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Dynamic crack propagation: quasistatic and impact loading

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Abstract

Simulation of dynamic crack growth under quasistatic loading was performed using finite element method with embedded incubation time fracture criterion. The uniqueness of the stress intensity factor – crack velocity relationship (K-v) is discussed. It is shown that the use of the structural–time approach and the fracture incubation time criterion enables us to predict successfully the results of experiments both on quasistatic and on impact loading of samples with cracks. Comparison of calculated K-v relationships with experimental data for various loading conditions leads to the conclusion that the dependence of the crack velocity on the stress intensity factor cannot be considered as a unique material law because the properties of this dependence are strongly determined by the sample configuration, the history, and the loading method.

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Keywords: Dynamic fracture; Incubation time; FEM; Stress intencity factor

1. Introduction

Stress intensity factor (SIF) K_I is often regarded as a key parameter in the framework of classic linear fracture mechanics. This parameter is used to define stress-strain field in the vicinity of a crack tip. A corresponding classic static fracture criterion is naturally extended to the case of dynamic crack propagation (see Owen et al. (1998)):

$$K_I\big(t, P(t), \Omega(t), \dot{L}(t)\big) \le K_{Id}\big(\dot{K_I}(t), T, \dots\big). \quad (1),$$

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where $P(t)$ is time-dependent loading, $\Omega(t)$ − varying specimen geometry, $L(t)$ − crack length which changes with time and $\dot{L(t)} = dL/dt$ is crack velocity. Right part of the expression (1) – K_{Id} − is called dynamic fracture toughness which is usually regarded to be function of loading rate $\dot{K_I(t)} = dK_I/dt$, temperature T and other material properties. According to classic dynamic fracture mechanics function K_{Id} is supposed to be defined from experiments *a priori*. Such approach is widely spread in the field of dynamic fracture research. However multiple experimental results (e.g. obtained in Ravi-Chandar et al. (1984), Kobayashi et al. (1997), Kalthoff (1983)) call into question analyses based on criterion (1) and existence (or at least uniqueness) of crack velocity – stress intensity factor dependence in particular. In K. Ravi-Chandar and W. Kauss (1984) it has been shown that almost constant values of crack speed may correspond to significant change of SIF in case of explicitly dynamic sample loading. The authors of these papers supposed energy flux to the crack tip to be unrelated to crack velocity, but to influence fracture surface pattern. On the other hand existence of clear and $\dot{L(t)} - K(t)$ dependence is observed in Kobayashi et al. (1977) and Kalthoff (1983) where precracked specimens of various geometry were loaded quasistatically. However, Kobayashi and Kalthoff note that such dependence might not be unique for particular materials and might be influenced by shape of specimens. On the other hand many experimental data confirm existence of stable dependence of crack velocity $\dot{L(t)}$ on crack length $L(t)$ (which can be regarded as dependence on SIF $K_I \sim \sqrt{L}$). This effect was observed in Fineberg et al. (1992) and Sharon and Fineberg (1999) where experiments on thin PMMA plates are described. Generally speaking, the crack behaviour observed in works by Ravi-Chandar, Kobayashi, Dally and Kalthoff does not contradict principles laying beneath condition (1) however one will encounter problem of determination of a functional from right part of (1) as this procedure might be very complicated. Besides this classic fracture criteria similar to (1) do not consider instabilities in dependencies of fracture toughness K_{Id} on $\dot{K_I(t)}$. Such diversity in experimental data on crack velocity – SIF dependence implies that stress intensity factor should not be treated as parameter which completely defines dynamic behaviour of the crack.

In this paper we summarize results for research of dynamic crack propagation for various loading conditions and in addition to this first results on investigation of $\dot{L(t)} - K(t)$ dependence using incubation time fracture criterion are presented. Experiments on various loading conditions (from explosion-like loading of crack faces to quasistatic stretching of specimens with initial crack) have been successfully simulated using finite element method with imbedded incubation time fracture criterion. The corresponding dynamic fracture theory was developed in Petrov (1996), Petrov and Morozov (1994), Petrov et al. (2003).

