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Recent Advances in Numerical Simulation Technologies for Various Dynamic Fracture Phenomena

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Abstract: Recent Advances in Numerical Simulation Technologies for Various Dynamic Fracture Phenomena are summarized. First, the basic concepts of fracture simulations are explained together with pertinent simulation results. Next, Examples of dynamic fracture simulations are presented.

keyword: Moving Finite Element Method, Critical total energy flux into Crack-tip criterion, Path Independent Dynamic J Integral, Fracture path prediction theories.

1 Introduction

Since dynamic fracture often causes fatal catastrophic failure of structures, the prediction of dynamic fracture paths (length, direction) is very important.

However, the dynamic fracture phenomena are extremely transient. Thus, the numerical simulation technologies are mandatory to establish the safety design methodology of structures.

Recently the present author has proposed several basic concepts of fracture simulations. In this paper, these concepts are explained together with pertinent simulation results. These concepts may also be useful for general fracture problems.

2 Basic concepts of fracture simulations

Dynamic fracture phenomena can be characterized by various dynamic states of crack tip. The dynamic states of crack tip are induced by impact or dynamic loads applied to the cracked solid, or by fast motions of the crack-tip itself. Thus, depending upon the dynamic states of crack tip, dynamic fracture mechanics may be further classified into impact fracture mechanics and fast fracture mechanics [Nishioka (1994,1995,1997,1998)].

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2.1 Types of Simulations

Dynamic fracture mechanics has been mainly treated as self-similar dynamic crack propagation. However, we often observe non-self-similar dynamic crack propagation such as dynamic crack curving and dynamic crack branching. So far, non-self-similar dynamic fracture mechanics has not been well established. Especially the simulation methodology for such non-self-similar crack propagation involves many inherent difficulties. In this section, the concepts of computer simulations for non-self-similar as well as self-similar dynamic fracture problems are explained.

2.2 Self-Similar Dynamic Crack Propagation

For straight self-similar crack propagation, computational simulations with specified initial crack length, specimen geometry, and applied load, can be conducted in either of two ways, as proposed by Kanninen [Kanninen (1978)]. One of these is "generation phase simulation" in which the variation of a fracture parameter such as the dynamic J integral [Nishioka and Atluri (1983), Nishioka(1999-a, 1999-b)], stress-intensity factor can be determined, using an experimentally measured crack-propagation history (a versus t curve or C versus t curve), where a, C, and t denote crack length and crack velocity, and time as the input data into the computational model. From this calculation, one can determine the fracture toughness as the material resistance against the crack propagation. The generation-phase simulation can also be considered as one of the techniques classified into the hybrid experimental-numerical method [Nishioka (2000)].

2.3 Non-Self-Similar Dynamic Crack Propagation

For non-self-similar crack propagation such as dynamic crack curving, recently Nishioka [Nishioka (2002)] has proposed three types of numerical simulation as depicted in Fig. 1. First, the generation phase simulation can be conducted similarly with the generation phase simulation for straight crack growth, except additionally using experimental data on the curved crack-path history (see Fig. 1(i)). In the application phase simulation for curving crack growth, two criteria must be postulated or predetermined, as indicated in Fig. 1(ii). One of them is the crack-propagation criterion which is almost the same as the one used in the straight crack-growth simulation. However, the crack-propagation criterion for the curving crack growth may involve mixed-mode fracture parameters. Thus, it should be described by a fracture parameter that takes into account mixed-mode conditions, such as the dynamic J integral [Nishioka and Atluri (1983)]. The other is a criterion for predicting the direction of crack propagation (propagation-direction criterion or growth-direction criterion).

The application phase simulations of curving crack growth have not fully developed except the application phase simulation of curving fatigue crack growth, due to several critical difficulties in those simulations for curving stable crack growth in elastic-plastic materials and for curving fast crack propagation in brittle materials. For instance, in dynamic brittle fracture, the crack-propagation criterion described by dynamic propagation toughness versus crack velocity relation (KID versus C) itself has the unsolved problems as pointed out by several researchers [Takahashi and Arakawa (1987), Nishioka, Syano and Fujimoto (2000)] .

Crack-length versus time relation used in the generation phase simulation can be used in the mixed-phase simulation. Thus, the increment of crack propagation is prescribed for the given time step sizes in the numerical simulation. In order to verify only the propagation-direction criterion such as the maximum energy release rate criterion, the present author [Nishioka (2002)] proposed a "**mixed-phase simulation**" as depicted in Fig. 1(iii)-(a).

