

Random hydrogen-assisted fatigue crack growth in steel plates

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ABSTRACT

A stochastic analysis of hydrogen-assisted fatigue crack growth in steel plates is presented. First, a simplified deterministic model of the process is proposed. It captures the basic empirical property that the influence of hydrogen diminishes, as the crack growth rate increases. However, it only applies to cases, when diffusion is rate limiting. Next, the model parameters are randomized to reflect the uncertainty inherent in the physical situation. On the basis of the obtained stochastic equation, probabilistic moments of the time, in which the crack reaches a critical length, are computed. Theoretical results are illustrated by a numerical example.

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1. Introduction

Hydrogen has significant influence on the properties of steel [1]. In particular, steel elements are much less resistant to cracking in hydrogen-rich environments than in air [2,3]. Hydrogen equally affects crack growth under static loads, in which it is the major factor behind crack propagation [4], and fatigue crack growth, in which it only plays an auxiliary role [5].

The case of hydrogen-assisted fatigue is much less recognized from the modeling point of view. Much work has been done on the subject experimentally [5–7] and towards understanding of the underlying phenomena [8], but computational models of the process are scarce [9,10]. The cited analyses are deterministic, and therefore require extension into the domain of parametric uncertainties for their use in reliability assessment.

It has long been recognized that stochastic methods are adequate for describing general fatigue phenomena [11,12]. Fatigue crack growth depends on material parameters which are hard to measure, and vary between and within samples which, for practical purposes, would be described as similar and uniform. It is therefore justified to use random material properties [13] in the description of hydrogen-assisted fatigue as well.

In the present paper, a simple stochastic analysis of hydrogen-assisted fatigue crack growth is presented. The considered system consists of a cyclically loaded plate, absorbing hydrogen through the surfaces of an existing crack. An attempt is made to obtain results, which are useful for reliability assessment. In particular,

the mean and variance of the time to failure of the plate are computed, on the basis of probabilistic characteristics of the physical setting.

2. Description of the physical problem

A thin elastic–plastic steel plate is considered, with a rectilinear through-crack of characteristic size a (a is typically the crack's length for an edge crack, or the crack's half length for an internal crack (Fig. 1)). The plate is externally loaded with a far-field cyclic stress $S(t)$ (t denotes time), perpendicular to the crack. It is also immersed in an aggressive environment, from which hydrogen diffuses into the interior of the plate. The lateral surfaces of the plate are assumed to be coated with a hydrogen-impermeable material, so that diffusion only takes place through the faces of the crack, and particularly through the crack tips (the crack is a spontaneously formed defect, and its surfaces are not coated against hydrogen absorption). It is also assumed that there is no hydrogen in the plate before the crack is formed. The material properties of the plate are uncertain—both on average, and in the sense that they vary within the plate in a manner, which is not precisely known. It is however assumed that the plate is so thin, that any variation of properties along its width can be neglected or averaged. The entire system is therefore considered to be effectively two dimensional.

The crack propagates under the action of the cyclic loading. Additionally, hydrogen diffuses into the plate and embrittles material at the crack tips, thereby accelerating crack propagation. There are three processes involved in the considered physical situation: cyclic loading, hydrogen diffusion and crack growth. Cyclic loading is considered fast compared with the other processes, in the sense

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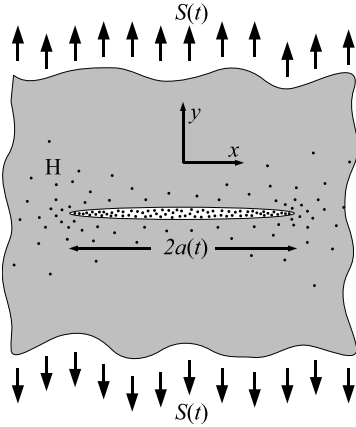


Fig. 1. A plate with a center crack, under cyclic loading and hydrogen diffusion.

that there is no appreciable change of a , nor of hydrogen concentrations in the plate, over a single cycle of S . S is also considered deterministic and independent of the other processes. Hydrogen diffusion, which originates at the propagating crack, geometrically depends on the crack tip's velocity $\dot{a}(t) = da(t)/dt$. This velocity, in turn, depends on S and on the amount of hydrogen in front of the crack tip. In this way, hydrogen diffusion and crack propagation are interrelated, and S affects them both.

3. Construction of a deterministic model

A model of hydrogen-assisted fatigue crack growth is constructed as follows. First, an empirical equation is chosen, which adequately describes fatigue crack growth in the plate in the absence of hydrogen. Then, the equation is modified, to make it reflect the influence of hydrogen. The proposed modification affects stress intensity factors, and depends on hydrogen concentrations in the vicinity of the crack tip. Finally, hydrogen concentrations ahead of an advancing crack are described. This closes the relation between the crack tip velocity, crack length, external loading and the given boundary concentration of hydrogen.

