Recent Advances in Hybrid Experimental-Numerical Methods for Dynamic Fracture Studies

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SUMMARY

In the first part f this paper, the concept of the hybrid experimental-numerical methods are explained. On the basis of this concept, various hybrid experimental-numerical methods used in dynamic fracture mechanic studied are classified. In the second part, the features of these hybrid methods are presented with pertinent results obtained by recent our studies regarding dynamic fracture mechanics. These are (a) governing criterion of dynamic crack bifurcation, (b) dynamic fracture path prediction, (c) concepts of separated dynamic J integral and separated energy release rate for dynamic interfacial fracture mechanics, (d) simulations of dynamic interfacial crack propagation, and (e) others.

1 INTRODUCTION

Until recent years, we had only two major approaches for research and developments in the fields related to mechanics, i.e., "experimental methods" and "analytical methods". Nowadays, "numerical methods" can be considered as the third approach. All three approaches in mechanics have inherent advantages and disadvantages. In early days, numerical tools have acted as supplement for the drawbacks of the experimental and mathematical approaches. However, recent rapid and great strides of computer technologies are producing borderless hybridization of those methods and approaches. Since most types of hybridization are based on digital computer technologies, most of these methods fall into the category of hybrid numerical method. The hybrid numerical methods in fracture mechanics were first reviewed by Kobayashi [1]. Later, three types of hybrid methods of analysis were discussed by Atluri and Nishioka [2].

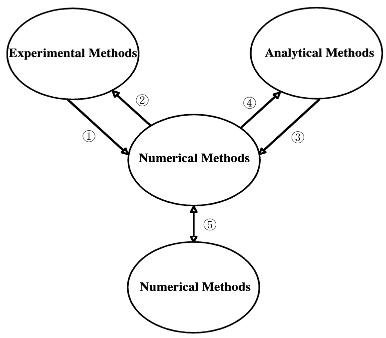
Due to very fast transient characteristics of dynamic fracture phenomena, detailed higher-order mechanical quantities are impossible to obtain from an experimental approach alone. For this reason, various hybrid experimental-numerical methods for dynamic fracture studies are developed by the present author [3]. The concept, applications, and features of the methods are presented in this paper.

2 CONCEPT OF HYBRID EXPERIMENTAL-NUMERICAL

For research and developments in the mechanics fields, experimental methods or experimental mechanics can be considered as the first approach. Experimental facts provide most important foundations for a related mechanics such as fracture mechanics. However, the experimental methods have several intrinsic drawbacks. For example, in most experimental methods, higher-order quantities such as various energy distributions are not directly measurable. Moreover, most experimental measurements are done on the surfaces of bodies. Especially, it is not possible for the current experimental technologies alone to directly measure the mechanical quantities at the inside of an opaque material.

The second approach in mechanics may be analytical (mathematical) methods or theoretical mechanics. The analytical methods unify the experimental facts and establish the related theories. However, most analytical methods cannot solve the problems with complex boundary conditions and those with some nonlinearity.

The third approach, i.e., numerical methods or computational mechanics will become more powerful due to a promising future progress of computer ability. The past progress of computer ability has promoted the advanced developments of the



① Hybrid Experimental-Numerical Methods
② Hybrid Numerical-Experimental Methods
③ Hybrid Analytical-Numerical Methods
④ Hybrid Numerical-Analytical Methods
⑤ Hybrid Numerical-Numerical Methods

Fig.1 Various types of hybrid numerical method conventional numerical methods such as the FDM, FEM and BEM, individually. However, each numerical methodology has its own intrinsic drawbacks. In the third approach, new methodologies such as the neural networks, genetic algorithm and molecular dynamics are growing rapidly. These new types of numerical methods heavily rely on the abilities of computer, and provide the solutions, which are not obtainable by the conventional numerical methods. However, they are also not fully developed, and have their own intrinsic drawbacks.

