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Fully automated mixed mode crack propagation analyses based on tetrahedral finite element and VCCM (virtual crack closure-integral method)

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ABSTRACT

The authors have been developing a crack propagation analysis system that can deal with arbitrary shaped cracks in three-dimensional solids. The system is consisting of mesh generation software, a large-scale finite element analysis program and a fracture mechanics module. To evaluate the stress intensity factors, virtual crack closure-integral method (VCCM) for the quadratic tetrahedral finite element is adopted and is included in the fracture mechanics module. The rate and direction of crack propagation are predicted by using appropriate formulae based on the stress intensity factors. In this paper, the crack propagation system is briefly described and some numerical results are presented.

1. Introduction

Some successful examples of three-dimensional crack propagation analyses can be found in literature [1–3]. However, performing such analyses is a difficult task due to their difficulties in finite element mesh generations for the crack models, in general. Commercially available mesh generation software such as Technostar TSV [4] is able to automate the mesh generation processes when the tetrahedral finite elements are adopted. However, a majority of fracture analyses have been performed by using the hexahedral finite elements (for example, see recent papers [5–8]). It takes a large amount of manual labor to generate a finite element model for a complex shaped three-dimensional structure with hexahedral finite elements. Thus, methodologies such as element free Galerkin method (EFGM) [9], s-Version finite element method (s-FEM) [10] and eXtended finite element method (x-FEM) [11,12] were proposed to obviate the processes of mesh generation and were applied to the fracture mechanics problems successfully. When the finite element method is applied to the crack propagation analysis, an automatic model generation methodology needs to be coupled with the finite element program. Some successful examples are seen in literature, such as Dhondt and Bremberg [13] and Wawrzynek et al. [14]. The methodologies of Dhondt and Bremberg (CURVECRACK) [13] and Wawrzynek et al. (FRANC3D/NG) [14], the automatic meshing techniques for the tetrahedral finite element are adopted. A layers of hexahedral elements are placed at the immediate vicinity of the crack front. They use a mixture of element types.

It should also be pointed out that many of algorithms to evaluate the fracture mechanics parameters such as the stress intensity factors and the *J*-integral were proposed for the hexahedral elements [15–18]. Recently, the tetrahedral elements were applied to the crack problems as seen in literature [19–22]. But they are not popular ways to perform three-dimensional fracture mechanics analyses. Use of the hexahedral finite elements is the standard way.

Okada et al. [21,22] have developed a virtual crack closure-integral method (VCCM) for tetrahedral finite elements. Based on the VCCM, a software system to perform crack propagation analysis is being developed by present authors, as presented in Okada et al. [23,24]. The system is consisting of automatic mesh generation software, a large-scale finite element analysis program and a fracture mechanics module to evaluate the stress intensity factors by using VCCM. When crack propagation analysis is performed, the rate and direction of crack propagation need to be predicted by using appropriate formulae (see, for example, Qian and Fatami [25]) based on the stress intensity factors. Mesh generation software that is a part of ADVENTURE project [26] is extended so that models with cracks can automatically be created. The cracks are regarded as local features in the three-dimensional analysis model

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("local models"). They are inserted in an existing finite element model without any cracks ("global model"). Thus, the geometry representation of the structure stays the same even though the shapes and the sizes of the cracks change as they grow. The "local models" are represented by a group of nodal points and they are inserted in the "global model". Hence, Delaunay triangulation technique is appropriately applied to generate the finite element mesh with the tetrahedral elements only.

In this paper, some numerical results are presented and are compared with the experiment. Also, it is noted that the example problem of stepped torsion bar has three-dimensional features such that it has surfaces with some curvatures. The crack also follows three-dimensionally curved path. It is noted that the example problems in the authors' previous publication [24] have the geometry of simple experimental specimen. Some remarks are presented as the conclusions.

2. Outlines of crack propagation analysis system

The crack propagation analysis system is consisting of parts/modules/programs for (1) model and crack geometry definition, (2) automatic finite element mesh generation with the quadratic tetrahedral finite elements [23], (3) finite element analysis using a parallel PC cluster, (4) evaluation for the stress intensity factors by using the virtual crack closure-integral method (VCCM) for the 10 node tetrahedral element [22] and (5) predictions for the direction and rate of crack propagation when the crack propagation analysis is performed, as depicted in Fig. 1.

The finite element analysis is performed by using Adventure Solid [26]. It allows us to perform large-scale parallel finite element analyses on a PC cluster. It is noted that VCCM for the tetrahedral element [22] does not require the hexahedral elements to be placed at the crack front. Therefore, we do not need to adopt a mixed element approach, greatly simplifying the meshing processes.

