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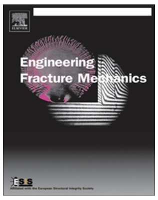

Crack closure effects during low cycle fatigue propagation in line pipe steel: An analysis with digital image correlation

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ABSTRACT

Fatigue crack growth was investigated in a line pipe steel. Severe straining conditions, like those experienced by pipelines, were considered during the experiments. Crack closure effects were investigated during the tests by adopting an innovative technique based on digital image correlation. Experimentally measured crack closure levels were implemented in a crack propagation model based on elastic–plastic fracture mechanics. A modified formulation of ΔJ_{eff}, necessary to accurately describe crack propagation driving forces, is presented and employed to assess fatigue life in presence of high plastic strains.

1. Introduction

Pipelines are employed in challenging harsh environments, where they have to sustain severe loading conditions. Especially when working in arctic-like environments, linepipe materials can be subjected to plastic straining cycles due to thermal cycling between service and shutdown and to occasional large plastic deformations induced by ice scouring in shallow water [1–3].

Fatigue properties (fatigue strength and life) can be conservatively predicted, assuming the presence of small shallow cracks with a depth corresponding to the detection limit of Non-Destructive Techniques (NDT) [4]. Therefore, an initial assessment of pipelines fatigue properties can be made considering a crack propagation problem in the Low Cycle Fatigue (LCF) regime, in which a crack starts propagating from the first load cycle [5]. Due to the presence of high plastic strains, traditional approaches based on Linear Elastic Fracture Mechanics (LEFM) cannot be applied in LCF [6]. On the other hand, crack growth rates in the LCF regime can be described as a function of the cyclic J-Integral, ΔJ. The idea to extend Rice's path independent J-Integral [7] to fatigue was originally proposed by Dowling [8], who modified Paris relationship [9], by replacing with ΔJ the stress intensity factor range, ΔK. ΔJ formulation was employed to analyze crack growth in the early propagation phase in [10], whereas in [11] a model based on the cyclic J-Integral was adopted to provide an assessment of fatigue life of specimens tested under LCF loading conditions. Such an approach was also adopted by Skallerud and Zhang for describing the growth of flaws in off-shore components under extremely high strain levels (prospective LCF life of 80–100 cycles under $\Delta\epsilon > 2\%$ [12]).

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Nomenclature

A_0	extension of the plastic zone surrounding the crack-tip
A_n	extension of the infinitesimal part of the plastic zone surrounding the crack-tip
a	crack length
a_0	initial crack length
a_f	crack length to failure
$2\,c$	surface crack extension
C, m	Paris law constants
$h(n_i)$	function for plastic J-Integral range description
k_i	cyclic strain/stress curve constant
n_i	cyclic strain/stress curve exponent
E	Young's modulus
R	strain ratio ($\epsilon_{min}/\epsilon_{max}$)
R_m	ultimate tensile strength
$R_{p,02\%}$	yield stress
$R'_{p,02\%}$	cyclic yield stress
Y	geometric factor
ΔJ	cyclic J-Integral
ΔJ_{el}	elastic part of the cyclic J-Integral
ΔJ_{pl}	plastic part of the cyclic J-Integral
ΔJ_{eff}	effective J-Integral range
ΔK	stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
ΔW_e	elastic strain energy density
ΔW_p	plastic strain energy density
$\Delta\sigma$	stress range
$\Delta\sigma_{eff}$	effective stress range
$\Delta\epsilon$	strain range
$\Delta\epsilon_{eff}$	effective strain range
$\Delta\epsilon_p$	plastic strain range
$\Delta\epsilon_{p,eff}$	effective plastic strain range
α	constraint factor
$\epsilon_{a,p}$	plastic strain amplitude
ϵ_{el}	elastic part of the total strain
ϵ_{max}	maximum strain during the fatigue cycle
ϵ_{op}	strain measured at crack opening
ϵ_{pl}	plastic part of the total strain
σ_0	flow stress
σ_n	stress in the direction normal to crack plane
σ_{cl}	crack closing stress
σ_{max}	maximum stress during the fatigue cycle
σ_{open}	crack opening stress
σ_{ref}	reference stress for data normalization

It has been shown that, at lower strain amplitudes, crack closure is an important factor, even during LCF crack growth. Seeger and Vormwald [13–15] measured crack opening levels during LCF experiments by placing a strain gage over the crack and measuring the changes in local strains. Starting from these observations, they proposed a different formulation of ΔJ, which implemented the effects of crack closure. The cyclic J-Integral equation was modified by replacing stress and plastic strain ranges with the effective ones, calculated by considering only the portion of the fatigue cycle in which the crack stays open. A similar approach was also proposed by McClung and Sehitoglu in [16,17] and by Pippan and Grosinger in [18]. In[19], ΔJ_{eff} formulation was rewritten and successfully applied to describe crack propagation under LCF at high temperature.

In these models, crack closure was modeled by means of the equations proposed by Newman [20]. The adoption of the model proposed by Newman, however, presents some limitations, since it was developed for cracks propagating under LEFM conditions and considering fully reversed loads.

In this work, crack closure mechanisms are investigated by adopting a recent technique based on computer vision, Digital Image Correlation (DIC). DIC was initially developed in the early 1980s at the University of South Carolina [21–24], with the idea to measure full-field in-plane displacements and displacement gradients of a strained body, but was also successfully applied to fracture mechanics. In [25,26], DIC was employed to characterize opening and closing levels by measuring the