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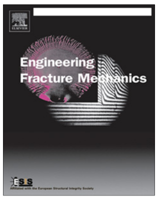

An efficient framework for rapid life assessment in industrial applications: Fatigue crack growth

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A B S T R A C T

In the last 30 years closed form solutions for stress intensity factors (Sih, 1973) [1] have been used extensively in crack propagation life assessment. While these low runtime solutions are very attractive for probabilistic type life assessments, they are constrained to simple geometries and loading conditions that would limit their application at component level. More recently, traditional 3D finite element techniques were developed to model incremental crack growth and estimate life. In contrast to the closed form solutions, finite element simulations can be more accurate capturing geometry and loading conditions but at a high runtime cost. An alternate method to make use of accurate 3D finite element based stress intensity factor solutions in a more efficient manner and to determine crack propagation life is proposed here. Bayesian hybrid modeling is utilized in this approach to provide a balance between the two techniques. Several Mode-I examples are presented herein to set a benchmark on accuracy and runtime efficiency of the proposed method.

1. Introduction

Life assessment based on fracture mechanics principles has become an integral part of most engineering organizations that design large industrial equipment. Manufacturers of aircraft engines, power generation, oil & gas drilling, production and downstream equipment use fracture mechanics principles to assess life of their most critical components under damage tolerant design framework [2]. Engineering analysis of crack growth to assess the life of a component under service conditions involves the following:

i. computation of stress intensity factors for an assumed flaw within the structure;
ii. use of crack growth rate (da/dN)-stress intensity factor (SIF) range correlation from coupon tests;
iii. information on maximum allowable crack size based on fracture toughness.

This type of life assessment analysis is vital for ensuring safe service life of critical structures such as pressure vessels, nuclear power plant equipment, aircraft engines and gas turbine rotors and discs [3].

The following two approaches are followed by practicing engineers to conduct life assessment of industrial components based on crack propagation: (1) use of handbook solutions for stress intensity factor that is limited to simplified geometries, (2) use of finite element solutions for stress intensity factors in actual component geometry. While the former approach is

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Nomenclature

Symbol	Description (Units)
a	crack depth (in.)
c	half crack width (in.)
c_0, a_0	subscript zero indicates initial crack size (in.)
C	Paris coefficient – refer Eq. (1) (no units)
n	Paris exponent– refer Eq. (1) (no units)
K_I, K_{Ic}, K_{Ia}, $K_{Ic,i}$	stress intensity factors under mode-I loading (psi·$\sqrt{in}$)
ΔK_I	range of variation of K_I ($K_{I,max}$–$K_{I,min}$) (psi·$\sqrt{in}$)
N	number of cycles (cycles)
σ	far-field stress (psi)
E	elastic modulus (psi)
ϕ	parametric angle – refer Figs. 3 and 7 (degrees)
T	thickness (in.)
W	width (in.)
H	height (in.)
D	diameter (in.)
X_c	crack center x-coordinate (in.)
Y_c	crack center y-coordinate (in.)
θ	crack transition angle – refer Figs. 11 and 21 (degrees)
3DFAS	three dimensional fracture analysis system/GE proprietary
DOE	design of Experiment
BHM	Bayesian hybrid model
API	application program interface

widely used in the industry due to its simplicity and efficient life prediction, it is known to be conservative and sometimes even inaccurate because of the simplified representation of the actual component. The handbook solutions are available for relevant representative crack geometries in recommended lifing practices such as BS-7910 [4], ASME Div. III [5], API-579 [6] and implemented in commercially available life assessment codes such as NASGRO [7], AFGROW [8], FASTRAN [9], SignalFFS [10] etc. These life assessment codes with interactive and easy-to-use GUIs make the handbook solutions very attractive to practicing engineers involved in lifing and design across different industries. When more accurate closed form solutions were required for life assessment of a component that has complex features, different researchers came up with solutions to address specific geometries or more complex far field loading: Pommier et al. [11] generalized solution for an elliptical crack into a semi-infinite body for an arbitrary far field loading; Kiciak et al. [12] developed corner crack solutions for plates under a varying far field stress; Millwater [13] addressed collinear two dimensional interacting cracks under arbitrary loading; Lin and Smith [14] provided closed form solutions for three dimensional corner cracks at fastener holes.

The latter, classical finite element approach, despite increased accuracy, is still not widely used in the industry because of the following disadvantages:

i. crack insertion and meshing using component level CAD models or orphan meshes is still a tedious process;
ii. automatic crack propagation is difficult with commercial finite element software;
iii. tracking of each point on the crack front during propagation is computationally expensive;
iv. numerical stability issues that arise due to stress intensity variations along crack front.

Although there have been a lot of recent improvements in commercial finite element software codes to ease the meshing of complex geometries in the presence of a crack, the other disadvantages described above still present significant challenges for a practicing lifing engineer to use the FEA approach as a viable option for life assessment. As an alternative, XFEM is still computationally intensive or insufficiently validated for industrial applications [15].

The objective of the proposed methodology reported in this article is to overcome these disadvantages, specifically ii-iv described above and make the FEA approach a more practical, computationally efficient and numerically stable option for fatigue crack growth life assessment. The next section details the steps involved in the new approach.

2. Methodology

In this section, first the traditional FE approach of sequential crack advancement as implemented in 3D Fracture Analysis System (3DFAS), a proprietary code of General Electric Company is described briefly and then, the steps involved in the newly proposed methodology are outlined. For a comprehensive review on crack propagation life assessment, we direct