Regarding the crack-propagation history, the same experimental data for the one used for the generation phase simulation. Then the propagation-direction criterion predicts the direction of crack path in each time step. Simulated final fracture path will be compared with the experimentally obtained actual one. If the considered propagation-direction criterion is valid, the simulated fracture path should exactly agree with the actual one. Therefore, this mode of mixed-phase simulation may be called "fracture-path prediction mode".

Another mode of mixed-phase simulation can be considered as depicted in Fig. 1(iii)-(b), i.e., "crack-growth prediction mode". In this mode, the experimental data for the fracture-path history and the crack-propagation criterion are used simultaneously. Thus, the direction of crack propagation is prescribed at each time step. In this case, crack propagates along the actual fracture path during the numerical simulation. Simulated crack-propagation history should agree with the experimentally obtained actual one if the postulated crack-propagation criterion is valid.

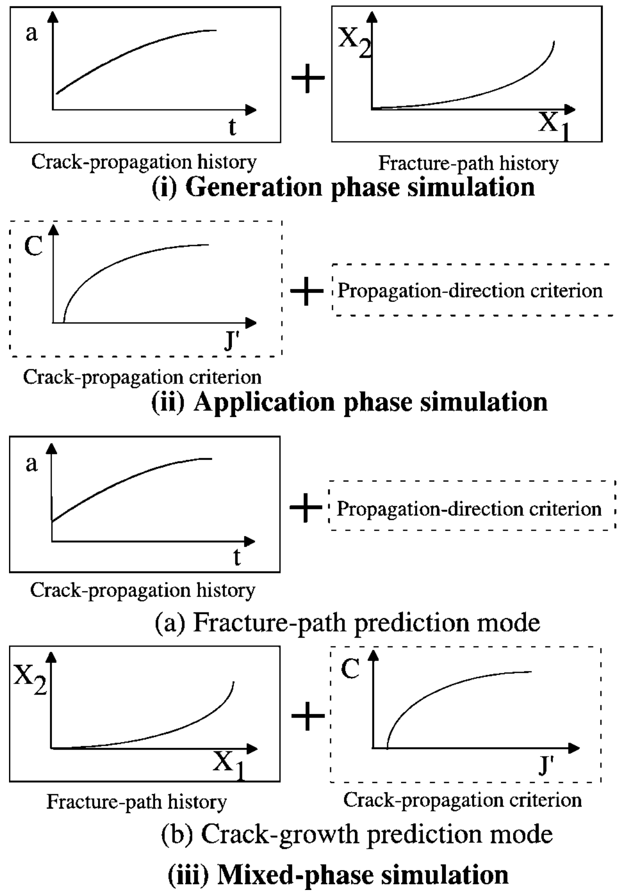

Figure 1 : Mixed-phase simulation for non-self-similar dynamic fracture.

2.4 Fracture path prediction theories

As explained in Section 3, in the mixed-phase fracture-path prediction mode simulation, a propagation-direction criterion is needed to be postulated. Many criteria have been proposed in literature.

Furthermore, Nishioka, Tokudome and Kinoshita [Nishioka, Tokudome and Kinoshita (2001)], Nishioka [Nishioka (2002)] classified these criteria into two categories:

(1) **explicit prediction theory** and (2) **implicit prediction theory**. Some of these criteria are listed below:

(i) maximum hoop stress criterion ($\sigma_{\theta\theta}$ max) (Erdogan and Sih, 1963),

(ii) minimum strain energy density criterion ($_{Smin}$) (Sih, 1972),

(iii) maximum second stress invariant criterion ($_{I2max}$) (Papadopoulos, 1988),

(iv) maximum stress intensity factor criterion ($_{KImax}$) (Nemat-Nasser and Horii, 1982),

(v) maximum energy release rate criterion (G $_{max}$) (Wu, 1978),

(vi) local symmetry criterion (K_{II} =0) (Goldstein and Salganik, 1974).

