Numerical Simulation of Dynamic Elasto Visco-plastic Crack Propagation with Wake Zone

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Summary

In this study, the developed moving finite element technique has been introduced to express residual plastic strain in wake zone of nonlinear crack propagation. Using the developed moving finite element method, the numerical results of dynamic elasto visco-plastic fracture phenomena have been reported. Under mixed mode loading, crack propagation direction has been numerically predicted based on the maximum hoop stress criterion. Here, the T* integral have been used as the nonlinear fracture criterion. The T* integral values have been estimated on the extending near-field path, which is located in wake zone.

Introduction

Fracture phenomena with plastic deformation have been occurred in many industrial fields. Therefore, many results of research for the elastic-plastic fractures have been reported. Under dynamic load, the material viscosity effects have been distinguished in the deformation and fracture behavior. For the dynamic nonlinear fractures, Atluri, Nishioka and Nakagaki proposed the T* integral [1]. In the T* integral measurements, the moving and extending models have been defined as crack tip near-field integral path Γ_ε [2][3]. And the difference of the T* values by the near-field integral path model was discussed by Okada and Atluri [2]. The T* integral has the dependence of the near-field path size. The relationship of near-field path size Γ_ε and process zone of plastic fracture has been discussed by some researchers.

In our previous study, the authors did the moving finite element analyses for fast crack propagation with elasto visco-plastic deformation [4]. From numerical results, the T* values were estimated using the moving path model (T^*_{mv}). In these results, the T* integral indicate excellent far-field path independence. However, the T^*_{mv} values for propagating crack tip are too small as compared with the fracture toughness T^*_C. Here, the authors consider to estimate the T* values using the near-field extending path model (T^*_{ex}). In the nonlinear fracture phenomena, the energy dissipations have been occurred by the irreversible deformations and the crack creations. Because the T^*_{ex} includes the effects of both energy dissipations, the T^*_{ex} value is not so smaller than T^*_C [2][3]. In many case of nonlinear fracture, higher plastic strains were remained near crack propagation area (wake zone). In numerical simulations of these fractures, accuracy of estimation of the wake zone is one of important factor to estimate the T^*_{ex}.

Nishioka and coworkers developed the moving finite element method for various complex fracture behaviors [5][6]. In this method, fracture behavior are exactly simulated because fine mesh subdivision moves with propagating crack tip. However, in the

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conventional moving finite element analyses, post crack propagation areas are regarded as elastic unloading area and coarse mesh subdivision are applied in these areas. In application of the moving FEM to the nonlinear fracture case, the measurements of residual plastic strains in wake zone are not sufficient.

In this study, the moving finite element method is developed to simulate crack propagation phenomena with wake zone. The fine mesh subdivisions are located near post crack propagation zone to express the residual plastic strain. From the numerical results for the elasto visco-plastic fracture, the application of T^*_{ex} for fast crack propagation is discussed.

Fracture mechanics parameter T* integral [1]

The T* integral was defined on the near field integral path Γ_ε, which surround crack tip [1]. The far-field measurement form of the T* integral is derived using the divergence theory. Recently, some researchers calculate the T* integral on the near-field integral path [2][7].

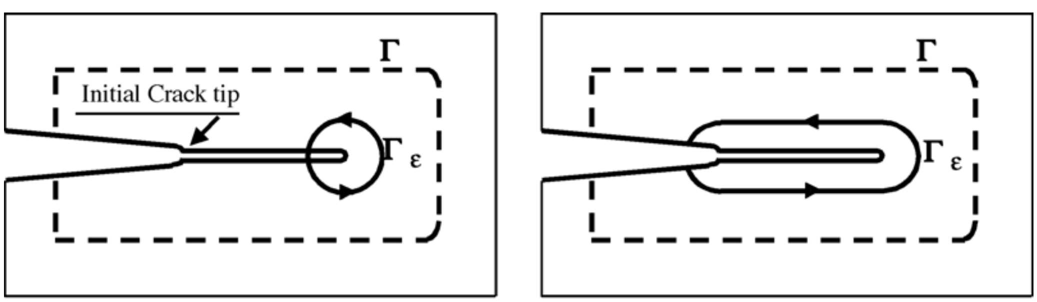
Path integral formulas to estimate the T* integral are shown by the following equations;