3. Crack propagation analyses – numerical demonstrations

3.1. Circular bar subject to tension and combined tension/torsion

Fatigue crack propagations in circular bars subject to tension and combined tension/torsion, as shown in Fig. 2, are considered. The magnitudes of fluctuations of torque and combined tension/torsion were set to be as shown in Table 1. $\bar{F}$ is the tension which produces 140 MPa of tensile stress and $\bar{T}$ is the torsion which produces 140 MPa of shear stress at the surface of the specimen. The magnitudes of fluctuations of the tension and combined tension/torsion are set to be $\bar{F}$ and 0.8 $\bar{F}$/0.2 $\bar{T}$, respectively. Initially inclined initial surface flow is assumed for the tension case. The inclination angle is $\pi/8$, as depicted in Fig. 2. For the combined tension/torsion load case, the initial crack is set to be perpendicular to the axis of the bar.

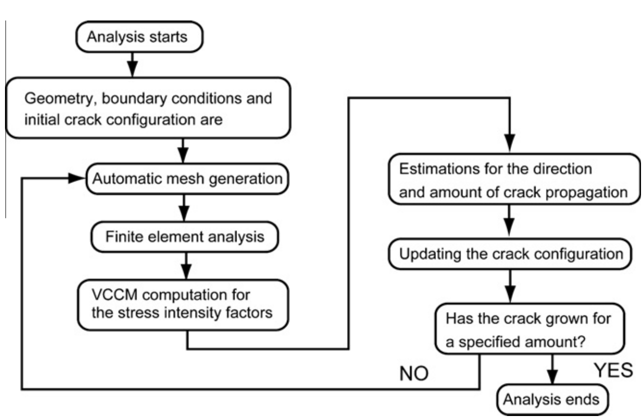

Fig. 1. The procedures in the crack propagation analysis in proposed analysis system.

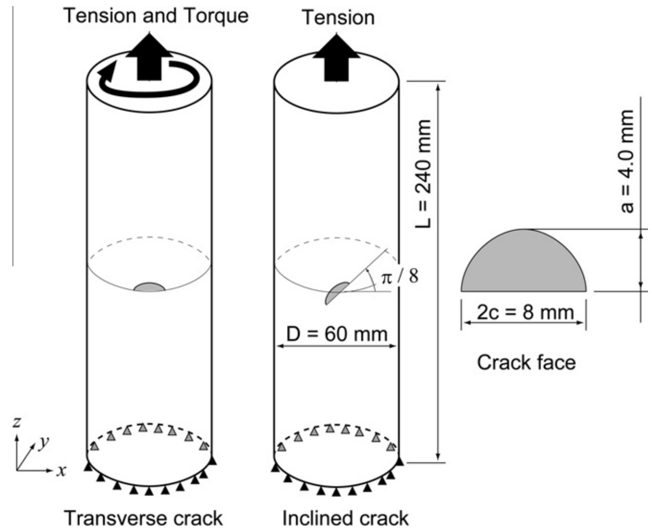

Fig. 2. Problems circular bar with a transverse/inclined surface flaw.

Table 1
Summary of the load fluctuation for the crack propagation analyses of cylindrical bar.

Case	Load fluctuation	
Analysis Case	Axial force	Torque
Inclined crack (angle: $\pi/8$)	$\bar{F}$	0
Normal crack	$0.8 \times \bar{F}$	$0.2 \times \bar{T}$

$\bar{F}$ produces the normal stress of σ = 140 MPa.
$\bar{T}$ produces the torsional stress of τ = 140 MPa.

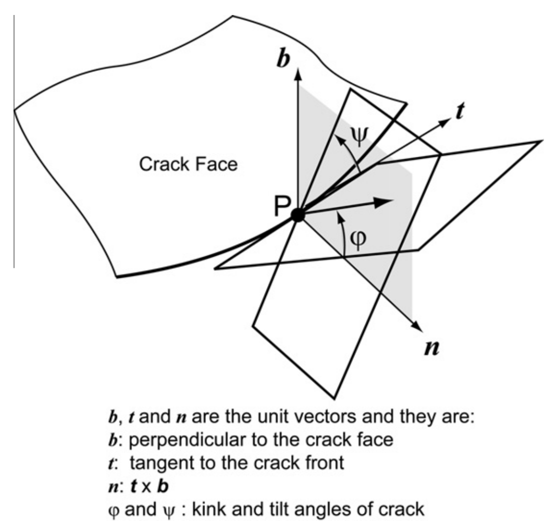

Fig. 3. Definitions of kink and tilt angles of crack (φ and ψ).

The stress intensity factors are evaluated along the crack front by using the VCCM. Kink and twist angles as illustrated in Fig. 3 and the rate of crack propagation are predicted based on the stress intensity factors. To do so, we adopted the criterion proposed by Richard et al. [27]. According to Richard et al. [27], the kink and the twist angles (φ and ψ) are given, by: