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Computations of stress intensity factors for semi-elliptical cracks with high aspect ratios by using the tetrahedral finite element (fully automated parametric study)

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ABSTRACT

The stress intensity factor (SIF) solutions of semi-elliptical cracks with high aspect ratios in plate and thick wall cylinder have been investigated under various assumed stress distributions. The authors have developed an automated analysis procedure to perform parametric studies on crack shapes and loading conditions. It consists of programs to perform automatic mesh generation, analysis execution including assignments of boundary conditions and SIF evaluations by VCCM (virtual crack closure-integral method). It was also found that SIF solutions for the thick wall cylinder and for the complex structure could be estimated by those for the flat plate.

1. Introduction

In this paper, stress intensity factor (SIF) distributions and their implications of semi-elliptical cracks with high aspect ratios are elucidated. Such surface flaws have been found at welded joints such as what found in Ohi-3 nuclear power plant, as reported by Nakamura et al. [1]. It was pointed out that the aspect ratio a/c where a and c are the depth and the half of surface length of flaw at the welded joint exceeded 2 when it is approximated to be a semi-elliptical crack. In such a case, the SIF data was not available in literature. The SIFs of semi-elliptical cracks with $a/c \leqq 1$ were provided by Raju and Newman [2] and Newman and Raju [3] and have been used as reference data by researchers and engineers. The available data does not cover the cases of surface flaws whose aspect ratios exceed 2.

Recently, articles by Malekian et al. [4] and Li et al. [5,6] presented the distributions of SIF of surface flaws whose aspect ratios a/c well exceeded 2. It was also pointed out that the maximum of the SIF does not take place at the deepest nor the surface point of the crack front in the case of semi-elliptical crack with very high aspect ratio. Thus, the standard practice that the SIFs at the deepest and the surface points are used assuming the flaw to be semi-elliptic in its shape may not be adequate in such cases. It is also noted that their computations were performed by the finite element method whose mesh discretizations were carefully designed such that hexahedral or prismatic finite element elements were placed along the crack front to evaluate the SIFs accurately. Generating such analysis models generally takes a large amount of manual labor. Furthermore, it is not easy to deal with structures with complex geometries.

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Nomenclature

σ_{Assumed}	assumed stress which has constant, linear, quadratic, cubic or quartic variation in the depth direction of the crack
a, c	depth and half-surface length of the semi-elliptical crack
ϕ	crack front angle
K_I	mode I stress intensity factor (SIF)
$G_p(\phi)$	a nondimensional number which expresses the variation of the SIF as a function of the crack front angle ϕ
G	energy release rate
σ_{2i}	cohesive stress connecting the ligament
$\bar{t}_i$	crack face traction
v_i	crack opening displacement
$\hat{f}_i^1, \hat{f}_i^2$	nodal forces, which are used in VCCM computations, arising from the cohesive stress
$\hat{t}_i^1, \hat{t}_i^2$	nodal forces, which are used in VCCM computations, arising from the crack face tractions
Δ	length of virtual crack closure

On the other hand, the authors have been developing a fracture mechanics analysis software system that can carry out automatic parametric studies on crack geometries and on loading conditions and crack propagation analyses. The readers are referred to Okada et al. [7] and Kaneko et al. [8]. The analysis system consists of the finite element mesh generation, analysis and postprocessing modules. The postprocessing module computes SIFs along the crack front and the direction and the rate of crack propagation based on an appropriate crack propagation criterion. To automate the finite element mesh generation, the quadratic tetrahedral element is adopted for the discretization. Virtual crack closure-integral method (VCCM) for the quadratic tetrahedral finite element that was developed by Okada et al. [9] is adopted for the computations of SIFs. VCCM is also called "virtual crack-closure technique" or "virtual crack-closure technology" depending on the authors. VCCM was first proposed by Rybicki and Kanninen [10] and was extended to the three-dimensional crack problems by Shivakumar et al. [11]. Early application of VCCM to problems concerning curved crack front was presented by Fawaz [12].

This paper discusses about the SIFs of surface flaws with high aspect ratios subject to various stress conditions and their influences on crack propagation behavior. A number of cases are presented for the SIF distributions, assuming various aspect ratios of the surface flaws and assumed stress distributions. It is noted that although Okada et al. [13] also presented the SIF solutions of deep semi-elliptical surface flaws they have completely been recomputed in present investigation as a flaw in the analytical procedures was found.

In subsequent sections, we discuss about the semi-elliptical cracks with high aspect ratios to be analyzed in this paper, analytical procedures including the brief descriptions of VCCM for the quadratic tetrahedral finite element subject to crack face tractions and automated analytical procedure to analyze a number of crack configurations at once. Then, we present the results of our computations and give some discussions. In the discussions, we compare our results with those of Li et al. [6]. Finally, present computational procedures are extended to perform the parametric analyses of surface flaw in more complex structure that is a mockup test piece emulating the control rod through-hole part of nuclear pressure vessel.

2. Semi-elliptical cracks with high aspect ratios under consideration

Flat plate and thick wall cylinder with surface flaws were analyzed in this paper, as depicted in Figs. 1 and 2. Various depth (a)-plate thickness (t) ratios and aspect ratios (a/c) as also shown in Figs. 1 and 2 were assumed and the SIFs are evaluated. Cracks in the thick wall cylinder were aligned in the axial and the circumferential directions. The aspect ratio a/c of the surface flaw was assumed to be 2, 4, 6 or 8. The depth-plate thickness ratio was set to be 0.2, 0.4, 0.6 or 0.8. We assumed various stress distributions of uncracked body. The variation of the assumed stress σ_{Assumed} in the depth direction of the crack was set to be constant, linear, quadratic, cubic or quartic, as:

$$\sigma_{\text{Assumed}} = \sigma_o \left(\frac{y}{a}\right)^p, \quad (p = 0, 1, 2, 3 \text{ or } 4) \tag{1}$$

where a is the depth of the crack and y is the coordinate value in the depth direction of the surface flaw in the plate or the cylinder. σ_o is the magnitude of the assumed stress and all the SIF values are normalized by σ_o when they are presented in present paper. The constant variation with $p = 0$ represents a uniform applied stress. Combination of the constant and the linear terms ($p = 0$ and $p = 1$) can express the out of plane bend deformation of the plate or of the cylinder wall. Furthermore, standards and codes such as the fitness-for-service code for nuclear power plants of JSME (Japan Society of Mechanical Engineers) [14] specify evaluation methodologies for flaws. The stress intensity factor data for semi-elliptical surface cracks are tabulated for various applied stress conditions. The applied stress conditions include the constant, linear, quadratic, cubic and quartic variations. Combining these variations appropriately, complex applied stress conditions due to service loads, residual stress, earthquake, etc. can be realized in the evaluations of structural integrities of damaged structures. Crack propagation analyses can be performed for the evaluations of residual lives of damaged structures.