2. Fracture criterion and simulation technique

2.1. Incubation time fracture criterion

Incubation time criterion for brittle fracture at a point x at time t reads as

$$\frac{1}{\tau}\int_{t-\tau}^{t}\frac{1}{d}\int_{x-d}^{x}\sigma(x',t')dx'dt' \le \sigma_c \quad (2),$$

where τ is the microstructural time of a fracture process (or fracture incubation time) a parameter characterizing the response of the studied material to applied dynamic loads (i.e. τ is constant for a given material and does not depend on problem geometry, the way a load is applied, the shape of a load pulse and its amplitude). d is the characteristic size of a fracture process zone and is constant for the given material and the chosen scale level. σ is normal stress at a point, changing with time and σ_c is its critical value (ultimate stress or critical tensile stress found in quasistatic conditions). x' and t are the local coordinate and time

Characteristic size d is calculated according to the following formula

$$d = \frac{2}{\pi}\frac{K_{Ic}^2}{\sigma_c^2} \quad (3),$$

where K_{Ic} is a critical stress intensity factor for mode I loading (mode I fracture toughness), measured in quasistatic experimental conditions. Criterion (2) has been successfully used to simulate and investigate fracture for the case of dynamic and quasistatic loading.

2.2. Simulation technique

Dynamic crack propagation is studied in thin plates made of various brittle materials such as PMMA, Homalite 100 or epoxy resin. All specimens are of single edge notch (SEN) type with various modifications of geometry and loading type application. In all cases specimens are supposed to behave as linear elastic bodies and thus stress-strain state was determined by dynamic equations of linear elasticity theory. ANSYS finite element package is used in order to solve linear elastic equations while implementation of (2) is controlled by an external program after each solution step. For all simulations 2-dimensional problem formulation is applied. In addition to this symmetry of the problem is used to simplify calculations – only half of the plate is simulated with crack path being coincident with symmetry axis.

Nodes along the crack path are subjected to symmetrical boundary conditions (restriction of movement in the direction orthogonal to the crack path) up to the moment when the condition (2) is satisfied at a particular node. At this moment the restriction on movement of the particular node is removed, a new surface is created and crack tip is moved to the next node. The technique used is similar to the node release technique. The size of elements along the crack path was chosen to be equal d (see (3)). Small elements are placed adjacent to the crack path to provide the needed accuracy of computation and correct implementation of criterion (2). Distant elements are larger in order to minimize the computational time.

3. Examples and results of the simulations

3.1. Dynamic loading case. Ravi-Chandar and Knauss experiments

Criterion (2) and developed numerical scheme was used to simulate the classical fracture dynamics experiments reported by Ravi-Chandar and Knauss (1984). Detailed description of the model used in simulations and results of simulation of these experiments using FEM with the incubation time fracture criterion as a condition for crack extension can be found in Bratov and Petrov (2007). In these experiments samples with preliminary created initial crack were loaded dynamically by two consequent pulses with trapezoid shape (see fig. 1a).

Material parameters typical for Homalite-100, used in the experiments of Ravi-Chandar and Knauss, were used in the calculations. The microstructural time of the fracture process, τ, for Homalite-100 was found by Petrov et al. (2003) from analysis of experiments from Ravi-Chandar and Knauss (1984) and is equal to 9 μs. The values of the critical stress intensity factor and the ultimate tensile stress available from various sources give a value for d according to (3). It appears to be 0.1 mm for Homalite-100 on a laboratory size scale.

