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Three-dimensional fracture and fatigue crack propagation analysis in structures with multiple cracks

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ABSTRACT

A methodology is presented for fracture and fatigue crack growth simulations of multiple cracks. Computed stress intensity factors and a crack growth law are used to predict incremented positions of crack front nodes. The procedure is repeated until failure criterion is reached. The cases presented in this study include structures containing two or more cracks which propagate, coalesce or grow as planar and non-planar cracks. Comparisons of results with literature data shows excellent agreement. Therefore, it is concluded that the presented procedure can be used to accurately to assess fatigue crack propagation behavior of structures with multiple three-dimensional cracks.

1. Introduction

Especially in the last six decades, the Science of Fracture Mechanics has been taking a greatly important role in assessing the safety of engineering designs and products to determine their remaining lives and tolerance to different types and sizes of flaws. The capability of being able to accurately assess remaining lives of structures and their damage tolerance is critical not only for safety, but also for economic reasons. For most cases, analyses of single cracks in engineering structures can be adequate due to either only one crack exists in the structure or the distances between cracks are far enough so that the interaction effects are negligible. However, for some cases inclusions of physically present multiple cracks with actual geometrical features (e.g., locations, sizes, orientations etc.) in the engineering analyses are unavoidable. These types of cracks or site damages can commonly be seen in engineering structures and machine parts. Depending on their locations and distances between the cracks, mutual interaction can also take place between them. This, in turn, results in changes in stress intensity factor distributions along crack fronts and their fatigue crack growth behavior. The capability of being able to model and analyze multiple cracks that grow under cyclic loading has great importance in such important engineering areas as aerospace, transportation and energy production. Thus, methodological and tool capabilities for accurate and efficient three-dimensional fracture analyses and crack propagation simulations of structures containing multiple cracks are needed.

In the literature, there are several numerical and experimental studies that deal with fracture and propagation analyses of multiple cracks. One of the numerical studies is by Wessel et al. [1]. In this study, Wessel et al. used boundary element method (BEM) for computations and compared their results to experimental data. Jonesa et al. [2] analyzed interacting multiple cracks using finite element method (FEM) and a hybrid formulation which represents stiffness changes. Yan [3] analyzed interacting multiple cracks and complex crack configurations in linear elastic media using an effective numerical method, which is an extended form of Bueckners' principle. Leonel and Venturini used two-dimensional BEM method for multiple crack propagation analyses [4]. They used maximum circumferential stress theory for evaluation of effective stress intensity factor and propagation angles, and Paris law for crack propagation lives. Another 2D linear elastic fracture mechanics (LEFM) problem is analyzed by Yan [5] using BEM for propagating multiple cracks. Yan also used maximum circumferential stress theory and Paris law. A Java-based boundary element program front end was developed by Hsieh et al. for fracture analysis of multiple curvilinear cracks in general anisotropic materials [6]. As a three-dimensional numerical analysis, Pierres et al. used extended finite element method (X-FEM) for simulating 3D fatigue crack propagations [7]. By using X-FEM and without a need for crack geometry-conforming mesh, they analyzed tribological fatigue problems. Citarella and Cricri compared DBEM and FEM methods by 3D fatigue crack growth of two anti-symmetric cracks [8].

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Nomenclature

a	crack depth in thickness direction of the geometry
a_{max}	maximum value of crack growth increment
BEM	Boundary Element Method
C	material constant
c	half crack width on the geometry surface
DBEM	Dual Boundary Element Method
Δa	crack growth incremental value
ΔK	stress intensity factor range
E	modulus of elasticity
FCPAS	Fracture and Crack Propagation Analysis System
FEM	Finite Element Method
K	stress intensity factor symbol
K_{IC}	fracture toughness for plane strain conditions
K_C	fracture toughness for plane stress conditions
$K1$	stress intensity factor under mode I loading
$K2$	stress intensity factor under mode II loading
$K3$	stress intensity factor under mode III loading
LEFM	Linear Elastic Fracture Mechanics
n	material constant
v	poisson ratio
N	number of load cycles
P	applied load
R	load ratio (min. load/max. load)
SCC	Stress Corrosion Cracking
SIF	Stress Intensity Factor
σ_{max}	maximum applied stress
X-FEM	Extended Finite Element Method