Simplifying assumptions are presented in detail during the construction of the model. Their purpose is to make the model simple enough for subsequent stochastic treatment, but let it capture the most characteristic kinetic properties of the processes involved.

3.1. Fatigue crack growth in the absence of hydrogen

Many equations have been proposed to describe fatigue crack growth under cyclic loading [11]. They have the general form

$$\frac{da}{dN} = F(K_{\max}, K_{\min}, m_1, \dots, m_n) \quad (1)$$

where N is the number of load cycles, K_{\max} and K_{\min} are the maximum and minimum mode I stress intensity factors over a cycle, m_i are material parameters, and F is an empirical function.

For simplicity it is assumed here that fatigue crack growth in the plate is adequately described by a specific form of Eq. (1), the Paris–Erdogan equation

$$\frac{da}{dN} = A(\Delta K)^m \quad (2)$$

where $\Delta K = K_{\max} - K_{\min}$, and A , m are parameters. If another equation was chosen, the treatment which follows would be analogous. Eq. (2) can be rewritten with respect to t , instead of N , for compatibility with the description of diffusion to be presented later. One obtains

$$\dot{a} = \frac{da}{dN} \frac{dN}{dt} = A(\Delta K)^m \nu \quad (3)$$

where ν is the frequency of S .

In general, the mode I stress intensity factor is given by [11]

$$K = BS\sqrt{\pi a} \quad (4)$$

where $B = B(a)$ is a coefficient, accounting for the plate and crack geometry. For an edge crack in a semi-infinite plate, $B \approx 1.12$; for a central crack in an infinite plate, $B = 1$. For simplicity, the latter value is used in all subsequent calculations. The stress intensity factor range becomes

$$\Delta K = \Delta S\sqrt{\pi a} \quad (5)$$

where $\Delta S = S_{\max} - S_{\min}$ is the amplitude of S .

An assumption was made implicitly, to make Eqs. (2) and (3) valid for a center crack. Since A and m are spatially uncertain, their values must be symmetric about the middle of the crack. Otherwise the two crack tips would move at different speeds, complicating the description. Another simplification was the use of the stress intensity factors (4), computed for a uniform plate, which neglect the inhomogeneous structure of the material.

3.2. Modification for hydrogen

Eq. (3) can be modified in various ways to make it reflect the presence of hydrogen. A possible approach is to change the stress intensity factors, which has the advantage that it can also be applied to other equations of type (1). It is therefore proposed that \hat{K} , which denotes a modified stress intensity factor, be used in the crack growth equation instead of K (and, accordingly, $\Delta \hat{K} = \hat{K}_{\max} - \hat{K}_{\min}$ instead of ΔK). The modified Eq. (3) takes the form

$$\dot{a} = \nu A(\Delta \hat{K})^m. \quad (6)$$

\hat{K} is a function of K and of hydrogen concentration ahead of the crack. It should model the experimentally observed increase in crack growth rates due to hydrogen. The following function is adopted for the present analysis

$$\hat{K} = \frac{K}{1 - \xi} \quad (7)$$

which entails in particular that

$$\Delta \hat{K} = \frac{\Delta K}{1 - \xi}, \quad (8)$$

where $\xi = \xi(C)$ quantifies degradation of the pre-fracture zone induced by the hydrogen concentration C . Formally, $\xi(C)$ is a functional defined on hydrogen distributions ahead of the crack tip. Here it is defined as

$$\xi(C) = \gamma C(d), \quad (9)$$

the value of hydrogen concentration at a distance d from the crack tip, multiplied by a coefficient of degradation γ . By assuming after [9] that

$$d = \eta \tilde{K}^2 \quad (10)$$

where $\eta \sim 1/\sigma_y E$ is a constant of the material (σ_y is the yield stress and E is the elastic modulus), and \tilde{K}^2 is the average of K^2 over a cycle of S (because of linearity, $\tilde{K}(S) = K(\tilde{S})$, where \tilde{S}^2 is the average of S^2 over a cycle), one receives for the present configuration (here $\tilde{K} = \tilde{S}\sqrt{\pi a}$):

$$d = \pi \eta \tilde{S}^2 a. \quad (11)$$

An assumption was made above that the modified stress intensity factors \hat{K} depend only on hydrogen concentrations in the immediate vicinity of the crack tip. This neglects the residual stresses, produced by a nonuniform hydrogen concentration in the plate. Their influence can be computed by the weight function method [14], and should be added to K before it is used to compute \hat{K} . However, the resulting correction is usually very small, compared with the effects of hydrogen degradation of the crack tips.

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