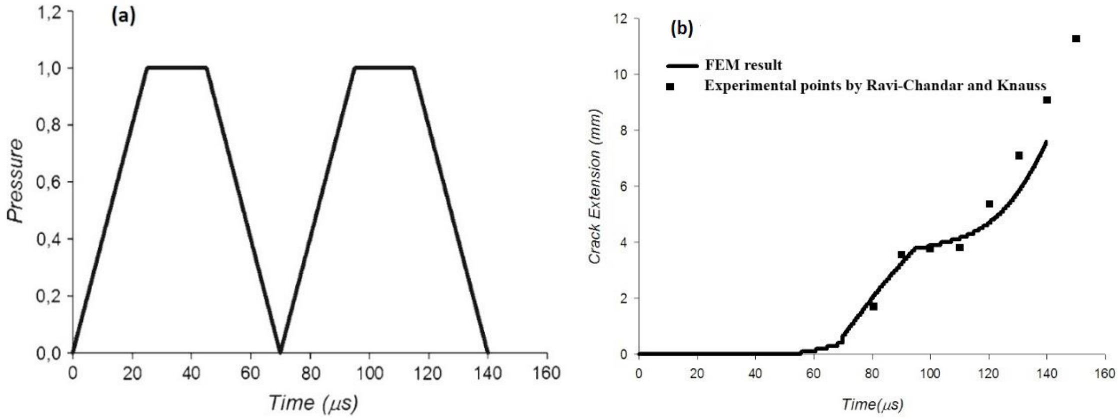

Fig. 1. (a) shape of loading pulses from Ravi-Chandar and Knauss (1984); (b) crack extension history

In fig. 1b the computational result for the pulse amplitude 5.1 MPa is compared to the experiments reported Ravi-Chandar and Knauss (1984). Numerical data fit accurately experimental points and thus incubation time based approach is proven to be robust method to predict crack evaluation in dynamic loading conditions.

3.2. Quasistatic loading case. Fineberg experiments

In experiments by Finberg et al. (1992) PMMA plates with the following dimensions were tested: width – 100-200 mm, height – 140-250 mm and thickness – 1.6-3.2 mm. Initial crack was of 4-6 mm length. The sample was then put into a tensile machine and stretched slowly and smoothly in order to eliminate influence of propagating elastic waves. The authors were able to register crack tip position and to measure crack speed. The stress field around crack tip which resulted into crack movement start was also registered

Incubation time for this material was found from experiments on dynamic loading of PMMA plates of the same dimensions and is equal to 1.5 μs. All other material properties such as elastic moduli, ultimate tensile stress and critical stress intensity factor were taken from literature. Details of this work might be found in Kazarinov et al. (2014).

Figure 2 depicts dependence of crack velocity on crack length. It is important to note that FEM simulation and incubation time fracture criterion provide correct terminal crack velocity – around 600 m/s, while theory based on Irwin's fracture criterion (see Freund (1998)) predicts much higher crack velocity limit value.

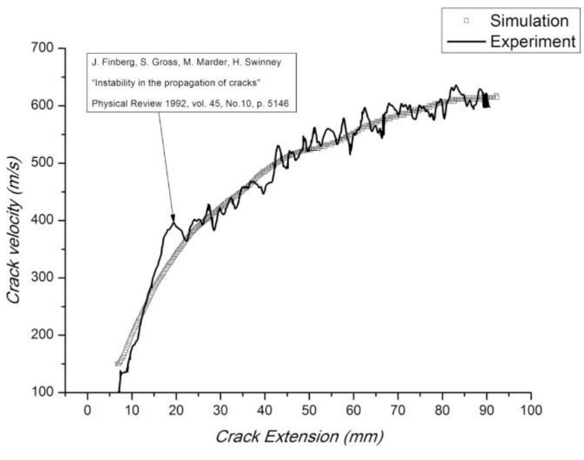

Fig. 2. Dependence of crack velocity on crack length

3.3. Stress intensity factor – crack velocity dependence. Uniqueness problem

As been noted above various authors stick to different opinions considering existence and uniqueness of $\dot{L}(t) - K(t)$ dependence. While Ravi-Chandar and Knauss (1984) claim that such dependence is not observed and considerable variation of SIF correspond to constant crack velocities, Kobayashi and Dally (1977) register two branches of $\dot{L}(t) - K(t)$ dependence for one material (KTE epoxy resin) depending on geometry of specimens. Figure 3 depicts two types of shapes used in Kobayashi and Dally (1977). Both of them are SEN specimens however they differ in load application method – in case of geometry (a) loading pins are placed in the center of the sample while geometry (b) supposes an offset of load application.

