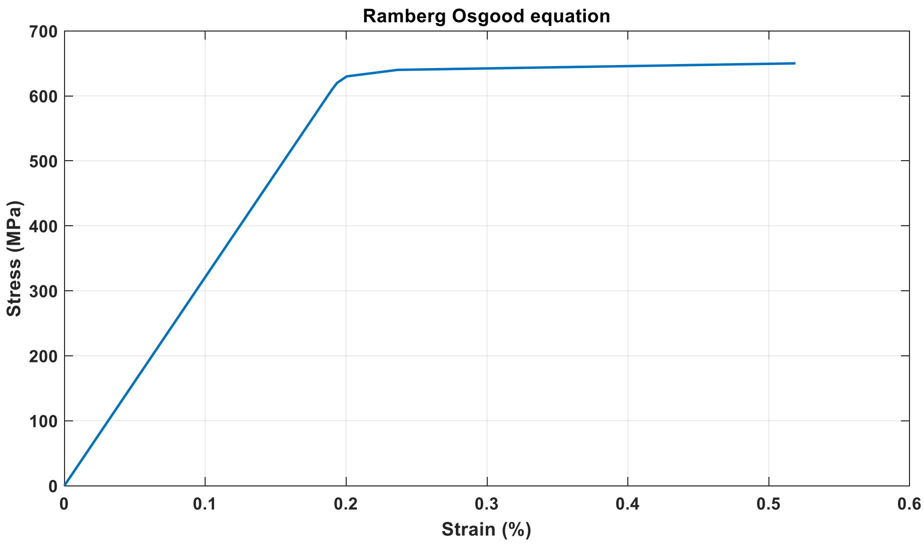

Figure 2. Ramberg-Osgood characteristic for the pressure tube in the transverse direction, Zr-2.5%Nb alloy.

It should be mentioned that this characteristic is valid for the transverse direction of the CANDU pressure tube under the conditions of prolonged irradiation. To be used in the finite element analysis software, the constitutive Ramberg – Osgood equation is converted into a bi-linear $\sigma - \varepsilon$ curve. With this implementation of the bi-linear characteristic $\sigma - \varepsilon$, it will be possible to perform the analysis of the field of mechanical stresses and deformations in the elastoplastic domain.

The principal stress around complex flaws (BPFF with DFF) with dimensions mentioned above is shown in Fig. 3. After obtaining the values of the main stress σ_1 and the accumulated deformation at the initial moment of the analysis, the methodology presented in Chapter 2 is used to obtain the relaxation of the mechanical stresses after a period of operation of 2 years, i.e., $t = 15780\ EFPH$ (Effective Full Power Hours). Both quantities are represented in Fig. 4.

For the process zone at the V-type flaw tip, the relaxation of the principal stress σ_1 achieved for time $t = 15780\ EFPH$, is shown in Fig. 5.

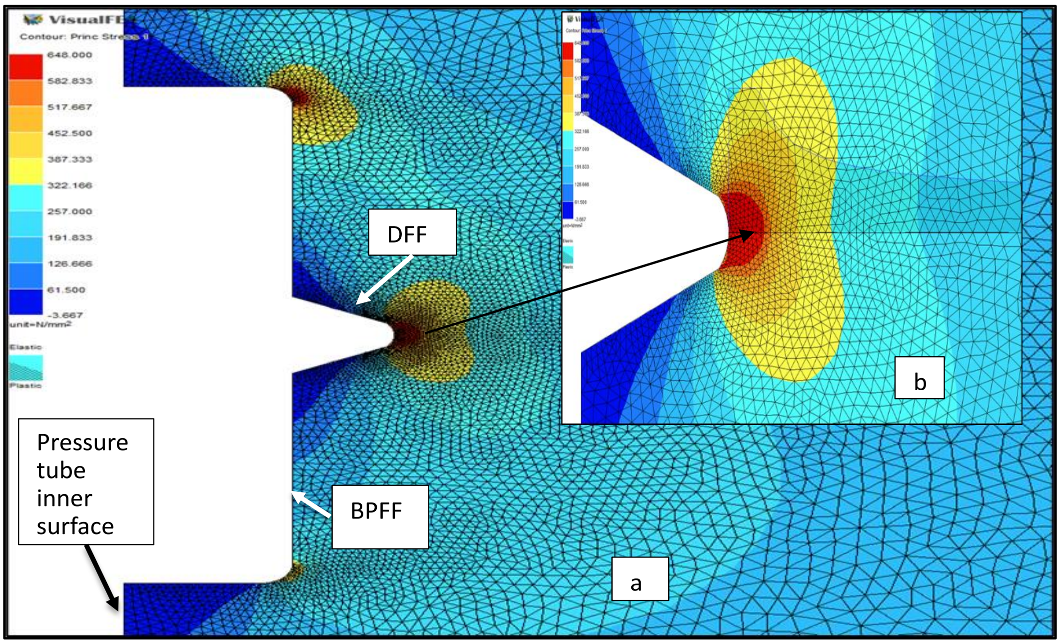

Figure 3. Finite element analysis of the Flaw (BPFF plus DFF): (a) principal stress σ_1, (b) detail in the process zone.

