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Load sequence effects on the fatigue crack growth in a cylinder subjected to combined rotary bending moment and axial force loads

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ABSTRACT

This study used a fatigue crack growth model of a semi-elliptical external surface crack in a hollow cylinder subjected to a combination of rotary bending moment and axial force. In the literature, several authors have explored the problem of crack growth in a hollow cylinder but only for each loading case separately: cyclic tension, rotary bending and cyclic bending. Furthermore, no one has studied the effect of load sequence for this case of structure and loading. In this paper, the study shows the evolution of crack geometry during loading cycles seemingly depends only on accumulated life fraction of the already applied cycles (life fraction is the ratio of the number of load cycles N and the crack growth life N_R corresponding to the constant cyclic loading). Therefore, the fatigue crack growth is independent of the load level and the load sequence. This remark can be used to explain the damage accumulation models in fatigue based on life fraction.

1. Introduction

The study of crack growth in a hollow cylinder subjected to combined rotary bending moment and axial force is important for the case of drill-string element fatigue. Faced with the complexity of the oil and gas wells drilled today, the fatigue phenomenon is the most significant cause of drill-string failure [1,2]. The complex trajectory of the wells induces a high mechanical stress in the drill-string, which contributes to the severity of drill-pipe fatigue. The rotation of drill-pipe in a curved section of well in which there is a change of hole angle and/or hole direction, commonly called “dog-leg”, creates a rotary bending moment and produces the cyclic bending loading in drill pipes. This is the main cause of drill pipe fatigue. Furthermore, the rotary bending stress and the axial force acting on drill-pipe are variable during drilling operations.

The fatigue crack growth in a hollow cylinder subjected to different loading types has been previously numerically studied in the literature [3–7]. Carpinteri and Brighenti [3] studied the fatigue crack growth in a pipe subjected to cyclic bending using a theoretical three-parameter model of a semi-elliptical crack (where the crack ellipse centre moves through the cylinder diameter). An important result shows that the ellipse crack centre is rapidly approaching the surface. Therefore, a two-parameter model is quite enough to describe this crack growth process.

Lin and Smith [4] used a 3D finite element simulation and a two-parameter crack model (the centre of the crack ellipse is fixed on the cylinder external surface) for studying a crack on hollow cylinder surface. The authors showed that all the defects of any initial shape change to semi-elliptical shape after some cycles of loading in a process of fatigue crack propagation. Therefore actually the semi-elliptical crack shape is most commonly used for the case of a hollow cylinder surface crack.

Carpinteri et al. have published a list of papers on the crack growth in a pipe under several loading cases separately: cyclic tension [5], cyclic bending moment [6] and rotary bending moment [7]. In the case of rotary bending moment, they have given the results only for a thick pipe ($R_{int}/T = 1$) [7]. Furthermore, the influence of the combination of the rotary bending moment and the tension on the crack propagation has not been studied.

Following these literature studies, Dao and Sellami [8] have presented a completed crack growth model for any hollow cylinder for the case of combined axial force and rotary bending loads. The crack model in this study is chosen by the following reasons: (i) In general, the crack is growing perpendicular to the principal stress. For the case of a hollow cylinder subjected to bending and tension loads, the principal stress direction is the cylinder axis. Thus, the crack is supposed to be in a cylinder cross section. (ii) For the reasons on the crack shape described above, the two-parameter semi-elliptical crack model where the crack ellipse

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Nomenclature

R_{int}, R_{ext}	cylinder internal and external radii
D_{int}, D_{ext}	cylinder inner and outer diameters
T	cylinder thickness
A	crack depth for the deepest point A, a semi-axe of the crack front ellipse
B	second semi-axe of the crack front ellipse
$A0, B0$	initial crack size
H	absolute value of crack front point x-coordinate
$\alpha = \frac{R_{int}}{T}$	a dimensionless ratio of cylinder geometry
$\beta = \frac{B}{A}$	aspect ratio of the crack front ellipse
$\gamma = \frac{A}{T}$	relative crack depth
$\xi = \frac{x_p}{H}$	normalized coordinate of the generic point P on the crack front
F, M	axial force and bending loadings
M_{x1}, M_{y1}	bending loadings about the axis O_1x_1, O_1y_1
Ψ	angle of bending moment vector
S_a, S_m	bending stress amplitude and mean stress
K_I	stress intensity factor (mode I)
$K_{I,F}, K_{I,M_{x1}}, K_{I,M_{y1}}$	stress intensity factor corresponding to each loading case
$F_{I,F}, F_{I,M_{x1}}, F_{I,M_{y1}}$	stress intensity dimensionless factors
$R = \frac{K_{min}}{K_{max}}$	stress ratio
C, m, λ	coefficients of Walker's crack growth law
E, ν	Young's modulus and Poisson's ratio of material
N	number of loading cycles or number of cylinder rotations
N_R	crack growth life: number of cycles during which the crack develops from the initial depth $A0$ to the cylinder thickness T

centre is assumed to be located on the cylinder outer surface is selected (see Fig. 1).