In order to overcome the drawbacks in each method, and to produce a new advanced method, many types of hybridization of two or more than two totally different methods can be considered. Among these hybrid methods, any method that more or less relies on the numerical methods may be included in the category of the hybrid numerical methods. The hybrid numerical methods can be conceptually classified as shown in Fig.1. Thus, the hybrid numerical methods are further divided as follows [3]:

(1) Hybrid Experimental-Numerical Methods
(2) Hybrid Numerical-Experimental Methods
(3) Hybrid Analytical-Numerical Methods
(4) Hybrid Numerical-Analytical Methods
(5) Hybrid Numerical-Numerical Methods

2.1 CLASSIFICATION OF HYBRID NUMERICAL METHOD

Let us consider the hybridization of two methods A and B. Depending on the state of connection of two methods, two types of the hybrid methods may be considered as depicted inFig.2. One of them is a non-mixed hybrid method in which the method A transfers necessary data to the method B. The method B gives the final solution of the problem considered. Means of the data transfer can be either on-line or off-line. In the off-line hybrid method, the methods A and B should be conceptually combined to lead a new solution technique for the problems that cannot be solved by the individual method alone. Other one is a mixed hybrid method in which a part or the entire of the method A is mixed or overlapped with the method B. Each method may be either of software ore hardware. In order to overcome the drawbacks in each method, and to produce a new advanced method, many types of hybridization of two or more than two totally different methods can be considered. Among these hybrid methods, any method that more or less relies on the numerical methods may be included in the category of the hybrid numerical methods.

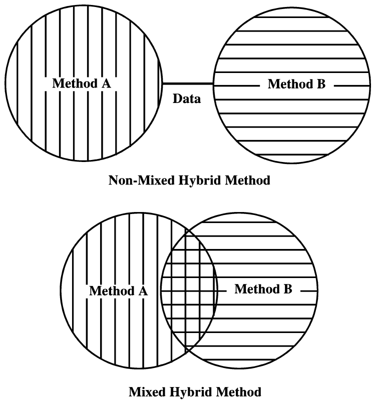


Fig. 2 States of connection in hybrid methods

Even using a full-field experimental measurement, the experimental method alone cannot give higher-order information on physical quantities of solid. In order to obtain more detailed information, the first-order information such as displacement must be processed numerically by using computer technologies. Many types of the hybrid experimental-numerical methods have been developed in relation to fracture mechanics [3]. Most of these may fall into the category of the non-mixed hybrid method.

2.2 TYPES OF FRACTURE SIMULATION

For non-self-similar fracture such as curving crack growth, three types of simulation were proposed by Nishioka [5]. First, the generation phase simulation can be conducted, using both experimental data of the crack-propagation and the curved fracture-path histories (see Fig.4 (i)).

On the other hand, in the application phase simulation for curving crack growth, two criteria must be postulated or predetermined as shown in Fig.4 (ii). One is the crack-propagation criterion that governs the rate of crack growth. The other one is a criterion for predicting the direction of crack propagation (propagation-direction criterion). However, the application phase simulations of curving crack growth have not been fully established, due to several critical difficulties in those simulations. For instance, in dynamic fracture, the crack-propagation criterion described by fracture-toughness versus crack-velocity relation itself has several unsolved problems.

To verify only the propagation-direction criterion such as the maximum energy release rate criterion, Nishioka [5] has proposed "mixed-phase simulation" as depicted in Fig.4 (iii). In "fracture-path prediction mode" of

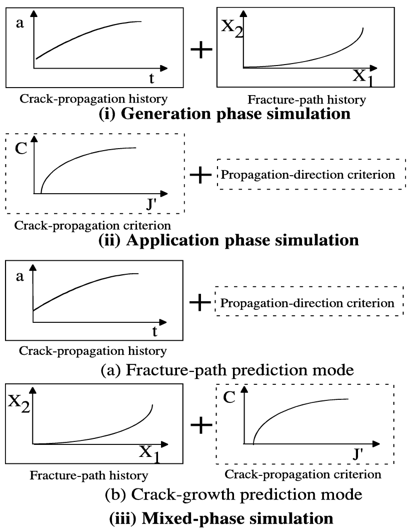


Fig.4 Types of numerical simulation for non-self-similar dynamic fracture

mixed-phase simulation, the experimental data for the a-t relation is used. Thus, the increment of crack propagation is prescribed for the given time-step sizes in this mode of simulation. Then a propagation-direction criterion predicts the direction of fracture path in each time step. If the simulated final fracture path agrees with the actual one, the postulated propagation-direction criterion is valid.