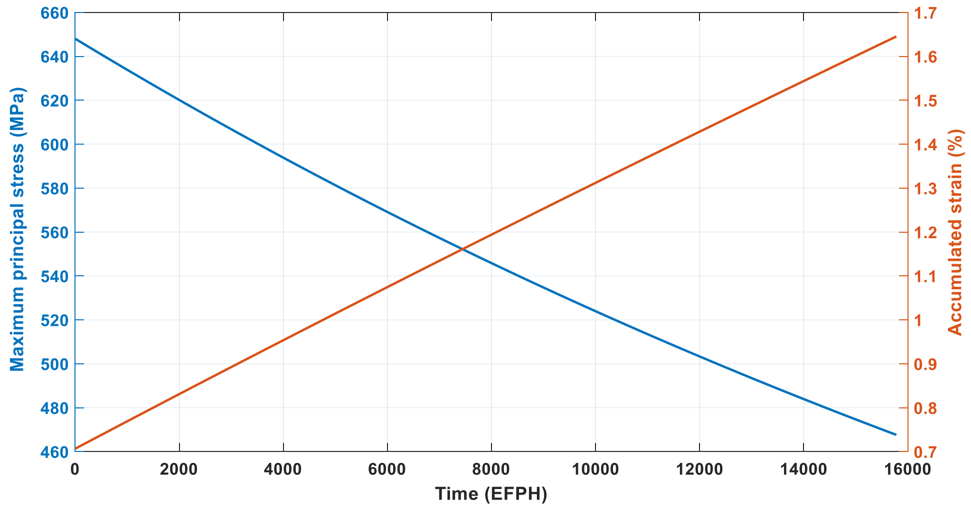

Figure 4. The variation of the maximum principal stress $\sigma_1$from the tip of the V-type flaw and the accumulated deformation for time $t = 15780\ EFPH$.

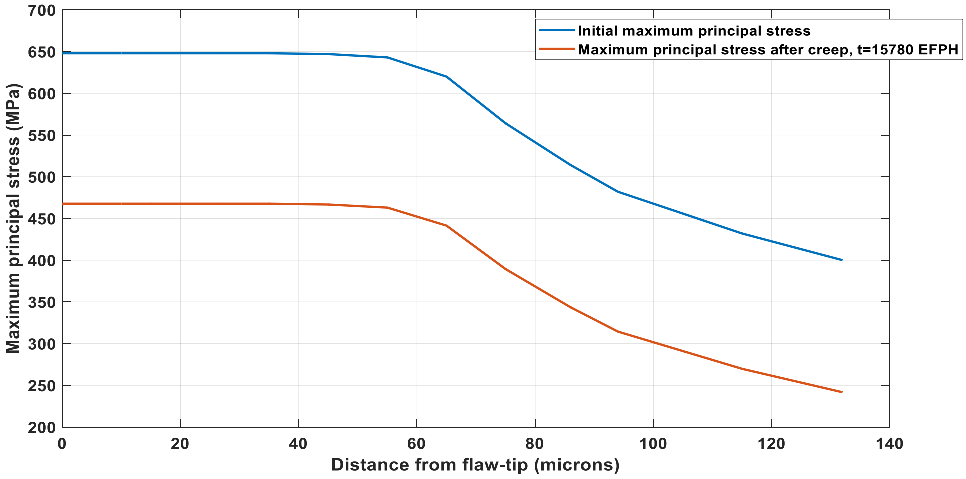

Figure 5. The relaxation of the principal stress σ_1 the process zone, for time $t = 15780\ EFPH$.

It can be seen from the analysis presented in Fig. 5 that, for the considered time interval, the stress relaxation has a value of approximately $200\ MPa$ at the flaw tip. This leads to the fact that through the phenomenon of stress relaxation due to creep, peak stress decrease by 30-45% of the initial value in the process zone, a particularly important fact in evaluating the initiation of DHC. Using the values of the principal stress obtained after creep, for an initial distance of $x_0 = 0.132\ mm$, measured from the tip of the flaw, the iteration process can be started, as it is described in reference [5], related to the process zone methodology. In this way, the process zone length, $\boldsymbol{s}$, as well as the opening at the tip of the process zone, v_T, is obtained, with which the prediction of the initiation of the DHC mechanism is evaluated. After the iterations related to the process zone algorithm carried out until the distance x_0, on which the polynomial approximation of the main stress is made, becomes approximately equal to the length of the process zone $\boldsymbol{s}$, and the polynomial function shown in Fig. 6 is obtained.

