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Local stress evaluation of rapid crack propagation in finite element analyses

Fuminori Yanagimoto[a,*], Kazuki Shibanuma[a], Yo Nishioka[a], Yuya Shirai[a], Katsuyuki Suzuki[b], Toshiyuki Matsumoto[c]

[a] Department of Systems Innovation, Graduate School of Engineering, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan
[b] Research into Artifacts, Centre for Engineering, University of Tokyo, 5-1-5, Kashiwano-ha, Kashiwa-shi, Chiba, Bunkyo-ku, Tokyo, Japan
[c] Research Institute, Nippon Kaiji Kyokai, 3-3, Kioi-cho, Chiyoda-ku, Tokyo, Japan

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ABSTRACT

The objective of this research is to perform the verification of finite element analyses with a nodal force release technique to simulate rapid crack propagation based on the local fracture stress criterion, and to propose a method suitable for the accurate evaluation of local stress. The verification of the accuracy and stability of local stress evaluation was first performed by generation phase analyses. The verification was first conducted for conventional methods, but there were large errors caused by violent vibration in local stress fields. Even though the nodal force release paths were optimized, the vibration in the local stress fields could not be sufficiently suppressed. Two types of artificial damping, the viscous term of the time integration method and Rayleigh damping, were then applied to the rapid crack propagation analyses. The results showed that only stiffness damping in Rayleigh damping could suppress the vibration and an appropriate degree of damping provided stably accurate local stress for all the crack velocities. This proposed method was then applied to the application phase analyses based on the local fracture stress criterion and successfully duplicated the exact solution of the crack velocity history.

1. Introduction

In spite of a long history of studies on brittle crack propagation and arrest behavior in steel plates, the governing equation has not been clear (Sumi et al., 2013). Although rapid crack behavior has generally been described by macroscopic fracture mechanics parameters, such as the stress intensity factor (SIF) K and J-integral, based on the energy balance (Fineberg and Bouchbinder, 2015), it has already been pointed out that the macroscopic fracture mechanics parameter cannot predict crack propagation and arrest behaviors (Machida and Aoki, 1972). Therefore, the concept of “the local fracture stress criterion” was first introduced to brittle crack propagation and arrest behavior in considering that cleavage fracture is governed by local tensile stress (Machida et al., 1997). They developed a model to successfully reproduce the dependency of crack arrest toughness on temperature, which was the most fundamental and important property of brittle crack arrestability, for the first time. This local fracture stress criterion is one of the typical local approaches and has been employed by other researchers (Berdin et al., 2008; Prabel et al., 2008; Berdin, 2012; Bousquet et al., 2012). In particular, Shibanuma et al. modified the first model based on the local fracture stress criterion by integrating with a model of unbroken side ligaments near the surfaces formed by the relaxation of plastic constraint at the crack front with crack propagation (Shibanuma et al., 2016a; Shibanuma et al., 2016b). The model successfully simulated the crack propagation and arrest behaviors in various crack arrest tests (Shibanuma et al., 2016b). Additionally, the model could explain the physical basis of crack arrest design which was employed in current international standards (International Association of Classification Societies, 2014). These results strongly supported the validity of the local approach as a criterion of the cleavage crack propagation in polycrystalline solids, especially steel. In addition, it was reported that the local stress in the vicinity of the propagating cleavage crack tip was constant (Yanagimoto et al., 2018). This result also indicated that the local fracture stress criterion is a promising criterion to explain the brittle crack propagation and arrest behavior in steels.

However, because the above model did not care the verification of the local stress evaluation, accurate evaluation of local stress is increasingly important to study brittle crack propagation and arrest behaviors in more detail. Thus, considering the rapid growth

* Corresponding author.
E-mail address: yanagimoto@struct.t.u-tokyo.ac.jp (F. Yanagimoto).

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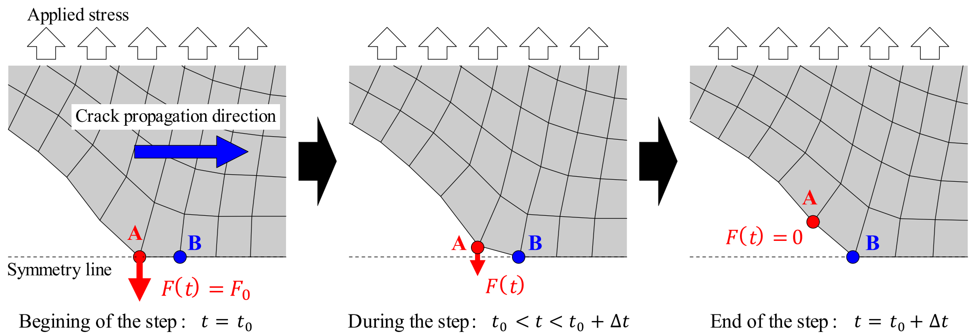

Fig. 1. Schematic of nodal fore release technique to simulate rapid crack propagation.

of computer performance, numerical methods is promising for the accurate local stress evaluation.