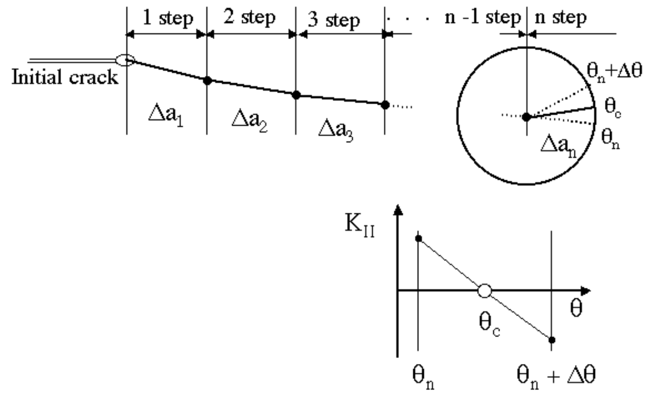

Figure 2 : Implicit fracture path prediction procedure based on the local symmetry criterion

2.5 *Explicit fracture path Prediction Theories*

An explicit fracture path prediction theory predicts [Nishioka, Tokudome and Kinoshita (2001)] the propagation direction satisfying the postulated criterion based on a physical quantity for the current crack tip. The criteria (i), (ii) and (iii) fall into this category. If the maximum hoop stress criterion is used, the crack is advanced in the direction of the maximum hoop stress (see, with a small crack-length increment ($\Delta a = C \cdot \Delta t$).

2.6 *Implicit fracture path Prediction Theories*

Contrary to the explicit fracture path prediction theories [Nishioka, Tokudome and Kinoshita (2001)], an implicit fracture path prediction theory seeks the propagation direction that satisfies the postulated criterion based on a physical quantity after the crack is advanced with a small crack-length increment(see Fig.2). An iterative process is generally needed to find the propagation direction. The criteria (iv), (v) and (vi) are classified into this category. It is known that in general, the implicit prediction theories are more accurate.

Nishioka et al. [Nishioka, Tokudome and Kinoshita (2001), Taniguchi (1992)] have succeeded in predicting a smooth fast curving fracture path in a DCB specimen, using the moving isoparametric element method based on the mapping technique. In these studies, the criteria (iv)-(vi) were tested in the mixed-phase simulation with the fracture-path prediction mode. It was found from these simulations that the predicted fracture path based on the local symmetry criterion (KII=0) most accurately agreed with the actual experimental fracture path.

Furthermore, Fig. 2 schematically explains the numerical procedures for the path-prediction mode of the mixed-phase simulation. In each time step, the crack is advanced by a small increment according to the experimental history (crack-length versus time curve).

The fracture path is predicted in an iterative manner as follows: In the following a superscript (i) denotes the iteration number. At a generic time step n, as the first trial, the crack is advanced in the tangential direction $\theta_n^{(i)}$(i=1) at the crack tip of the step n-1. If an employed propagation-direction criterion, for example, the local symmetry (KII=0) criterion, is satisfied at the attempted crack-tip location, the crack is advanced in this direction,$\theta_n^{(i)}$. If the KII value is negative, the crack is tentatively advanced in the direction of $\theta_n(i+1) = \theta_n^{(i)} + \Delta\theta$ as the next trial. If the KII value is positive, $\Delta\theta$ is taken as negative. Then, the satisfaction of the criterion at the trial crack tip location is checked. If the criterion is not satisfied and the value of the KII value at the present trial is different with that of the previous trial, the next trial direction $\theta_n^{(i+1)}$ that satisfies the employed propagation-direction criterion is predicted by the KII versus θ curve as shown in Fig. 13. If the predicted angle θc largely differs from the trial angle of the current iteration $\theta n^{(i)}$, the next trial direction is taken as $\theta_n^{(i+1)} = \theta_n^{(i)} + \Delta\theta$ the crack is advanced in this direction and the satisfaction of the criterion is checked. These procedures are repeated until the criterion is satisfied. At each iteration, remeshing is needed if the implicit criterion is used, as explained above.