Another mode of the mixed-phase simulation can be considered as depicted in Fig.4 (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. In this case, the crack is forced to propagate 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.

3 RECENT APPLICALTIONS OF HYBRID EXPERIMENTAL-NUMERICAL METHODS

3.1 DYNAMIC CRACK BRANCHING

Many researchers have attempted to clarify the mechanism of crack branching. However the governing condition of dynamic crack branching had not been fully clarified until our recent studies [19]. Furthermore, we have succeeded to developed the moving finite element method [20] for complex dynamic fracture simulations

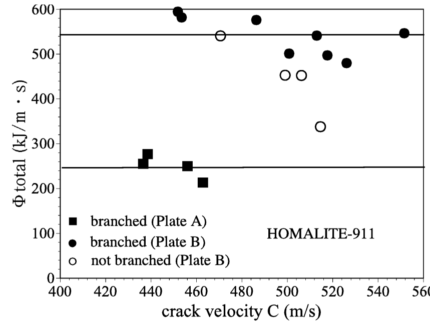
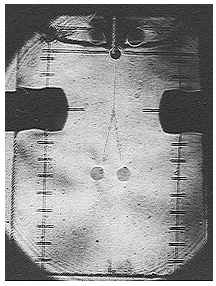
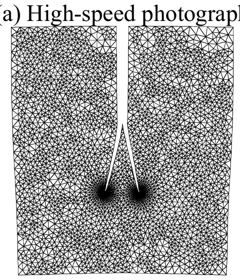


Fig.6 Energy flux at crack branching



(169.6 μs)
(a) High-speed photograph



(170.7μs)
(b) Moving FEM simulation
Fig.5 Dynamic crack branching

Figure 5(a) shows a high-speed photograph for dynamically branching fracture in Homalite 911. The crack bifurcated at the line of the lower loading system. Regarding the numerical simulation of dynamic crack branching, we developed a moving finite element method based on Delaunay automatic triangulation. Using this method, themixedphase fracture-path prediction mode simulations [25] were carried out, based on the experimentally recorded fracture histories by a high-speed camera [19]. Using the local symmetry criterion fort both branched crack tips numerical results was obtained as shown in fig.5 (b). The numerically predicted fracture paths almost perfectly agree with the one taken by the high-speed camera.

The total energy flux at dynamic crack branching are evaluated by $\Phi_{total} = J' \cdot C$, and plotted in Fig.6. The total energy flux into the tip of a branching crack is constant for various crack velocities at the instance of dynamic crack branching. Thus, it can be concluded that dynamic bifurcation occurs when the total energy flux Φ_{total} into the process zone or into the tip of a propagating crack reaches a critical material resistance.

3.2 MIXED-PHASE FRACTURE-PATH PREDICTION MODE SIMULATION FOR DYNAMICALLY CURVING FRACTURE

Numerical prediction of dynamic fracture path is extremely important research subject not only for academic interest but also for the establishment of a safety design methodology that prevents catastrophic overall failures of structures. However, numerical fracture-path predictions of non-self-similar dynamic fracture phenomena have not been succeeded until recently, due to various inherent difficulties. To establish a simulation method for complex crack propagation, a moving finite element method based on Delaunay automatic triangulation was developed [20,21].