Experimental studies dealing with multiple cracks can also be seen in the literature. Kamaya and Totsuka performed some experimental tests for specimens in which large number of cracks initiated because of stress corrosion cracking (SCC) [9]. They also performed interacting multiple crack propagation simulations to compare results to experimental data. They used body force method to calculate SIFs. Kagawa et al. analyzed multiple parallel edge notches in four-point bending specimens [10]. They also performed crack propagation simulation and compared numerical results to experiments. Zhao et al. developed an analytical method for two cracks adjacent to a hole in a plate and compared the results to those from the finite element method [11]. In [12], Judt et al. performed numerical analyses for multiple-crack systems in anisotropic structures using FEM. They also performed experiments on aluminum alloy Al-7075 specimens and compared the results to those from numerical analyses.

In this study, a methodology for analyses of multiple cracks in structures and some related case studies, which serve as validation examples, are presented. As explained in the following section, the method makes use of three-dimensional enriched finite elements to compute stress intensity factor (SIF) distributions for each three-dimensional crack in the structure. These SIF distributions along with a crack growth criterion are, then, used to predict the following incremental crack fronts and crack growth rates. The presented case studies are analyzed using FCPAS, Fracture and Crack Propagation Analysis System, which is a software that encompasses programs such as model translators, finite element solver, post-processors and user interface. The main finite element solver within the FCPAS program is FRAC3D, which computes the stress intensity factors using enriched elements. Some of these details are given in the following section. The case studies included in this paper, one of which was presented in [13], are; multiple-crack specimen with five holes including 4 and 8 cracks, multiple crack specimen with two unequal surface cracks, a thin plate with two lateral edge cracks, plate with coalescing two surface cracks and a plate containing two cracks with considerable size differences. For these analyses, finite element models are generated by using ANSYS™ [14] finite element software, converted into FRAC3D format, solved using FRAC3D and fatigue crack propagation predictions are performed within FCPAS [15]. Since the cracks are modeled explicitly in the finite element models, the interaction effects between them are also included. Having evaluated the obtained results and compared them with available literature data, it is concluded that the presented method is capable of analyzing structures with multiple three-dimensional cracks accurately and efficiently.

2. Description of analysis procedure

In this section, details of the employed procedure for the analysis of structures with multiple 3-D cracks is presented. Fig. 1 shows three of the many arbitrarily oriented three-dimensional cracks that may be present in a solid structure. As seen in the figure, crack fronts are divided into and defined by nodes, which belong to elements named as “enriched crack tip elements” [16].

Three-dimensional displacement fields of a typical enriched element are given by [16],

$$\begin{aligned} u(\xi,\eta,\rho) = &\sum_{j=1}^{m} N_j(\xi,\eta,\rho)u_j \\ &+ Z_0(\xi,\eta,\rho)\left(f_u(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)f_{uj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_I^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(g_u(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)g_{uj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{II}^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(h_u(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)h_{uj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{III}^i\right) \end{aligned} \quad (1)$$

$$\begin{aligned} v(\xi,\eta,\rho) = &\sum_{j=1}^{m} N_j(\xi,\eta,\rho)v_j \\ &+ Z_0(\xi,\eta,\rho)\left(f_v(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)f_{vj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_I^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(g_v(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)g_{vj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{II}^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(h_v(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)h_{vj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{III}^i\right) \end{aligned} \quad (2)$$

$$\begin{aligned} w(\xi,\eta,\rho) = &\sum_{j=1}^{m} N_j(\xi,\eta,\rho)w_j \\ &+ Z_0(\xi,\eta,\rho)\left(f_w(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)f_{wj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_I^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(g_w(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)g_{wj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{II}^i\right) \\ &+ Z_0(\xi,\eta,\rho)\left(h_w(\xi,\eta,\rho) - \sum_{j=1}^{m} N_j(\xi,\eta,\rho)h_{wj}\right)\left(\sum_{i=1}^{ntip} N_i(\Gamma)K_{III}^i\right) \end{aligned} \quad (3)$$