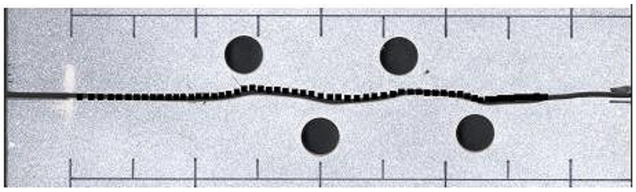

Figure 3 : Predicted and actual fracture paths

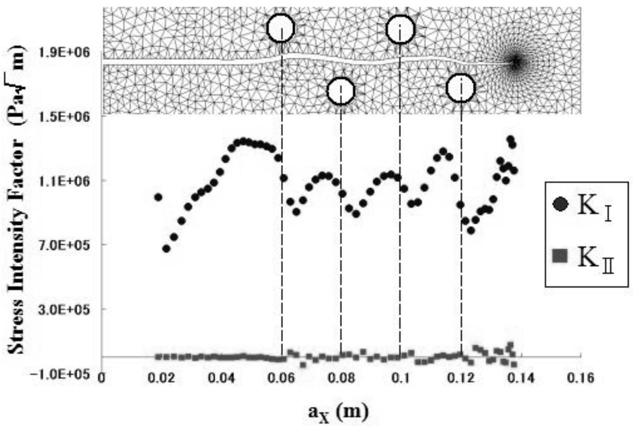

Figure 4 : History of Stress Intensity Factor

After finding the propagation direction that exactly satisfies the postulated criterion, the time step proceeds to the next step.

3 Dynamic Fracture Simulations

3.1 Dynamic fracture in a Structure containing multiple holes

The multi-site cracking caused serious problems in aircraft structures. Dynamic fracture in a structure with multiple holes may represent the dynamic fracture caused by the multi-site cracking. Thus, Dynamic fracture path prediction in a structure with multiple holes is very important to assess the integrity of the aircraft structures. The mixed-phase path prediction mode simulation was carried out in [Nishioka, Maruoka and Fujimoto (2004)] using the moving finite element method based on Delaunay automatic triangulation [Taniguchi (1992)].

The dynamic fracture phenomenon was recorded by using the world-most advanced ultrahigh-speed video-camera (maximum framing rate: one million frames per second, 100 frames, 312x260 pixels per frame,10 nanosecond exposure time for each frame)[Homepage]

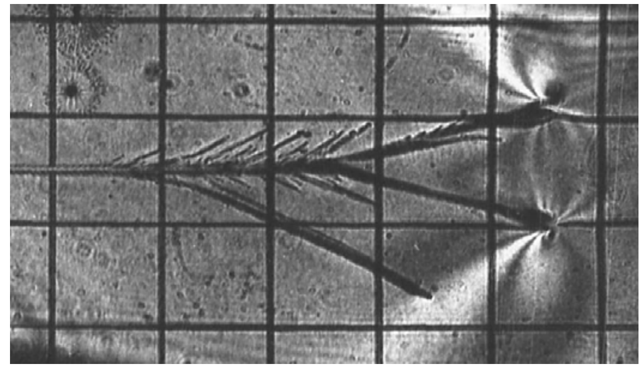

Figure 5 : A high-speed photograph of multiple crack branching

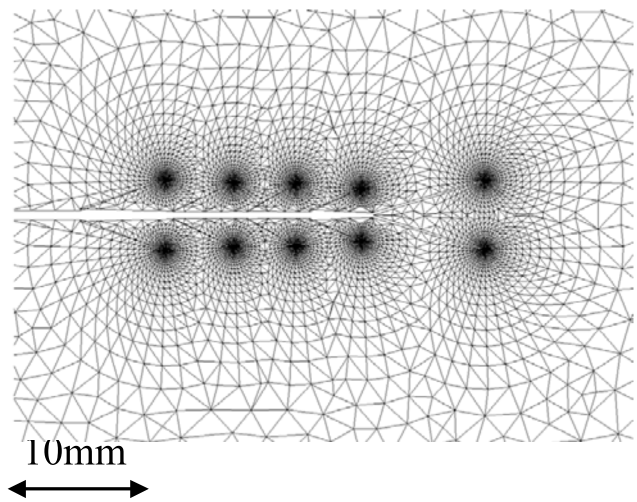

Figure 6 : Deformed mesh pattern at the crack branching area (150μs)

Fig. 3 compares experimentally obtained fracture specimen and numerically predicted fracture paths.

The numerically predicted fracture path (see doted line in Fig.3) exactly agrees with the actual one (see black line).

The maximum hoop stress criterion was used to predict the dynamic fracture path. The histories of dynamic stress intensity factors are shown in Fig.4.

The mode II stress intensity factors are almost zero, throughout the event. Thus, the local symmetry criterion (KII=0)is well prevail.

As seen in Figs.3 and 4 the holes attracted the crack. Thus, this is the reason that the wavy fracture path was formed.