Using the automatic moving finite element method, the mixed-phase simulation with fracture-path prediction mode is carried out for mixed-mode impact fracture tests [22]. The local symmetry (K_{II}=0) criterion was employed in this simulation. Figure 7 shows the deformed shape (magnified by 30 times) and the predicted fracture path by the mixed-phase fracture-path prediction mode simulation. The simulated fracture path

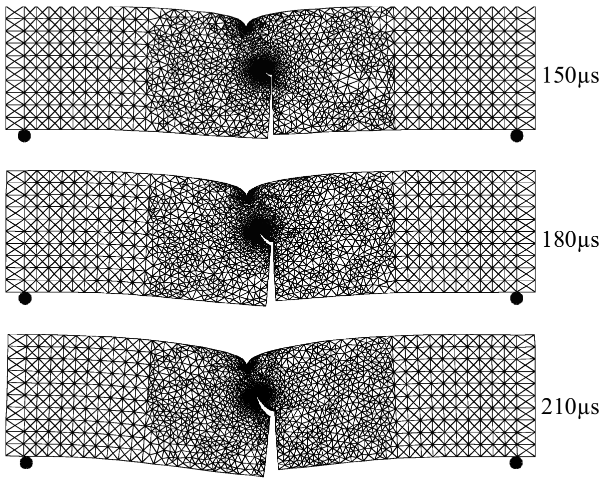


Fig7 Dynamic fracture path simulated with the local symmetry criterion

excellently agrees with the experimental fracture path [12].

3.3 DYNAMIC INTERFACIAL FRACTURE

In related studies, in impact interfacial fracture experiment, transonic ally propagating cracks were observed. We firstly succeeded to record the caustic patters influenced by the emach shock waves emanated from the crack tip. Based on the analytical solution [25] of dynamically propagating interfacial cracks in bimaterials. The theory of caustics [26] for a transonic ally propagating interfacial crack were developed [26]. Furthermore, we have derived the separated dynamic Integral, which have physical significance of the separated energy release rates from the individual martial sides of bimaterial.

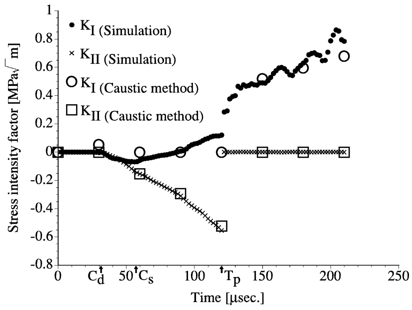


Fig.8Dynamic stress intensity factors

Based on the experimentally recorded crack propagation histories, the generation-phase simulations were done using the moving finite element method based on Delaunay automatic mesh generation. And the contact function based on the penalty method was newly developed to consider the crack face contact near the propagating interfacial crack tip.

It was succeeded to visualize in 3-dimensional aspects of the Mach shock waves emanated from the propagating crack tip. And it was tried for the transonic ally propagating crack problem that solving the energy flows through the contact zone or along the Mach shock wave line emitted from the crack tip. The energy flow patterns into the crack tip were also visualized. Furthermore, from the values of the separated dynamic J integrals, it was found that the dynamic J integral is non-zero even for transonic fracture region and the most of the energy release rate is provided from the more compliant material epoxy.

Moreover, to treat a contact on the crack face, frictionless contact based on the penalty method was considered as a gap element on the crack face.

Furthermore, the algorithm of contact/non-contact was considered at the loading point and the supporting points in the simulation. This makes it possible to simulate the phenomenon, which the specimen becomes free from the hammer and the support pin during the loading process. In the analysis, the state of a plane stress was assumed and the Newmark-β method was adopted as a technique of the time integration, where the time increments were 0.0768625 μ sec and the total calculation steps were 1600.

First, as the results of numerical simulation(28) the deformation at 120.2μsec is shown in Fig.6, where the deformation is scaled to 5 times. It is seen that the deformation of the aluminum alloy side is larger than epoxy side and the shear mode is caused.

