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Non-planar crack growth analyses of multiple cracks in thin-walled structures

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ABSTRACT

Non-planar crack propagation analyses for thin-walled structures containing multiple cracks are performed using Fracture and Crack Propagation Analysis System (FCPAS) finite element software. Numerical results from FCPAS, which employs three-dimensional enriched finite elements and is applied first time to multiple non-planar cracks, agree well with numerical and experimental data from the literature. In order to validate FCPAS crack growth results for non-planar multiple cracks in thin-walled structures, three different problems are solved and the corresponding results are compared with available data. Comparisons of obtained results show very close agreement with the available numerical and experimental data in terms of crack paths and stress intensity factors (SIF) under Linear Elastic Fracture Mechanics (LEFM) conditions. Therefore, it is concluded that FCPAS is capable of predicting non-planar multiple crack growth behavior in thin-walled structures.

1. Introduction

Structures may undergo non-planar crack propagation due to mixed mode loading or geometrical asymmetries. This behavior may also occur for multiple cracks, in such geometries as integral panels of aircrafts. Interaction effect takes place between multiple cracks. Therefore, crack growth speed or direction may change due to interaction of cracks.

Numerous experimental and numerical studies exist in the literature dealing with this phenomenon. One of the numerical studies is by Wessel et al. [1]. In that study, Wessel et al. used boundary element method (BEM) and compared their results to experimental data. Jones et al. [2] analyzed interacting multiple cracks using finite element method (FEM) and a hybrid formulation which represents stiffness changes. Yan 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 [3]. Leonel and Venturini used two-dimensional BEM method for multiple crack propagation analyses [4]. They used maximum circumferential stress theory for evaluating stress intensity factors and propagation angle, and Paris' law to predict structural fatigue life. 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 [5]. Citarella and Cricrì compared dual boundary element method (DBEM) and FEM methods by 3D fatigue crack growth of two anti-symmetric cracks in a notched shaft under torsion [6]. Price and Trevelyan analyzed two eccentric crack that propagate non-planarly in a thin geometry [7]. Bouchard et al. used maximum circumferential stress criterion, strain energy density fracture criterion and maximum strain energy release rate criterion for single and multiple non-planar crack growth analyses [8].

The objective of this study is to apply, demonstrate and validate usage of Fracture and Crack Propagation Analysis System (FCPAS) for multiple cracks propagating in a non-planar manner under fatigue loading. In the study, finite element method with enriched finite elements is used to obtain stress intensity factors (SIFs) [9]. In this study, FCPAS and the underlying three-dimensional enriched finite elements are applied first time to multiple and non-planar crack propagation problems. SIF values are calculated during solution phase for nodal displacements, which is a fundamental step in finite element (FE) calculations. By using enriched element method, SIFs are calculated accurately and no special meshing techniques and post-processing of results are needed. It is shown that FCPAS results for multiple non-planar cracks agree well with those from the literature.

2. Method used

FCPAS finite element software is used for analyses of multiple-cracks in thin-walled structures growing in a non-planar manner.

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Nomenclature

a	crack length
a_{max}	maximum value of crack growth increment
BEM	boundary element method
C	Paris law constant
E	modulus of elasticity
FCPAS	Fracture and Crack Propagation Analysis System
FE	finite element
FEM	finite element method
K	stress intensity factor
K_I	stress intensity factor under Mode I loading
K_{II}	stress intensity factor under Mode II loading
n	Paris law constant
N	loading cycle counted
R	load ratio (min. load/max. load)
SIF	stress intensity factor

Nomenclature for Greek Symbols

Δa	crack growth incremental value
ΔK	stress intensity factor range
ν	Poisson ratio
σ	applied load
σ_{max}	maximum stress loading applied

For generating FE model of the cracked geometry, ANSYS™ [10] commercial FE software is used. All calculations for SIFs and propagation process are performed using FRAC3D solver within FCPAS. Crack propagation process used consists of FE modeling of cracked geometry, solution step, propagation of the cracks and best ellipse fit for the propagated cracks. These steps are repeated until failure or some other geometric limit. Work flow scheme of multiple crack analyses employed in FCPAS is shown in Fig. 1. As can be seen in Fig. 1, FE model data such as element, node, boundary conditions, and load data are taken as output files from ANSYS™ software and converted into a single finite element data (∗.geo) file (convert_ansys_frac3d.exe). Solution information is written into a run file by (writerun_frac3d.exe) and solution is performed by FRAC3D solver. After solution phase, crack tip node coordinates and calculated SIFs are stored in prop1 and crk files. Next crack profiles are predicted (crkpropagation.exe) and an ellipse is fitted for all crack fronts during simulation for Mode-I problems. Once ellipse parameters are obtained, they are used as new crack dimensions for modeling the updated fracture model using ANSYS™ software. This procedure is repeated until failure.

FRAC3D solver uses enriched element method for calculating SIFs [11]. A general form of displacements for enriched elements is given in Eqs. (1)–(3):

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

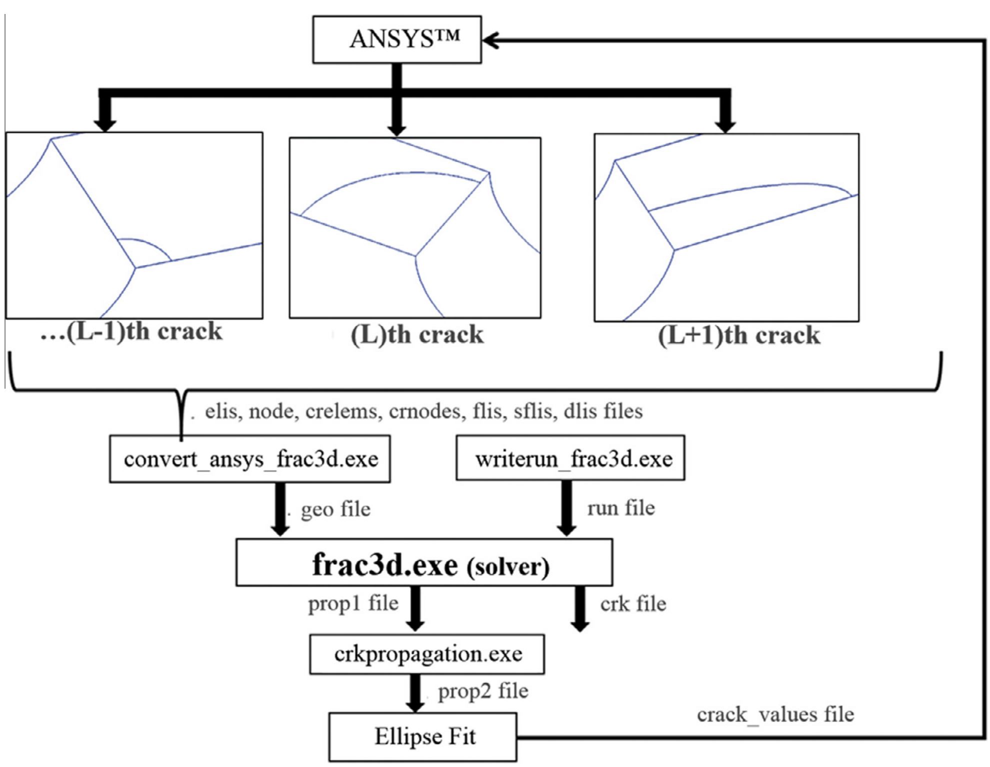

Fig. 1. Work scheme of FCPAS finite element software for analysis of multiple cracks.