3.2 Multiple dynamic branching fracture

Until our recent experimental study [Nishioka, Kishimoto, Ono, and Sakakura (1999)], The governing condition of dynamic crack branching has been unsolved problem for humankind. We elucidated the governing condition of dynamic crack branching as follows: dynamic crack branching occurs when the total energy flux (Φ_{total}) in to the propagating crack tip exceeds the material critical value $(\Phi_{total})_c$[**total energy flux to crack tip criterion**] [Nishioka, Furutsuka, Tchouikov and Fujimoto (2002)]

Furthermore, we [Nishioka, Furutsuka, Tchouikov and Fujimoto (2002), Nishioka, Tchouikov and Fujimoto (2001, 2002), Tchouikov, Nishioka and Fujimoto (2004, 2005)] firstly succeeded to predict dynamic two crack branching path using the moving finite element method based on Delaunay automatic triangulation.

Fig.5 shows a frame of the ultrahighspeed video camera at 150 microsecond after the onset of dynamic fracture in the specimen. multiple crack branching can be seen.

The variations of the energy flux (Φ_{total}) in to each crack tip are shown in Fig.7.

The generation phase simulation using the moving finite element method and the experimentally obtained fracture histories. Fig.6 shows the mesh pattern of the moving finite element method at 150microsecond. The moving finite element method is capable to express complicated dynamic fracture pattern.

The dynamic Integrals [Nishioka and Atluri (1983)] for all crack tip is evaluated by the switching method of the path independent dynamic J integral. [Nishioka (2001), Nishioka, Tchouikov and fujimoto (2004)] It can be seen from Fig.7 that the total energy flux criterion works very well.

3.3 Three-dimensional dynamic fracture simulations

Dynamic fracture fronts in a relatively thick plates are usually not straight [Nishioka (1995), Nishioka, Yoshimura, Nishi and Sakakura (1995)]

In order to accurately simulate three-dimensional dynamic crack propagation with a curved crack front, Nishioka and coworkers developed the moving 20-noded isoparametric finite element method.

The moving 20-noded finite element method [Nishioka, Ichikawa and Maeda (1995), Nishioka, Stan and Fujimoto (2002), Nishioka and Stan (2003)] firstly elucidated dynamic fracture parameters for naturally propagating three-dimensional dynamic curved crack fronts [Nishioka, Stan and Fujimoto (2002)].

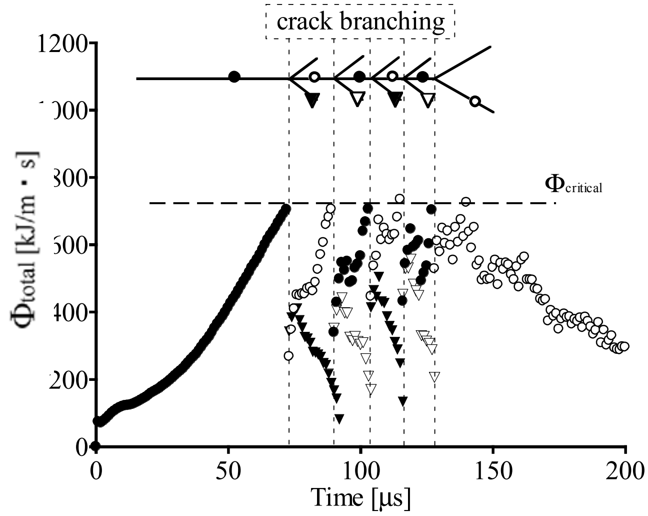

Figure 7 : Variations of energy flux

4 Conclusions

In this paper, fundamental concepts that are useful for general fracture problem including dynamic fracture problems are explained The powers of the moving finite element method on Delaunay automatic triangulation have been already demonstrated for many problems [Nishioka (1994,1995,1997,1998), Nishioka, Tokudome and Kinoshita (2001), Nishioka, Hashimoto and Fujimoto (2001), Fujimoto and Nishioka (2001)]. Some of them are presented here. Furthermore, moving isoparametric finite element methods [Nishioka, Hu and Fujimoto (2001), Nishioka, Stan and Fujimoto (2001)] are also very powerful. For instance, three-dimensional fracture parameters for naturally propagating and curved crack fronts are firstly elucidated [Nishioka, Stan and Fujimoto (2001)].

Furthermore, it was found that the total energy flux to crack tip criterion is also valid for multiple dynamic crack branching.

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