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Principle management of NPP typical structural components safety operation using specific failure models

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Abstract

The Fukushima tragedy has initiated rising activities to remove a number of NPPs from operation all over the world. An aggressive hydrogen environment influence is supposed to accelerate a precipitateness of the fatigue fracture process in the considered NPP structure components. Consequently, technical risk and means for defrayment of this risk (in other words, means for NPP safety operation) will increase. It is possible to optimize these means using developed special engineering models of crack propagation in structure components subjected to aggressive hydrogen environment and cycling.

Keywords: Risk; Crack; Hydrogen

1. Introduction

Each NPP structure component should meet requirements for safety maximization and cost minimization. The technical risk conception is used to describe this actual problem. Different tragedies, such as Fukushima one, for instance, led to increasing means for NPP safety operation. Each structure component apparently has numerous defects (cracks, for instance) with their shape, sizes, etc. being of probabilistic nature. An aggressive hydrogen

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environment influence is supposed to accelerate a precipitateness of the fatigue fracture process in the considered structure component. Therefore, specific crack propagation models should be used to optimize the means to be considered as necessary for defrayment of the technical risk of NPP structure component under consideration.

2. The principle of the technical risk optimization

Each structure component technical risk increases in the course of operation, and different NPP structure components are not exceptions. Each structure component has its own lifetime $t^*$, which can be defined by specific model, and this lifetime depends on the initial crack length, loading frequency, etc. Technical risk of the considered structure component $R(t)$ is defined by Monte Carlo method. The initial crack length value $l_0$ is supposed to be random. Safe level of technical risk is $P_f = [R]$ (see Fig. 1). Naturally $[R] < 1$.

A nondestructive inspection can be used to detect and repair the considered NPP structure component (at time $t_c$, for instance, see Fig. 1a. As a result the technical risk of the component decreases. This may allow us to extend the life of considered component to $t^*$. Suppose that a defrayment of this technical risk is in direct proportional to it. This may result in the gradually increasing subsidiary to support safe operation of considered component. It should be noticed that a nondestructive control may supposedly need the means for visual inspection, start-stop operations, personal equipment etc. Therefore, life extension of the considered NPP structure component may be very expensive. The curve in Fig. 1b should take it into consideration. Technical risk function of typical NPP structure component subjected to hydrogen environment and cycling could be calculated using a specific engineering model which is presented below.
3. The specific engineering model for the NPP structure components life estimation

The developed engineering model could be applied to the components which are subjected to aggressive hydrogen environment and cycling. Numerical life estimation of structure components under consideration is possible by means of the developed model on the assumption that both the hydrogen environment and the fatigue have an independent effect on the structure component. Thus, either the aggressive hydrogen environment influence or the plastic strain accumulation caused by cycling, initiate a local fracture process in the considered NPP structure component. The life of a structure component \( t^* \) is over when the crack reaches its critical length \( 2l^* \) (Tarakanov, 2013).

3.1. The crack growth rate due to simultaneous action of hydrogen and cycling

The crack growth rate due to simultaneous action of hydrogen and cycling is described as follows (Tarakanov et al., 2012)

\[
\dot{L}_i \approx a \left[ \min \left( \Delta t'_{h}, \Delta t'_{f} \right) \right] = F \left( [X], [Y], \sigma^*, l_0, t \right)
\]

where \( \Delta t'_{h} \) and \( \Delta t'_{f} \) are the crack growth time from \( l_i \) to \( l_i + a_i \) caused by the hydrogen embrittlement combined constant loading and by the fatigue, respectively, \([X]\) and \([Y]\) are mechanical and environment parameters, \( l_0 \) is an initial half-length of the crack, \( t \) is a time of operation.

3.2. The crack growth rate due to cycling

The crack growth rate due to fatigue process in developed model is defined as follows (Anderson, 2005)

\[
\dot{L}_f = A Y \Delta \sigma^* \sqrt{\pi l}
\]

where \( A, n \) are Paris-Erdogan constants, \( Y \) is a crack shape factor, \( \sigma^* \) is a stress far from the crack, \( l \) is half-length of the crack.

3.3. The crack growth rate due to hydrogen embrittlement

The special model to estimate the crack growth rate in the considered structure component due to hydrogen environment influence and static loading is presented below. This model is developed for the structure component with a crack under mode I loading. The considered structure component is made from homogeneous solid isotropic material. Suppose that hydrogen penetrate into the hydrogenated region through the crack tip, see Fig. 2.

\[ \sigma^* \]

Hydrogen penetration into material lattice is defined as follows (Panasyuk et al., 1988)

Fig. 2. Considered crack under mode I loading.
\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} + f \left( \left[ \Psi \right] \right) \frac{\partial C}{\partial x} \frac{\partial \bar{\sigma}}{\partial x}; \quad C(0, t) = C^0; \quad C(x, 0) = C^0 G(x)
\]  

(3)

where \( x \) is a coordinate from the crack tip, \( C = C(x, t) \) is a hydrogen distribution function, \( \bar{\sigma} \) is stress distribution near the crack tip, \( C^0 \) is the current hydrogen concentration in the material-environment interface, \( f \left( \left[ \Psi \right] \right) \) is a function of environment and material parameters.