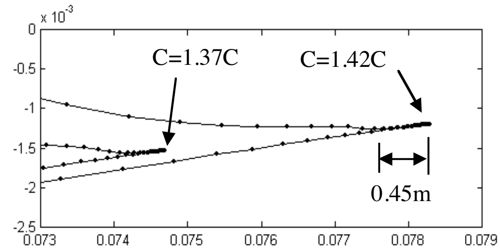


Fig.9 Crack surface contact

It is found that that more compliant material epoxy provides much more fracture energy than the stiffer material aluminum alloy. And it is found that the separated dynamic J integration value of the epoxy side begins to increase from transonic region again and keeps non-zero values even if the propagating crack velocity speed C exceeds the shear wave velocity Cs of the compliant material epoxy. That is, the crack singularity is non-zero even for transonic region. Rosakis et al. show that the value of the singularity exponent is zero at C=Cs and increases monotonically with crack tip speed till it reaches a maximum value at C=$\sqrt{2}Cs$ [4].

Next, the deformation shape of the crack face from the start of the crack propagation (at time 61.49μsec) to the end of the analysis (at time 122.98μsec) is shown in Fig.8 every 12.298μsec. The upper side of the figure is the epoxy side and the

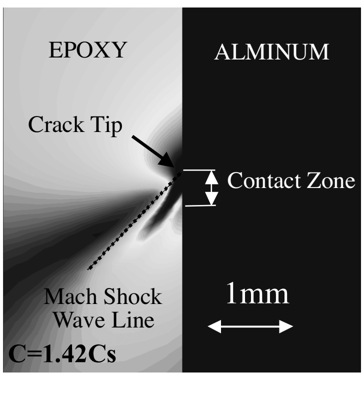


Fig.10 Contour of the Maximum shear stress

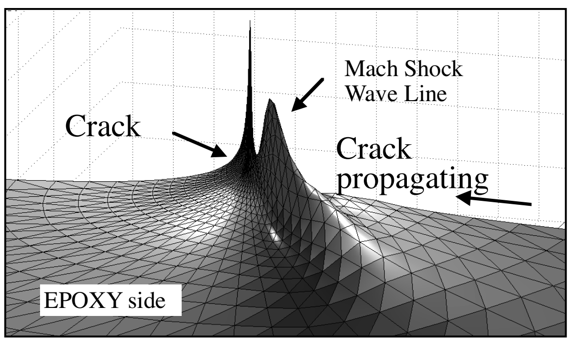


Fig.11 3-D form of the Mach shock wave

lower side is the aluminum alloy side, and the crack propagates from the left side to the right side in the figure. The index in the figure shows the rate of the crack propagating velocity C to the shear wave velocity Cs of the compliant material. It is found that the crack tip shape becomes sharper in the transonic regimes (C/Cs>1.0). Where, the displacement of the crack opening direction is scaled to 20 times.

Moreover, details of the crack tip at time 119.91μsec（C=1.37Cs）and 122.98μsec (C=1.42Cs) are shown in Fig.9. In the transonic regime, it can be seen that the crack face contact has occurred. In addition, the crack face contact has begun from time 110.8μsec (C=1.22Cs). The maximum length of the contact zone is very small as about 0.45mm.

The 2-D and 3-D displays of the distribution of maximum shear stress of the domain of 4mm of the crack tip at time 122.98 μ sec (C=1.42Cs) is shown Fig.10 and Fig.11 respectively. In Fig.10, the dotted line shows a theoretical Mach shock wave line. The angle of the shear shock wave can be obtained as $\theta_s = \tan^{-1}\{(C^2 / C_s^2 - 1)^{-1/2}\}$. The Mach shock wave emanated from crack tip, which obtained from the simulation, appears clearly in the epoxy side. Moreover, in Fig.11, it is found that the maximum shear stress increases rapidly along the Mach shock wave line and a deep cliff appears and theoretical Mach shock wave line matches the front of the shock wave obtained by the simulation.

