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Development of a damage propagation analysis system based on level set XFEM using the cohesive zone model

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ABSTRACT

The level set extended finite element method (XFEM) is applied to two-dimensional and quasi-three-dimensional crack propagation analyses using cohesive zone models (CZMs). The proposed method uses no asymptotic basis functions near the crack tip and uses only the Heaviside function. The crack geometry is approximated by two signed distance functions (SDFs). Elements that include a crack are then classified into several partitioned patterns according to nodal SDF values, and enriched nodes are determined. A CZM is introduced to the crack line or the surface including a discontinuous displacement field modeled by XFEM. In order to solve the discretized governing equations, the implicit method and the explicit dynamic method are used. The proposed method is applied to the crack propagation analysis of a three-point bending beam and fracture analyses of carbon fiber reinforced plastic (CFRP) laminates considering the interaction between the matrix cracks and delamination.

1. Introduction

There are two approaches by which to perform crack propagation analyses in conjunction with the finite element method (FEM) in the field of computational fracture mechanics. The first is a method based on linear elastic fracture mechanics (LEFM), and the second is based on a cohesive zone model (CZM) [2,3]. Although the LEFM approach requires the assumption of an initial crack in a structure and the computation of the stress intensity factor and energy release rate at the crack tip for post-processing in the stress analyses, only relative coarse finite element models and linear elastic analysis can be used. On the other hand, the CZM approach can consider stress-based crack initiation and energy-based crack propagation. Therefore, crack initiation and propagation phenomena can be simulated without the assumption of an initial crack. However, a fine model is generally required in order to capture the process zone near a crack tip [4], and materially nonlinear analysis is indispensable for considering the relationship between the relative displacement and the traction force at the cohesive crack. In LEFM, where stress intensity factor is evaluated by the domain integral method, computation accuracy for evaluation of singular stress field near a crack tip is not much required. Therefore, the mesh refinement criteria near a crack tip for LEFM is not severer than that for CZM. According to the reference [5], the element size should be smaller than the evaluated specified size $L_C = E\ G_C/\sigma_C^2$, where E, G, and σ_C are elastic modulus, fracture energy, and strength, respectively.

In the crack propagation analysis based on LEFM and the CZM using FEM, a crack is modeled at the interface of an element through double nodes, and an interface element is used in order to introduce the CZM. Conventional FEM in conjunction with automatic mesh generation is still difficult to perform crack propagation analyses. Therefore, in order to solve such a problem, the extended finite element method (XFEM) [6,7] was proposed. XFEM can model the displacement field, including the discontinuity near a crack, independently of finite elements through approximation functions that satisfy the partition of unity (PU) condition [8]. Moreover, XFEM in conjunction with the level set method [9] can model cracks efficiently [10,11]. On the other hand, cracking particles method [12], meshfree methods [13], extended meshfree methods [14], edge rotation method [15], numerical manifold method [16], and have been proposed for far more than XFEM. Among them, XFEM is direct extension of the existing FEM, which is used for general purpose and therefore the authors think that XFEM has a great potential for application to various practical problems.

In the XFEM analysis of a crack in a homogeneous isotropic linear elastic material, the Heaviside function and four asymptotic

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basis functions [6,7,17], which can reconstruct the asymptotic displacement field near a crack tip, are used. On the other hand, XFEM analyses for a crack in an orthotropic material [18] and for an interface crack between dissimilar materials [19] have been proposed. However, the basis functions used for these analyses are rather complicated. In addition, a blending element [20], which cannot reconstruct asymptotic basis functions completely, may exist if asymptotic bases are enriched. Some methods by which to resolve such problems have been proposed [21,22]. However, the procedures generally tend to be complicated. Although Moës et al. [23] performed XFEM analysis of a cohesive crack using asymptotic basis functions, the asymptotic basis functions are not required for a cohesive crack because the stress singularity at the crack tip disappears. Asymptotic basis functions include branch functions [24], which express the discontinuous displacement field near a crack tip and can model the displacement field for the case in which a crack tip is included in the element. On the other hand, the approximation function using only the Heaviside function without asymptotic basis functions can model such a case. Zi and Belytschko [25] performed two-dimensional crack analysis by XFEM using interpolation functions enriched with only the Heaviside function.

In FEM analysis using a CZM, even if infinitesimal deformation and a linear elastic material are assumed, the material nonlinear problem should be solved in order to consider the nonlinearity of the constitutive equations for the CZM. The governing equations discretized in space can be solved implicitly using the Newton–Raphson method in the framework of the incremental analysis [26,27]. However, for some practical crack propagation problems, the converged solution cannot be obtained by the implicit method. For unstable crack propagation problems, Ricks method [3,27] can be utilized. Alternatively, an explicit dynamic method, which never requires iterative procedures, can be used to obtain a quasi-static solution. An explicit dynamic method uses the central difference method to perform time integration, and the time increment is restricted within the range of the stable time increment, which is very small compared with the time increment used in the implicit method. For quasi-static analysis, actual time scale is not important. In order to obtain numerical results within practical computation time, load or displacement speed can be increased in the range that the total kinetic energy is not excessively larger than total strain energy. The same thing can be realized by the mass scaling method [27], where the mass density is increased larger than actual value.

