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Service life of corrosion pitted pipes subject to fatigue loading and hydrogen embrittlement

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ABSTRACT

The structural service life of brittle material pipes with exterior corrosion pits is likely to depend on crack initiation and crack development and this may be influenced by pressure loading fluctuations and the possibility of material hydrogen embrittlement. Recently developed methods are used to estimate the cracking pattern, the failure state of the crack development from external pits and the rate of Hydrogen-Assisted Cracking under fluctuating loadings. The effect of hydrogen from the surrounding environment on the cracking rate is formulated using a generalized form of Paris' law. The depth of cracks initiated from surface pits is estimated as a function of pipe age. A realistic example is presented and the results discussed.

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Introduction

Water supply pressure pipes typically are subject to daily operating pressure variations that are essentially low frequency loading [1]. Conventionally the resulting crack development is considered in the context either of Stress Corrosion Cracking [2,3] or of corrosion fatigue [1,4–7]. Where hydrogen is involved, the crack growth rate usually is considered to increase with decreasing loading frequency since hydrogen has more time to diffuse into and within the metal under lower frequencies [4,7–11].

Many numerical studies [12–16] and experimental reports [17–20] show that cracks along pipes often commence at the sites of corrosion pits [21,22]. Stress concentrations at corrosion pits magnify the effects of hoop stress resulting from pressure fluctuations in a pipe. Thus, compared with the intact surface of a pipe, pitted sites receive a wider range of

stresses. This intensifies the fatigue loading at pits. Cracking from corrosion pits can be modelled using the approach proposed in Refs. [23,24]. This situation is magnified if there is also the presence of hydrogen. Under certain exposure conditions hydrogen can reach into pits, gouges and cracks in the microstructure on the external surface of pipes [25–27]. Also, in aqueous soil environments hydrogen can be generated electrochemically on the external surface of ferrous pipes [28].

Hydrogen embrittlement can reduce the structural strength [29–31] and the ductility [32–34] of metals and thus increase the rate of fatigue cracking. As such, rate of fatigue cracking increases with hydrogen pressure in pipelines [35–38]. When the crack is assumed to be of a simple, pre-defined general shape, the approach described in Ref. [1] can be used for modelling crack propagation from pits under hydrogen conditions (herein termed Hydrogen-Assisted Fatigue Cracking, HA-FC). However, more realistically, the shape of a crack starting from a pit is likely to be influenced by the

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stress field in the neighbourhood of the crack front and this is likely to be influenced by pit shape. Ideally, therefore, both the crack front and the pit shape should be incorporated in modelling the development of the crack. For this a computational model coupling hydrogen diffusion and crack propagation is required. Computational models for representing Hydrogen-Assisted Fatigue Cracking (HA-FC) usually are classified in two general categories according to the effect hydrogen has on material fracture properties [39]. In the first category the failure of hydrogen affected region is attributed to hydrogen enhanced decohesion” (HEDE). In this approach a so-called “traction separation law” [40–43] is used to overcome the singularity of the crack tip. The second category includes methods in which failure is attributed to “hydrogen enhanced local plasticity” (HELP) [44,45].

Herein a novel methodology based on Linear Elastic Fracture Mechanics (LEFM) is used to estimate the service life of pipes affected by corrosion pitting and influenced by Hydrogen-Assisted Fatigue Cracking. The main concepts of the approach used are as follows. First, for a pipe under the influence of hydrogen the likely cracking patterns are estimated using the cracking pattern in the equivalent unaffected pipe. Second, the failure state of a pitted pipe is defined, based on the state of crack development from the pits. In the third step, the rate of cracking under HA-FC is estimated by reducing the material fracture toughness as a consequence of hydrogen diffusion from the crack front, using the method proposed in Ref. [46]. Finally, having available the rate of crack development from the previous step, the location of the crack front is estimated under a HA-FC mechanism and the time required to reach the failure state is estimated. Fatigue formulation herein has been adopted from authors previous works and are based on experimental tests by others. The theory on which service life prediction method is based on in this paper should be an incentive to conduct future long term experimental observations/tests to validate the method proposed in here.

Hydrogen diffusion under low frequency cyclic loading

Like all diffusion processes, the diffusion of hydrogen is driven by the gradient of hydrogen concentration (potential) [43]. Several material factors influence the diffusion process. These include the diffusivity ‘constant’ D , the extent of local plasticity, the rate of plastic strain, the presence of sites that trap hydrogen and the intensity and form of the local stress field [47–50]. Herein these are taken into account by an equivalent (or apparent) diffusivity, D_{app} . For most water pipes under normal operational conditions the pressure fluctuations cause only a limited amount of fluctuation in the range of stress intensity (ΔK) at the tip of any crack that may have formed. This means it is plausible to assume D_{app} changes only slightly with ΔK and hence it is reasonable to assume a constant value of D_{app} in calculations. In the following only one-dimensional diffusion is considered. This is based on reports that diffusion in the direction normal to the crack plane does not influence the distribution of hydrogen concentration ahead the crack

and is therefore of minor influence in governing diffusion [43,51,52].

Based on these assumptions, the diffusion equation can be simplified to:

$$\frac{\partial u}{\partial t} = D_{app} \frac{\partial^2 u}{\partial x^2} \quad (1)$$

in which:

u : Relative concentration of hydrogen in the metal, defined

as $\left(\frac{\text{concentration of hydrogen in the metal}}{\text{concentration of hydrogen in the environment}} \right)$

t : Elapsed time, starting from the formation of a new crack tip

D_{app} : Apparent diffusivity of hydrogen in the metal

x : Distance in the direction of the crack direction, from the crack tip to where the hydrogen concentration is being considered.

For simplicity, let the relative concentration of hydrogen at the tip of the crack, where the metal is in direct contact with hydrogen, be assumed to be unity, irrespective of the hydrogen pressure in the surrounding environment. This means that the boundary conditions are assumed to move with the crack as it grows. Thus, to solve Equation (1) under moving boundary conditions the origin of the coordination system is reset to be at the crack tip for each incremental computational step. In consequence, the boundary conditions for each increment of crack growth are:

$$u_n(0, t) = 1 \quad (2)$$

$$\lim_{x \rightarrow \infty} u_n(x, t) = 0 \quad (3)$$

in which u_n is the relative concentration of hydrogen in the metal after the occurrence of the n th computational increment.

As noted, the solution of Equation (1) can be considered as a moving boundary condition problem, with the initial condition for the next increment being the solution of the previous increment. Recalling that the origin is set at the crack tip, the initial condition for n th increment is:

$$u_n(x, 0) = u_{n-1}(x + x_n, t_n) \quad (4)$$

Let it now be assumed that the rate of cracking in fatigue is slow and that the frequency of applied loading is low. As a result, there is more time for hydrogen to diffuse through the metal. It is therefore reasonable to assume that the hydrogen concentration at the crack tip is similar to that in the surrounding environment. Further, this is likely to be the case at every stage in the development of the crack. Some notion of the hydrogen concentration ahead the crack tip can be obtained by considering just the first increment (i.e. the time at which the crack just starts to grow). In this first increment of crack growth, hydrogen is unlikely to have diffused fully into the metal so the initial condition, Equation (4), is zero. The hydrogen concentration in this step of development is obtained as a simple closed form solution of the diffusion problem [53]:

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