$$T_k^* = \int_{\Gamma_\varepsilon} \left[(W+K)n_k - t_i u_{i,k}\right] dS \qquad \text{(Near-field integration)}$$

$$= \int_{\Gamma+\Gamma_c} \left[(W+K)n_k - t_i u_{i,k}\right] dS + \int_{V_\Gamma - V_\varepsilon} \left[\sigma_{ij,k} u_{i,k} + \sigma_{ij} u_{i,jk} - \rho \ddot{u}_i u_{i,k} - W_{,k}\right] dV \qquad \text{(Far-field integration)}, \quad (1)$$

where, W and K mean the stress working density and the kinetic energy density, respectively. n_k, t_i, u_i and ρ are the direction cosines, the traction, the displacement and the mass density, respectively. Γ_ε, Γ □□□ Γ_c denote the near-field path, the far-field path and the crack surface path, respectively. V_Γ and V_ε mean the far-field domain and the near-field domain.

The original T* integral have been defined on the near-field integral path Γ_ε, as shown in Eq.(1-1) and Fig.1. For crack propagation problems, moving and extending models have been suggested as the near-field integral path [2][3]. The T^*_{ex} indicate the



(a) Moving path model (b) Extending path model

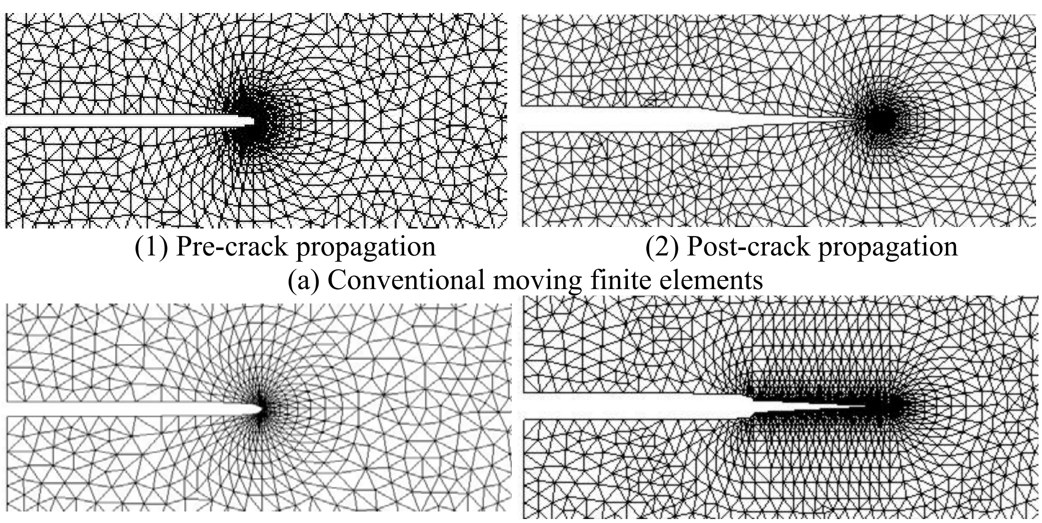
Figure 1 Integral path models of T* for crack propagation problem sum of the irreversible deformation energy rate in wake zone and the energy release rate for crack creation, because the T^*_{ex} is measured as the energy flow rate into the extending domain. On other hand, the T^*_{mv} are corresponding to energy release rate. Therefore, the T^*_{ex} values are larger then the T^*_{mv} values in almost case of nonlinear fracture. The T^*_{ex} will be regarded as the practical parameter to express nonlinear fracture resistance. In this study, the extending path model is used to estimate the T* values.

Numerical procedure

In the finite element analyses for crack propagation, the dual node technique (the nodal release technique)[8] is one of popular method. In this method, the crack propagation line is restricted on the element boundaries. Therefore, numerical prediction of unknown fracture path and exact expression of the fracture path boundary are very difficult using the dual node technique.

Other hand, in the moving finite element method [5], exact boundary condition near a propagating crack tip is always satisfied by the fine mesh subdivision near the propagating crack tip. In this moving FEM using triangle elements, the mesh generation is controlled based on the Delaunay automatic triangulation technique [9]. Therefore, many type of the moving FEM [5][6] have been used in the numerical simulation to predict the crack propagation path. For the nonlinear fracture, the modified variational principle was proposed to achieve the nonlinear moving finite element method [10].