Next, we consider of the energy flow through a contour Γ with normal vector NJ to the crack tip as

$$\Phi = J'^{(m)}_1 \cdot C = \int_{\Gamma_\varepsilon} C \cdot [(W+K)\delta_{1j} - \sigma_{ij} u_{i,1}] n_j dS = -\int_{\Gamma_\varepsilon} \varphi_j n_j dS \tag{3}$$

We can get the following equations that mean the energy flow flux vector.

$$\varphi_1 = -C \cdot [(W+K)\delta_{11} - (\sigma_{11} u_{1,1} + \sigma_{21} u_{2,1})])] \tag{4}$$

$$\varphi_2 = -C \cdot [(W+K)\delta_{12} - (\sigma_{12} u_{1,1} + \sigma_{22} u_{2,1})] \tag{5}$$

This Φ gives the instantaneous rare of energy flow through a contour Γ with normal n_j to the crack tip [6]. The sign in Eq. (4) (5) is chosen so that the vector φ_i pointing toward the crack tip corresponds to an energy flux into the crack tip. The energy flow flux vector (φ_1, φ_2) defined by the above equations at the domain of 10mm and 1mm of the crack tip at time 122.98 μ sec (C=1.42Cs) is shown in Fig.12 and Fig.13 respectively. In these figures, all vectors are the same length so that the orientation, but not the magnitude, of ϕ_i is indicated. In Fig.12, two dotted lines show the boundary between inflow and outflow to the crack tip. The dotted line on the left-hand side of the figure is almost corresponding to the theoretical Mach shock wave line. And the energy does not flow across a characteristic line that turns out to be a shock wave. In Fig.13, it is found that the energy transmitted through the contact zone will flow from the epoxy side to the aluminum alloy side. It is thought that the energy made to propagate the crack flows to the stiffer material side from the compliant material side. This will be suggested also from that the separated dynamic J integral of the epoxy shown in Fig.7 begins to decrease after passing over the starting time 110.8 μ sec of the crack face contact.

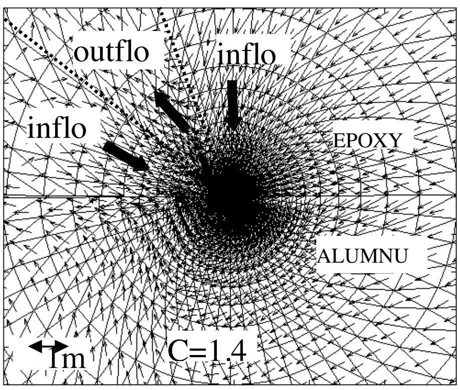


Fig.12 Energy flows in crack tip

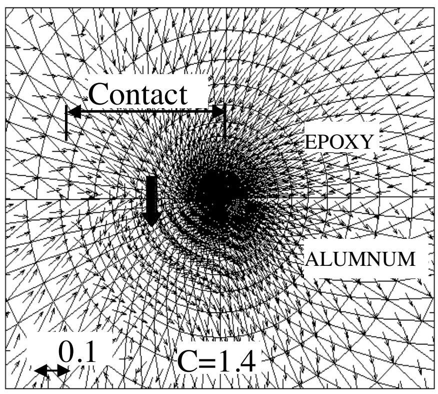


Fig.13 Energy flows on contact zone

4 CONCLUSIONS

In the numerical simulation, the Mach shock waves emanated from the propagating crack tip and the energy flow patterns into the crack were successfully visualized. It was shown that the energy flow pattern for the transonic ally propagating crack indicates not only the inflow energy but also the outflow energy along the Mach shock wave from the crack tip and the energy flows through the contact zone on crack face from the compliant material to the stiffer material.

Furthermore, from the values of the separated dynamic J integrals, it was found that the dynamic J integral is non-zero even for transonic fracture region and the most of the energy release rate is provided from the more compliant material epoxy.

In related experimental studies, the curved crack front of dynamically propagating three-dimensional fracture firstly recorded using an ultra-high speed camera. In numerical studies, moving 20noded isoparametric element method, which can model accurately the propagating, curved crack front. Then, based on the experimental fracture histories, the generation-phase simulations were carried out. Consequently, the dynamic J integral distributions were firstly elucidated. The hybrid experimental-numerical method made it possible to achieve it.

5 CONCLUDING REMARKS

In this paper, first, the concepts of of hybrid experimental-numerical method were presented. The hybrid experimental-numerical method can achieve a new ability that cannot be obtained by the experimental method alone. The effectiveness and usefulness of various hybrid experiment-numerical methods are explained by using the results of our recent studies.

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