Modulus of elasticity, fracture toughness, etc. in hydrogenated region differ from the similar parameters in non-hydrogenated part of the same body. Numerous experimental data validates it, for instance (Toribio et al., 1997). So, conditional stress intensity factor (CSIF) and conditional fracture toughness (CFT) \( \tilde{K}_j \) and \( \tilde{K}_{\text{c}} \) are introduced instead of \( K_j \) and \( K_{\text{c}} \) in the hydrogenated region near the crack tip and a criterion of the crack propagation is described by eq. (4) (Tarakanov, et al., 2014)

\[
\tilde{K}_j \left( \bar{\sigma}^*, l \right) \geq \tilde{K}_{\text{c}} \left( \bar{C}_a \right)
\]  

(4)

where \( \tilde{K}_j = Y \bar{\sigma}^* \sqrt{l} \), \( \bar{C}_a \) is an average hydrogen concentration in a prerupture region \( a(l) \) of the material. This region is much smaller than the hydrogenated one.

Crack growth rate in hydrogenated material depends on a specific pair, i.e. environment and material used in different experiments. Therefore, authors have introduced a new material-environment characteristic \( \Omega \) to relate the current hydrogen concentration in the crack tip \( C^0 \) (environment, initial condition of eq. (3)) to the maximum solubility of the hydrogen in material \( C^* \) (material), in other words \( \Omega = C^0 / C^* \) (Tarakanov, et al., 2014).

CFT \( \tilde{K}_{\text{c}} \) versus \( \bar{C}_a \) is described by the eq. (5):

\[
\left( \left( \tilde{K}_{\text{c}} - \tilde{K}_{\text{c}}^0 \right) / \left( \tilde{K}_{\text{c}}^0 - \tilde{K}_{\text{c}}^* \right) \right)^{\alpha} + \left( \Omega \bar{C}_a / C^0 \right)^{\beta} = 1
\]  

(5)

where \( \tilde{K}_{\text{c}}^* \) is CFT of the material with uniform hydrogen concentration equals \( C^0 / \Omega \), \( \tilde{K}_{\text{c}}^0 \) is CFT of the non-hydrogenated material, \( \alpha, \beta \) are constants.

Eq. (5) describes the experimental data in the field concerned for various curves of the CFT versus \( \bar{C}_a \). A typical curve is shown in Fig. 3.

![Fig. 3. CFT versus hydrogen concentration.](image-url)
Crack propagation process in the presented model includes three main stages i.e. incubation, stable, and unstable ones. The latter determines the end of unsafe operation of considered structure component.

The structure of the developed engineering model is described by six diagrams, which are connected to each other. These diagrams are shown in Fig. 4 to represent the following: solution of eq. (3), the fracture mechanics problem, environment-metal characteristic, characteristic $l(t)$, auxiliary diagram and diagram of crack re-growth.

Fig. 4. Crack propagation engineering model structure.

The diagram D4 is compulsory to determine the crack growth rate in hydrogenated material subjected to static loading.

Here, three main stages of crack propagation due to hydrogen embrittlement and static loading are described in details (Tarakanov, et al., 2012).
• The first growth stage is an incubation one which could last quite long. It depends on the diffusion constant, temperature, etc. The incubation stage is an accumulation of hydrogen near the crack tip in the prerupture region. Process of hydrogen accumulation is described by the eq. (3). As time passes, the average hydrogen concentration in the prerupture region reaches maximum which is defined by the eq. (5). When the value of CSIF reaches CFT one the crack starts growing. Thereby initial half-length of the crack becomes $l_0+a(l_0)$. Besides, the new prerupture region is formed near the crack with initial half-length $l_0+a(l_0)$. It should be noticed, that the regrowth value $a(l_0)$ of the crack in the incubation stage is constant and it depends on the metal lattice.

• The second stage is a stable crack growth. After the incubation stage completing, the initial hydrogen concentration in the current prerupture region exceeds the initial one in the previous prerupture region (see points $P^2_0$, $P^2_1$, $P^2_2$, etc. in the Diagram 2, Fig. 4). Therefore, each regrowth of the crack in the current stage lasts not as long as the incubation one. The stable crack growth proceeds till the initial average hydrogen concentration in the prerupture region does not exceed the critical one in the current prerupture region.

• The third stage is an unstable crack growth. It proceeds when the initial average hydrogen concentration is greater than the critical one. Naturally, this stage means a failure of the considered structure component.

Lifetime of the structure component, subjected to hydrogen aggressive environment and static load, is determined by means of the developed model. Eq. (1) could help to determine the crack propagation in the structure component due to hydrogen embrittlement and cycling. Therefore, lifetime and the technical risk function of the considered structure are determined as well. Consequently, means for defrayment of this technical risk may be defined and optimized.

4. Conclusions

The proposed principle management of NPP structure components safety operation may allow optimization of means to defray the technical risk. This principle management is based on the specific model of crack propagation in NPP structure components subjected to aggressive hydrogen environment and cycling. It is possible to estimate the life of the considered structure components by developed specific model and to define the technical risk function.

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