In the conventional moving FEM, the fine mesh subdivision is located to estimate accurate stress singular distribution near the propagating crack tip. Because main targets of the conventional moving FEM were elastic dynamic fracture, the fine mesh



(1) Pre-crack propagation (2) Post-crack propagation
(a) Conventional moving finite elements

(1) Pre-crack propagation (2) Post-crack propagation
(b) New finite elements setting to estimate wake zone
Figure 3 Numerical models

subdivision was not applied near post crack propagation area (Fig.2(a)). In order to obtain the exact nonlinear fracture resistance using the T^*_{ex}, accurate measurement of the irreversible deformation energy is required, because plastic strain singularities were remained in wake zone. Therefore, the many finite elements have to be supplied into the post-crack propagation area.

In this study, the authors develop the moving mesh technique in moving FEM. The fine elements subdivision is applied in the post-crack propagation area, as shown in Fig.2(b). The residual plastic strain distribution can be accuracy simulated by the fine mesh subdivision in wake zone. Moreover, numerical prediction of non-straight crack propagation path with higher plastic strains can be demonstrated in this numerical method.

Numerical models

In this study, elasto visco-plastic deformations are treated with crack propagation. The constitutive formulations are shown in the Ref.[4], which based on the large deformation theory proposed by Tomita [11]. The relation between the equivalent stress $\bar{\sigma}$ and the equivalent visco-plastic strain $\bar{\varepsilon}^{vp}$ is expressed by the following form [12];

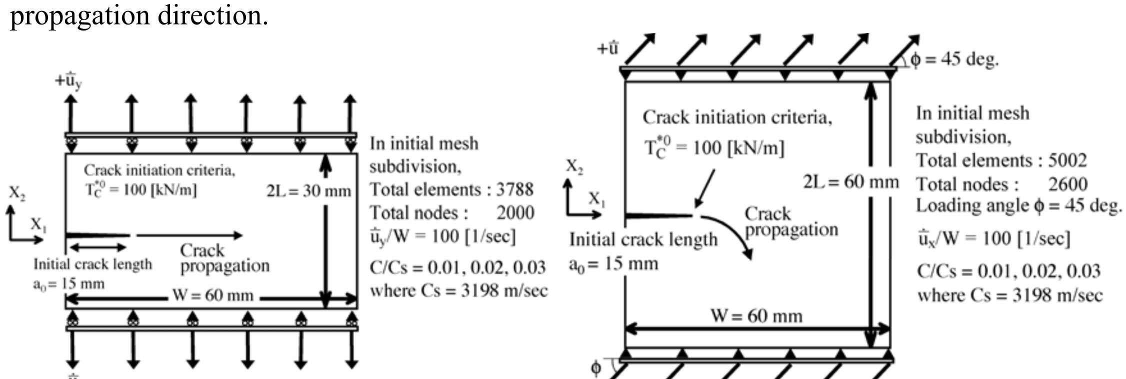
$$\bar{\sigma} = F \cdot (\bar{\varepsilon}^{vp})^n \left(1 + D\dot{\bar{\varepsilon}}^{vp} \right), \qquad (2)$$

where, F, n, D and $\dot{\bar{\varepsilon}}^{vp}$ denote the referential stress, the strain hardening exponent, the visco-plastic coefficient and the equivalent visco-plastic strain rate, respectively. Table 1 shows the value of each parameter and elastic parameters of the material.

Table 1 Material properties

Young's modulus	E = 210 GPa
Poisson's ratio	ν = 0.3
Visco-plastic coefficient	D = 0.001 sec.
Referential stress	F = 300 MPa
Strain hardening exponent	n =0.2
Mass density	ρ = 7900 kg/m³

Figure 3 shows the shapes of specimens for straight crack propagation (model(a)) and non-straight crack propagation (model(b)). Various constant crack propagation velocities are assumed in each model. In the model (b), the maximum hoop stress criterion [13] is used to predict crack propagation direction.