In fact, numerical methods are indispensable approaches for studying rapid crack propagation problems owing to experimental difficulties. Although several numerical techniques analyzing dynamic cracks, e.g. the finite difference method (Chen, 1978), peridynamics (Ha and Bobaru, 2010), and element-free Galerkin method (Khosravifard et al., 2017), have been utilized for rapid crack propagation analyses, the finite element method (FEM) is one of the most reliable and common numerical methods for dynamic crack propagation problems (Kishimoto et al., 1980). Based on the fundamental FEM frameworks, modifications and evolutions have been conducted for rapid crack propagation analyses. For example, XFEM, PDS-FEM, and cohesive zone model are powerful numerical methods available for analyses of dynamic crack propagation of materials (Grégoire et al., 2007; Hori et al., 2005; Salih et al., 2015). Actually, some studies applied them to the analyses of brittle crack propagation and arrest behavior in steels (Pandolfi et al., 2000; Valoroso et al., 2014), although they could not provide sufficient explanation to the behavior.

However, almost all of the conventional studies using the numerical methods such as XFEM and cohesive methods have just aimed to obtain the macroscopic fracture mechanics parameters or dissipation energy, and they have not considered the evaluation of the local stress in the vicinity of a propagating crack tips. Accordingly, while there have a lot of efforts to develop numerical methods which can evaluate fracture mechanics parameters accurately, the accuracy of the local stress evaluated by the numerical methods has not been investigated in spite of the importance of the local fracture stress to study brittle crack propagation and arrest behavior in steels. Although there are a few studies focused on local stress (Berdin et al., 2008; Prabel et al., 2008; Berdin, 2012; Bousquet et al., 2012), the numerical accuracies were not sufficiently verified.

According to the above background, this paper presents strict verification of the finite element analyses for rapid crack propagation based on the local stress criterion as a foundational but significant investigation, and proposes an effective method to evaluate local stress near the crack tip with accuracy and stability. These investigation were conducted using elastic problems because there are the established theoretical local stress field in the vicinity of the dynamically propagating crack tip in elastic materials. Abaqus 6.14 was employed as a finite element analysis solver for all analyses in this paper (Dassault Systems, 2014).

2. Nodal force release technique and finite element mesh

In this study, crack propagation is represented by the nodal force release technique (Kuna, 2010), which is schematically illustrated in Fig. 1. In the nodal force release technique, the time length of the time step Δt is defined as the time it takes for a crack to pass through an element. For example, in Fig. 1, node A corresponds to the crack tip and the reaction force at node A is $F(t) = F_0$ at the beginning of the present step, i.e., $t = t_0$. Defining the present step, i.e., $t_0 < t < t_0 + \Delta t$, the reaction force $F(t)$ monotonically decreases from F_0 to 0. At the end of the present step, i.e., $t = t_0 + \Delta t$, $F(t)$ is zero and node B corresponds to the crack tip. Because the length of the time step Δt is the time duration for the crack to propagate through one element, Δt is determined by the mesh size and crack velocity. Therefore, the dynamic condition can be considered by setting the length of the time step needed for the crack to propagate through one element according to the crack velocity.

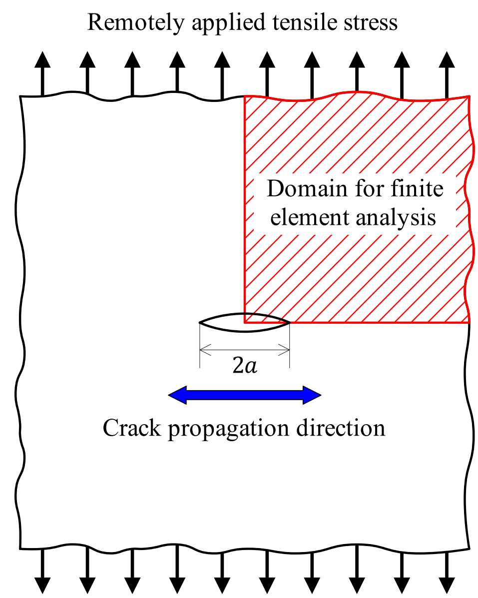

Fig. 2. Infinite elastic media with a center crack under remote tensile stress and the domain for finite element analyses.

Although there are several methods to simulate rapid crack propagation in the FEM frameworks as described in Section 1, we employ the nodal release technique because it is the simplest and most fundamental method in finite element analyses (Kuna, 2010).

The problem analyzed in this study is schematically illustrated in Fig. 2. The media is an infinite plate with a central crack under remotely applied tensile stress. The crack propagates only in the normal direction of the tensile stress. This is the most fundamental mode I fracture mechanics problem (Anderson, 2005).

As this study required a series of many finite element analyses, a mesh generator that can produce reasonable finite element models to analyze the rapid crack propagation problem was developed to reduce numerical costs. This mesh generator constructs finite

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