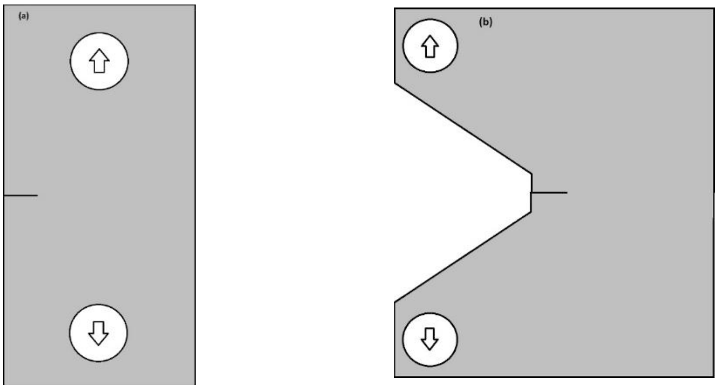

Fig. 3. Specimen geometry from Kobayashi and Dally (1977). (a) – central loading application; (b) – offset loading application

Two branches of crack velocity – SIF dependence from Kobayashi and Dally (1977) are depicted on fig. 4a. This paper is the first attempt to investigate phenomenon of existence of different branches in $\dot{L}(t) - K(t)$ dependence by means of numeric simulations and incubation time fracture criterion (2). The following parameters were used for the simulations: $\tau = 10\ \mu s$, $d = 0.19\ mm$. Most of material properties were taken from Kobayashi and Dally (1977). Fig. 4b shows two branches for the $\dot{L}(t) - K(t)$ obtained by means of finite element method simulations. Discrepancy between experimental data and numerical simulations might be explained by incompleteness of the list material properties in paper Kobayashi and Dally (1977). While phenomenon of different $\dot{L}(t) - K(t)$ dependences for samples of the same material but of different shape was qualitatively investigated in this work, more precise numerical analysis is matter of further research.

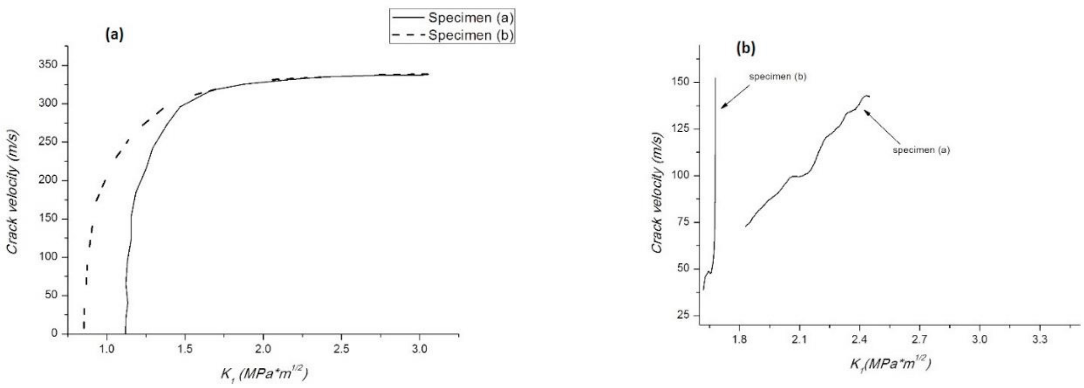

Fig. 4. Crack velocity – SIF dependencies. (a) – experimental data; (b) – numeric analysis

4. Conclusions

Incubation time fracture criterion appears to an effective tool for simulation and investigation of dynamic crack propagation process. Application of incubation time approach makes it possible to simulate crack movement for a wide range of materials, loading conditions and specimen shapes. This approach let us step aside from classic and widespread fracture criteria which are unable to take into account microstructural processes leading to fracture development. In addition to this incubation time approach makes it possible to investigate (at least qualitatively) phenomenon of two branches in crack velocity – stress intensity factor dependence relating to two different shapes of the investigate samples.

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