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SIMULATION OF DYNAMIC CRACK PROPAGATION UNDER QUASISTATIC 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 [1]. Experimental data, used for comparison was taken from [2]. ANSYS finite element software package was used in order to receive FEM solutions. The fracture criterion was implemented as an external procedure written in C++. The developed model is not using and "trimming" parameters. Only initial experimental conditions and material properties measured in separate experiments are used. Received dependencies for crack velocities as a function of time closely follow those observed in experiments by J.Finberg. Simulation results provide a possibility to conclude that the incubation time approach is an effective method to predict fracture initiation as well as crack propagation at various loading rates. Dependencies of an instant crack velocity on the current level of stress intensity factor received in this work for quasistatic loads and in [4] for high-rate loads is discussed and compared to those experimentally observed by K. Ravi-Chandar and W.G. Knauss [5] and J. Finberg [2].

Introduction

Stress intensity factor (SIF) K_I is a key parameter, which determines stress fields around crack tip within the framework of classic linear fracture mechanics. A corresponding classic static fracture criterion is naturally extended to the case of dynamic crack propagation [1]:

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

In this formula $P(t)$ is time-dependent loading, $\Omega(t) -$ current geometry of the specimen, $L(t) -$ crack length which changes with time, $\dot{L}(t) = dL/dt$ is current crack velocity. The right part of the expression (1) is the function called dynamic fracture toughness which is usually regarded as a material function of loading rate $\dot{K_I}(t) = dK_I/dt$, temperature T and other material properties. The right part of the expression (1) 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 works [3-5]) impugn analyses based on criterion (1) and existence of crack velocity – stress intensity factor dependence in particular. In [3-5] K. Ravi-Chandar and W. Kauss have 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 speed, but to influence fracture surface pattern. Thus conclusions made in [3-5] contradict commonly applied approach based on linear fracture mechanics postulates and condition (1).

The crack behaviour effects described in [3-5] appeared to be successfully predicted and simulated with use of structure-time approach built on a concept of incubation time [5-7].

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 papers [9] and [10] where experiments on thin PMMA plates are described. The experimental scheme involved quasistatic stretching of samples with an initial crack which resulted in crack acceleration followed by dynamic propagation of the crack through whole sample. Generally speaking the crack behavior observed in [9] and [10] does not contradict principles laying beneath condition (1) however one will encounter problem of determination of a functional from right part of (1) this procedure might be very expensive and complicated. Besides this classic fracture criteria similar to (1) do not consider instabilities in dependencies of fracture toughness K_{Id} on $\dot{K_I}(t)$.

Comparing of experiments carried out in different conditions but on the same material lets us conclude that critical stress intensity factor cannot be treated as an invariant with respect to history and conditions of loading material property which completely defines dynamic behaviour of the crack.

To explain and simulate crack propagation under high rate impulse loading conditions incubation processes which accompany macrofracture should be taken in account as it was shown in [6-8]. Use of these results let us successfully perform numeric simulation of experiments from [3] and [4] including crack's start, propagation and arrest [11].

Both types of experiments (with explicitly dynamic loading and with quasistatic loading) can be simulated with use of structure-time approach. Experiments from papers [9] and [10] were simulated using finite element method in ANSYS software with external procedure in C++ which implemented incubation time fracture criterion and controlled solution progress. The corresponding dynamic fracture theory was developed in works [6-8].

Structure-time fracture theory

According to structure-time approach critical condition for fracture in point x at time t may be formulated as follows:

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

Here τ is an incubation time – a characteristic microstructural time parameter which is specific for a given material and for the preset scale level. $d -$ is a characteristic size of a "process zone" where fracture occurs. It is also considered to be a material constant for a given scale level. $\sigma(x,t) -$ is stress in the investigated point x at time t. σ_c is a critical stress measured on samples of similar dimensions comparing to investigated sample in classic static experiments. It is important to notice that d should not be regarded as a purely geometric size parameter and for example should not be related to lattice cell size. We treat parameter d as a scale level identifier, which means that it sets the lower limit for the size of a considered scale level [12,13]. This way d defines minimal size for a fractured element. d can be calculated using formula (3):

$$d = \frac{2}{\pi}\frac{K_{Ic}^2}{\sigma_c^2}. \tag{3}$$

Here K_{Ic} and σ_c are supposed to be measured on the same scale level.

Experiment description. Simulation technique.

In experiments by J. Finberg [9,10] PMMA plates with the following dimensions were tested: width – 10-20 cm, height – 14-25 cm and thickness – 1.6-3.2 mm. Samples with maximal dimensions were chosen for the simulation in this paper. An initial crack of length 4-6 mm was made in the middle of the sample side before applying loads. The sample was then put into a tensile machine and stretched slowly and smoothly so that wave processes could be eliminated. 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.

The behaviour of the material is assumed to be governed by dynamic equations of linear elasticity theory

$$\rho \frac{\partial^2 U_i}{\partial t^2} = (\lambda + \mu)\nabla_i(\nabla \cdot \overline{U}) + \mu \Delta U_i \qquad (4)$$

$$\sigma_{i,j} = \delta_{i,j}\lambda \nabla \cdot \overline{U} + \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

with corresponding initial and border conditions

$$\overline{U}(X, t = 0) = \frac{\partial \overline{U}}{\partial t}(X, t = 0) = 0$$

$$\sigma_{i,j}(X, t = 0) = \frac{\partial \sigma_{i,j}}{\partial t}(X, t = 0) = 0$$

$$U_y(X \in \Gamma_1, t) = vt$$

$U_y(X \in \Gamma_2, t) = 0$ – symmetry condition

$$\sigma_y(X \in \Gamma_3, t) = \sigma_{xy}(X \in \Gamma_2 \cup \Gamma_3, t) = 0.$$

In these formulas $X = (x_1, x_2) = (x, y)$ – coordinates and $\overline{U} = (U_1, U_2) = (U_x, U_y)$ – displacement vector, v – speed of the tensile machine grabs.