Wells and Sluys [28], Mariani and Perego [29], Simone [30], Combescure et al. [31], and Moës et al. [23] have applied PUFEM and XFEM in conjunction with CZM to crack propagation analyses. In this study, the level set XFEM in conjunction with CZM using only the Heaviside function as an enrichment function, which can employ a crack tip element, is proposed. The method uses two-dimensional linear triangular elements and three-dimensional pentahedral elements, which are obtained by extruding the 2D model in the thickness direction, in order to perform crack propagation analyses for not only two-dimensional but also quasi-three dimensional practical problems. Specifically, the proposed quasi-three dimensional approach provides an efficient method to solve fracture problems of composite laminate. An arbitrary crack is modeled by two types of signed distance functions, and each element is classified into several patterns in order to partition for numerical integration and to determine the nodal enrichment. Since only the Heaviside function is used as an enrichment function, the selection of an asymptotic basis consistent with the material property and countermeasures against blending problems are not required. In order to model a crack tip inside an element without the branch function, a crack tip element (tip element) [25,32] is used. When the converged solution cannot be obtained by the implicit method using the Newton–Raphson method, the explicit dynamic method is alternatively used to obtain a quasi-static solution.

The remainder of the present paper is organized as follows. Section 2 presents an analysis method based on the level set XFEM using a two-dimensional three-node linear triangular element. Section 3 presents an analysis method based on the level set XFEM using a three-dimensional six-node linear pentahedral element. Section 4 describes the outline of the developed system based on the proposed method. In Section 5, crack propagation analyses of a three-point bending beam and fracture analyses of CFRP specimens considering matrix cracks and delamination are performed and validated. Finally, the present study is summarized in Section 6. This paper is based upon Nagashima and Sawada [1], but the current paper includes applications of the proposed method to fracture analyses of carbon fiber reinforced plastic (CFRP) laminates as additional research.

2. Two-dimensional XFEM

2.1. Basic equations

The boundary-value problem for a two-dimensional elastic body, as shown in Fig. 1, is considered. An arbitrary crack, expressed as line Γ, where the upper and lower sides of the crack are indicated by Γ^+ and Γ^-, respectively, is assumed inside the elastic body. Both Γ^+ and Γ^- are mechanical boundaries, and the cohesive force may act on both crack surfaces as traction forces. The global coordinate system denoted as x_i ($i = 1, 2$) and the local coordinate system $\tilde{x}_i$ ($i = 1, 2$) aligned with the lower crack surface are used to describe the traction and displacement components. The principle of virtual work can be described as follows:

$$\iint_A \sigma_{ij}\delta\varepsilon_{ij}dA + \int_\Gamma \tilde{t}_i\delta\tilde{u}_i d\Gamma = -\iint_A \rho\ddot{u}_i\delta u_i dA + \iint_A \bar{b}_i\delta u_i dA + \int_{\Gamma_C} \bar{t}_i\delta u_i d\Gamma \quad (1)$$

where σ_{ij}, ε_{ij}, and u_i are the stress, strain, and displacement components, respectively, A is the analyzed area, Γ_σ is the mechanical boundary, and $\bar{b}_i$ and $\bar{t}_i$ are the prescribed body force and traction, respectively. In addition, $\tilde{t}_1$ and $\tilde{t}_2$ are the cohesive tractions in the shear and normal directions, respectively, and $\tilde{u}_1$ and $\tilde{u}_2$ are the relative displacements in the shear and normal directions, respectively. The inertial term with the mass density ρ is also added in order to extend the analysis to dynamic analyses.

2.2. Interpolation functions

For two-dimensional analyses, a two-dimensional three-node linear triangular element is used. An arbitrarily shaped crack is

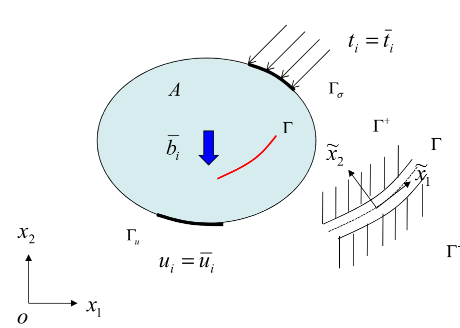

Fig. 1. Two-dimensional boundary-value problem for a cracked elastic body.

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