RANDOM HYDROGEN-ASSISTED FATIGUE CRACK GROWTH IN STEEL PLATES

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1. Introduction

Hydrogen lowers the endurance of steel. In particular, it accelerates fatigue crack growth, thereby shortening fatigue lifetime of structures [1]. In the present paper a simple model of the influence of hydrogen on fatigue crack growth is presented. The model is then employed to perform a stochastic analysis of crack growth in a thin plate with a random hydrogen content.

2. Description of the problem

The analysis is performed in the simple case of an infinite, thin plate with a rectilinear crack of length $2a$. The plate contains hydrogen and is subjected to a remote, cyclic loading $S(t)$, perpendicular to the crack. It is assumed that diffusion is very slow, so that hydrogen concentration in the plate does not change significantly during crack propagation. There are small variations in the hydrogen content of the plate, resulting from hydrogen trapping and material inhomogeneities. From the stochastic point of view, hydrogen concentration in the plate is described by a two-dimensional stationary random field $C(x,y,\gamma)$, where x, y are the coordinates on the plate, and γ is the parameter of randomness.

3. Mechanical model

Empirical equations of fatigue crack growth in hydrogen free metals usually take the form [2]

$$\frac{da}{dN} = f(K_{\max}, K_{\min}, \textit{material parameters}) \tag{1}$$

where N is the number of load cycles, and $K_{\max}$, $K_{\min}$ are the maximum and minimum stress intensity factors at the crack tip over a cycle of loading. It is postulated that, in the presence of hydrogen, fatigue crack growth can also be described by equations of type (1), after suitably modifying the stress intensity factors. The following assumptions are made:

- There is a Barenblatt-Dugdale cohesive zone in front of a crack tip,
- Hydrogen degradation follows the hydrogen enhanced decohesion mechanism, with a linear dependence of cohesive forces on hydrogen concentration [3],
- Hydrogen concentration is approximately constant in the cohesive zone,
- Residual stresses along the crack are negligible; fatigue crack growth is only influenced by hydrogen degradation of the crack tips [4].

For the considered geometry, the modified mode I stress intensity factors take the form

$$K = \frac{\sigma_0 S}{\sigma_0 - \alpha C}\sqrt{\pi a} \tag{2}$$

where σ_0 is the cohesive force in the absence of hydrogen, α is the coefficient of degradation, and C is the hydrogen concentration in the cohesive zone. It is assumed that fatigue crack growth in the presence of internal hydrogen can be adequately described by combining equations (1) and (2).

4. Stochastic analysis

The presented model allows a convenient stochastic analysis of crack growth in the random hydrogen field $C(x,\gamma)$ - here restricted to one dimension, along the extension of the crack. $C(x,\gamma)$ has a constant mean $\overline{C}$ and a correlation function $K_C(x_1,x_2)$.

A simple example problem can be obtained by specifying (1) to the Paris equation

$$\frac{da}{dN} = A\Delta K^m \tag{3}$$

where $\Delta K = K_{\max} - K_{\min}$, and A, m are constants of the hydrogen-free material. Equation (2) gives

$$\Delta K = \frac{\sigma_0\,\Delta S}{\sigma_0 - \alpha C}\sqrt{\pi a} = \frac{\Delta S}{1-\xi}\sqrt{\pi a} \tag{4}$$

where $\Delta S = S_{\max} - S_{\min}$ is the amplitude of the cyclic loading S, and $\xi = \alpha C/\sigma_0$ is a stationary random field. The following treatment is similar to the one presented in [5].

From (3) and (4) one receives (after noting that - with high probability - $\xi \ll 1$, and by making a linear approximation)

$$dN = B(1-\xi)^m a^{-m/2} da \approx [x + y(\xi - \bar{\xi})] a^{-m/2} da \tag{5}$$

where $B = 1/(A\Delta S^m \pi^{m/2})$, $x = B(1-\bar{\xi})^m$, $y = -Bm(1-\bar{\xi})^{m-1}$, and $\bar{\xi} = \alpha\bar{C}/\sigma_0 = E(\xi)$.

From equation (5) it is easy to obtain the basic probabilistic characteristics of the critical number of cycles N_{cr} (number of cycles to failure). The mean and variance are

$$E[N_{cr}] = E[\int_{a_0}^{a_{cr}} dN] = nB(1-\bar{\xi})^m [a_{cr}^{1/n} - a_0^{1/n}] \tag{6}$$

$$Var[N_{cr}] = E[(N_{cr} - E[N_{cr}])^2] = z^2 \int_{a_0}^{a_{cr}}\int_{a_0}^{a_{cr}} (a_1 a_2)^{-m/2} K_C(a_1,a_2)\, da_1 da_2 \tag{7}$$

where $m \neq 2$, $n = 2/(2-m)$, $z = y\gamma/\sigma_0$, and a_0, a_{cr} are the initial and critical crack lengths, respectively. Generally, equation (7) must be computed numerically.

In the case when $C(x,\gamma)$ is a Gaussian process, N_{cr} is by equation (5) also Gaussian, and therefore is described completely by the mean and variance given in (6) and (7). The accuracy of this result is limited by the linear approximation made in equation (5) and by the fact that $C(x,\gamma)$ must be positive and so can not be strictly Gaussian.

5. Conclusions

A method of describing fatigue crack growth in thin steel plates containing hydrogen was briefly outlined. The method is convenient in performing stochastic analysis of crack propagation, when hydrogen concentration in the plate is described by a random field.

6. References

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