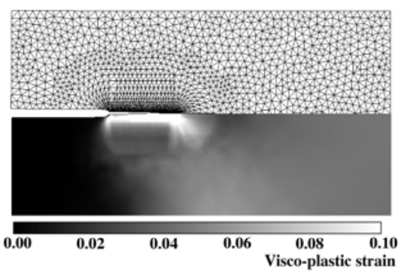
(a) Mode I load (b) Mixed mode load

Figure 3 Numerical models

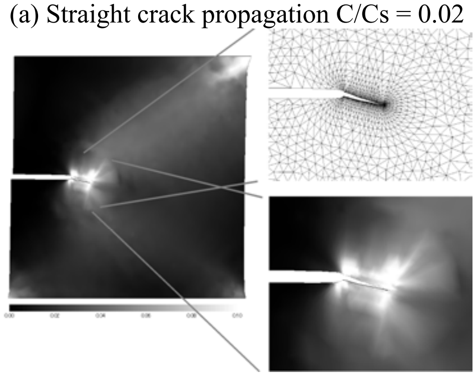
Numerical results

From the numerical result, the residual plastic strain distribution is shown in Fig.4. Accurate residual plastic strain distribution can be estimated by the fine mesh subdivision in the wake zone. Figure 5 shows the near-field extending path with crack propagation. In the numerical simulation, the extending integral path is automatically calculated based on the fracture path. The integral surfaces Γ and Γ_ε in Eq.(1-2) are not located on the element boundaries. Therefore, the numerical integrals are operated on each incremental line ΔS and in integral area ΔV. The excellent far-field path independence of the T^*_{ex} is shown in Fig.6. In the developed moving FEM, similar T^*_{ex} integration can be operated in the non-straight crack propagation simulations.

For the elasto visco-plastic fracture, the T^*_{mv} values during fast crack propagation are too smaller than the fracture toughness T^*_C [4]. Figure 7 shows the T^*_{ex} histories of during crack propagations. Figure 7 indicate that the T^*_{ex} values is not too small as

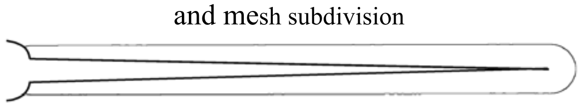


(a) Straight crack propagation C/Cs = 0.02



(b) Non-straight crack propagation C/Cs = 0.02

Figure 4 Equivalent plastic strain distributions and mesh subdivision



Crack propagation length 10mm, Dimameter of $\Gamma_\varepsilon \fallingdotseq$ 1mm

Figure 5 Near field integral path line

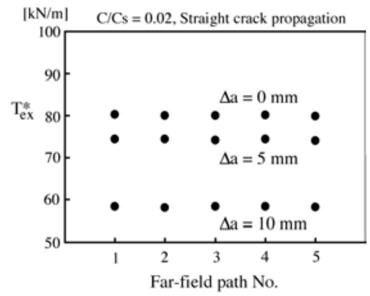
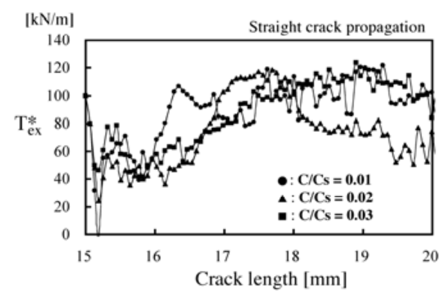
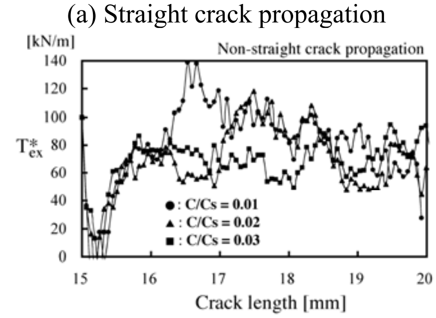


Figure 6 Far-field path independence of T^*_{ex}



(a) Straight crack propagation



(b) Non-straight crack propagation

Figure 7 T^*_{ex} histories for crack propagation problems compare with T^*_C. The T^*_{ex} include the plastic work effects in wake zone (This effect was called the crack opening energy in Ref. [2].). This irreversible energy effect prevents decrease of the T^*_{ex} for propagating crack.

Further discussions for non-straight crack propagation and others will be explained on the presentation of the conference.

Conclusions

In this study, the moving finite element method is developed to estimate residual plastic strain in wake zone. From the numerical results, the far-field path independent T^*_{ex} can be calculated. For the crack propagation with elasto visco-plastic deformation, the T^*_{ex} values are larger than the T^*_{mv}. The T^*_{ex} is expected as practical parameter for elasto visco-plastic fracture. Because this method is able to estimate the T^*_{ex} in the fracture path prediction simulation, this method can be applied to predictions and measurements of various complex nonlinear fracture problems.

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