The element size was chosen to be equal d and consequently minimal crack propagation also equals d. This perfectly fits structure-time approach. Deleting constraints on nodal displacements when condition (1) is satisfied allows us to simulate sample geometry change. Due to symmetry of the problem only half of the sample was modelled.

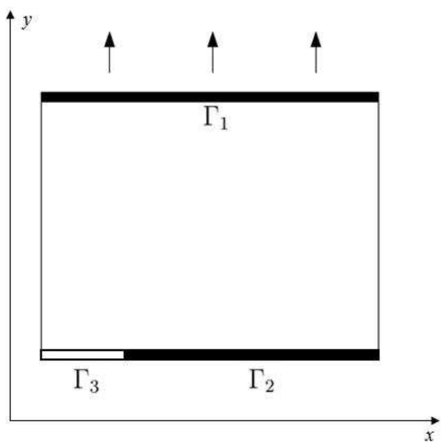

Fig. 2. Simulation scheme for J. Finberg experiments

Results

The results of the simulation are shown in figure 2. Dark line stands for experimental data and light line depicts simulation results. Numerical results for crack velocity fit well experimental data especially in the region of steady crack tip motion.

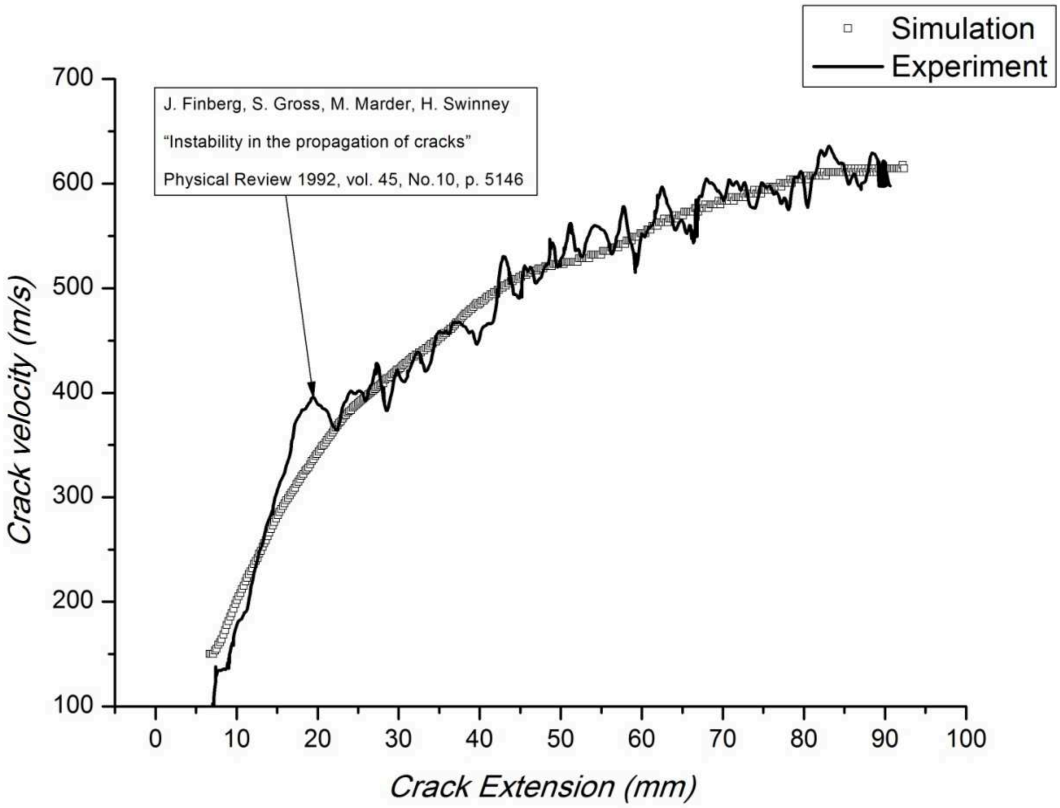

Fig. 2. Simulation results for experiments by J. Fineberg. Crack velocity – crack length dependence

Thus both "explosive" and "quasistatic" types of experiments were predicted and simulated using one universal approach, based on the concept of incubation time. This approach let us refuse from classic method which involves so called dynamic fracture toughness K_{Id} which cannot be regarded as material property and cannot be used for dynamic fracture description as it strongly depends on sample geometry and loading history [6-8].

The dependence of crack velocity on a stress intensity factor should not be regarded as a characteristic property for a material as it is defined by specimen geometry and way of loading.

A new parameter – incubation time τ – is introduced to predict dynamic fracture. τ is constant if we restrict ourselves within one scale level. Moreover incubation time is a material property and can be found experimentally in independent tests and can be used in any dynamic problem. Incubation time τ together with standard material parameters and d calculated using formula (3) make it possible to predict wide range of dynamic fracture effects.

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