The Walker fatigue crack growth law [9] is used in order to take into account the mean stress effect on the crack growth. Newman-Jr et al. [10] have shown that in the case of short cracks, the crack grows much faster than would be predicted. Therefore the Walker's law is not valid for the short crack problem and this model is only used with the assumption that an initial macroscopic crack exists on the cylinder surface.

The Stress Intensity Factors (SIFs) are calculated from a database built using 3D finite element simulations (CAST3M code developed by the French Alternative Energies and Atomic Energy Commission) [11]. Different results of SIF calculation using this database were presented in [8]. The comparisons have shown that this model of SIF calculation agrees well with the results of Carpinteri et al. [7] for the rotary and cyclic bending cases in a thick pipe ($R_{int}/T = 1$), and with those of Shahani and Habibi [12] for the bending and tension loadings in a thin pipe ($R_{int}/T = 10$).

The crack growth model presented in Dao and Sellami [8] brings the following important advantages in comparison with those existing in the literature: (i) It takes into account the combination of rotary bending moment and axial force. (ii) The SIF database is built for a wide range of cylinder dimensions (various R_{int}/T ratios). Therefore, this database allows the application of the model to several cases of drill-pipe dimensions.

Several papers in the literature have presented the models and some results on the crack growth for several loading cases [5–8]. However, studies on the crack evolution in a hollow cylinder were limited to the case of constant loads. No one has studied the effect of load sequence on crack growth, which is the focus of this paper.

Loading sequence effect on fatigue crack growth has been investigated experimentally in the literature [13,14]. However, these studies were carried out on the simple sample subjected to a simple cyclic load. The numerical simulation is proposed to study this effect for a complicated geometry configuration subjected to multiply loads.

In this paper, we will mostly investigate relationships between the crack geometry parameters (relative crack depth A/T and crack aspect ratio B/A) and the life fraction N/N_R. The crack growth life N_R in this study is considered as the number of cycles during which the crack develops from the initial depth $A0$ to the cylinder thickness T. This corresponds to the fact that in practice, a large part of the crack growth life is due to the growth of a small crack. In the case of constant cyclic loading (bending stress amplitude S_a and mean stress S_m are constant), for a given cylinder, N_R is a function of the cyclic loading (S_a, S_m) and the initial crack size ($A0, B0$). An example of crack growth is illustrated in Fig. 2.

The study in this paper uses hypothesis of Linear Elastic Fracture Mechanic (LEFM). It does not take into account the effect of the nonlinearity behavior of material. In fatigue crack growth, the crack tip plasticity is an important parameter, which can result a compressible residual stresses developing in the plastic zone around crack tip during unloading phase of the cycle. During the next cycle, the applied load must overcome the residual compressive stress present in the plastic zone to open the crack. This is the phenomenon of crack closure induced by plasticity in fatigue crack growth.

In general, the crack closure can be taken into account in fatigue crack growth by using the variation of effective stress intensity factor $\triangle K_{eff} = K_{max} - K_{op}$ where K_{op} is crack opening threshold of stress intensity factor [15]. This crack opening threshold K_{op} is a

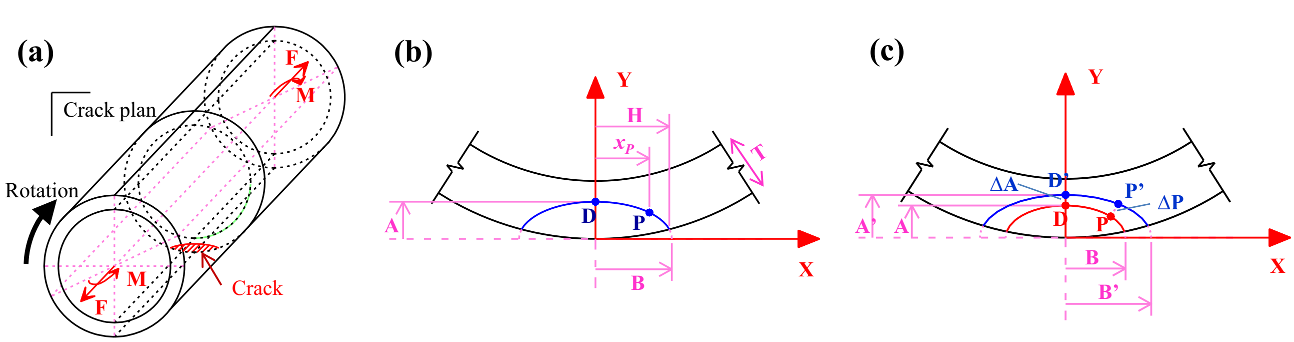

Fig. 1. (a) Cracked cylinder and loading, (b) 2 parameters fatigue crack growth model, and (c) crack growth after a calculation iteration.