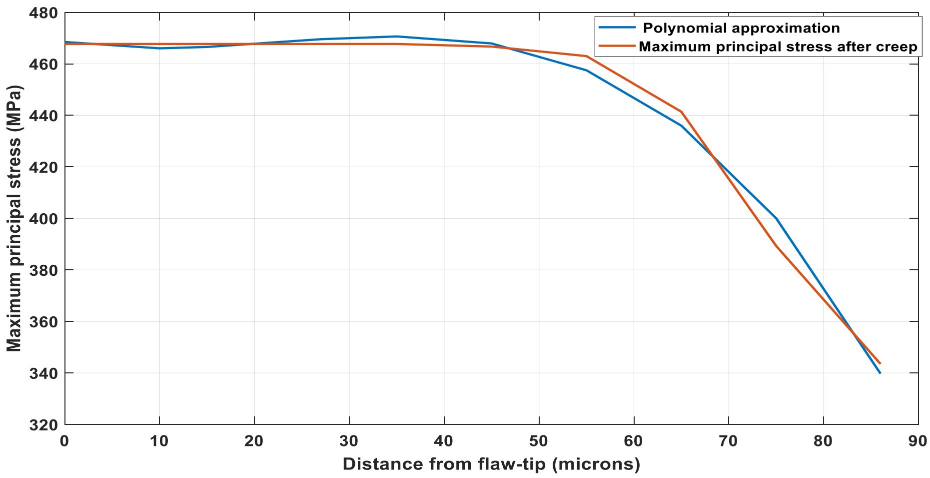

Figure 6. Polynomial approximation of the dependence of the principal stress, σ_1, on the distance measured from the tip of the V-type flaw.

From Fig. 6, the polynomial approximation is quite good compared to the mechanical stress results after creep. Next, after several successive iterations performed automatically in the program implemented in MATLAB, a value of $\boldsymbol{s} = 72.3\ \mu m$ is obtained in this case for the process zone length. The opening at the process zone tip is v_T=0.09 μm. For critical displacement, the value $v_C = 0.38\ \mu m$ is obtained. According to the CAN CSA standard N285.8-21 [5], the condition is checked:

$$1.15 \times v_T < v_C \tag{16}$$

That means:

$$1.15 \times 0.09\ \mu m < 0.38\ \mu m \tag{17}$$

Relation (17) indicates that DHC crack initiation does not occur at the inlet end of the CANDU pressure tube, under the mentioned analysis conditions for the complex flaw. As it was mentioned in [8] if plasticity is not taken into account, then DHC initiation predictions can be too conservative. This is in line with the consideration from the reference [19].

The application presented in this article can be used as a model for any type of volumetric flaw, found on the inner surface of a CANDU pressure tube, Zr-2.5%Nb alloy, knowing the material data, the operation history in the reactor and the geometric characteristics of the flaw.

The study is part of the methodology developed at RATEN ICN regarding the evaluation in the operation of the flaws revealed by the periodic inspections carried out on the fuel channels from Units U1 and U2 at Cernavoda CNE.

5. CONCLUSIONS

The paper presents a method to evaluate the Delayed Hydride Cracking phenomenon and the integrity of the CANDU 600 pressure tube, Zr-2.5%Nb alloy, considering the integration of the phenomenon of relaxation of mechanical stresses through in-service creep phenomena in the process zone procedure stipulated in the Canadian standard N285.8- 21.

This method has practical values, for obtaining the relaxation of mechanical stresses from the tip of a flaw through creep, by combining the algorithm for obtaining iterative numerical solutions in creep, with the explicit function of the radial deformation rate of the pressure tube CANDU (Zr-2.5%Nb alloy). The explicit function was obtained by the Multilayer Feedforward Neural Network (MFNN) method under the conditions of creep under irradiation specific to the CANDU fuel channel. It was developed within the framework of the research activities that constituted the support by RATEN ICN Pitesti, in the "Prediction of Axial and Radial Creep in CANDU 6 Pressure Tubes" CRP Project, which ended with a document developed under the auspices of the IAEA.

Based on the methodology presented in the paper, an application was developed for the evaluation of a complex volumetric flaw consisting of a Bearing Pad Fretting Flaw (BPFF) plus a Debris Fretting Flaw (DFF), with dimensions like those detected by periodic inspections on the CANDU pressure tube. The defect was analysed for material properties and thermo-mechanical stress conditions given by the inlet position of the pressure tube.

From the structural integrity analysis carried out in the study, following the Canadian standard CAN/CSA N285.8-21, for the BPFF plus DFF type complex flaw, placed at the inlet end of the pressure tube, the V defect having the tip radius $\rho = 50\,\mu m$ and the depth $a = 0.8\,mm$, analysed by the process zone methodology, it was found that DHC initiation is not possible.

The results of the work are part of the methodology developed at RATEN ICN Pitesti for the evaluation of the results of the periodic inspections carried out on the fuel channels from CNE Cernavoda, units U1 and U2.

Acknowledgements: *The authors gratefully acknowledge financial support from RATEN ICN Pitesti, Romania.*

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