Threshold Characteristics of Pulse Loads Causing Fracture on an Example of Concrete and Rocks

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Abstract: The technique of definition of threshold parameters of an impact is shown. The experimental results on crack extension in concrete and rocks under the short pulse (2 μs) of loading are presented. The loading was carried out on the crack surface by means of an installation of conductor explosion. The dependence of the crack length on the stored energy allows to define the threshold amplitude of the impact for the given duration of the pulse. The possibility in principle of definition of effective surface energy of fracture within the limits of the developed approach is shown.

Key words: threshold pulse; crack extension; electrical explosion of conductor; fracture energy; concrete; rocks

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1 Introduction

The principle of limit loads is used to estimate the material strength under slow loading. For example, the criterion of maximum static strength of a material is introduced into tests for rupture [1]:

$$\sigma \geqslant \sigma_c . \tag{1}$$

This principle has well proved in the case of quasi-equilibrium processes in a material. However, there is still no common point of view on the fracture criterion under the action which leads to failure in the moment of transient processes of energy distribution on the object. The given fact arises from the circumstance that researchers are trying to extrapolate classical principles of fracture theories from quasi-statics in the domain of nonequilibrium processes. Nevertheless, the simple cases of quasi-statics should follow as a special case of the dynamic process [2].

Since we speak about dynamic processes, time parameters should be entered into the fracture theory: duration of the action, fracture time, the time between a maximum of the loading in the point of fracture and the moment of fracture, etc. Nikiforovsky and Shemjakin have suggested the criterion of a power pulse [2-3]:

$$J \geqslant J_c . \tag{2}$$

This means that failure occurs at the value of the pulse greater than the critical pulse. However, the momentum depends on the duration T, amplitude P and velocity of the pulse front $\dot{P}$, hence, the threshold amplitude and duration determine the threshold pulse (minimal fracture pulse):

$$\begin{cases} J = J(P, T, \dot{P}), \\ J_c = J_c(P^*, T^*). \end{cases} \tag{3}$$

Here it is necessary to notice that the threshold values of amplitude and duration can be any for the same value of the threshold pulse. If we increase the pulse duration, then we obtain the criterion for the quasi-static case, and the threshold pulse amplitude

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aspire to the so-called static strength of the material (Fig. 1). If the duration of the action is comparable with the duration of fracture, then various dynamic effects of failure become apparent. The matter is that any material has the finite time of failure (for a given scale of fracture), and the duration of stress pulse can be less than the duration of the fracture process.

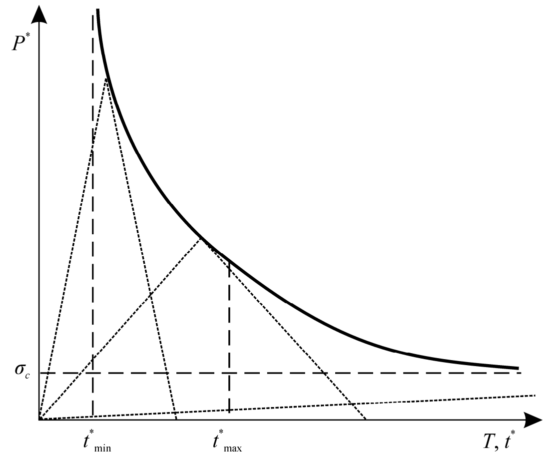


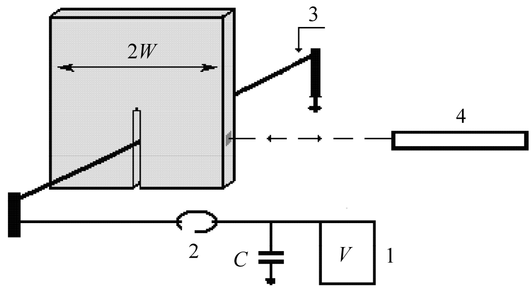
Fig. 1　The threshold amplitude P^* vs. the duration T (for the pulse of triangular shape). t^*_{min} and t^*_{max} represent minimum and maximum time required for a given fracture.

In works [4-5], it is shown that strength parameters of materials, such as spall strength, fracture toughness, etc. depend on threshold loads. Overload of the threshold pulse does not give an objective picture about strength, so it is important to study strength characteristics at threshold parameters of the action. The question arises about the definition of these thresholds.

2　Experimental procedure and calculations

As an example of definition of threshold loads, we will consider one of experiments which were carried out in St. Petersburg State University. In the experiments the crack length was measured as a function of energy stored in the capacitor. The experimental setup is shown in Fig. 2.

Samples of sandstone, dolomite, gabbro-diabase and concrete were in the form of plates 150/150 mm



1: charging device, 2: discharger, 3: exploding wire, 4: laser interferometer, W: half-width of the sample

Fig. 2　The experimental scheme for testing of samples with a notch

with a thickness of 15 mm. The notch with a length of 70 mm and width of 3 mm was made in the middle of the sample for crack imitation.

The tests were carried out on the installation of electrical explosion of conductors with parameters: capacitance $C = 6$ mF, voltage $Uc \leqslant 50$ kV, stored energy $\xi \leqslant 7.5$ kJ. A copper wire (diameter of 0.6 mm) was placed between the crack faces and perpendicular to the plane of the plate at a distance of 20 mm from the notch tip. The wire was passed through cambric of PVC with a diameter of 0.7/3.5 mm for better acoustic contact.

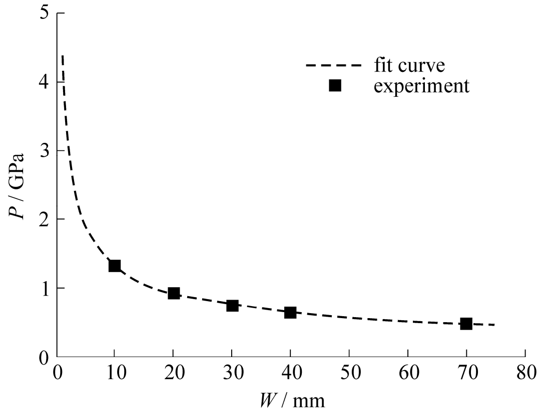
This method of loading raises the question: how to determine the amount and shape of the impact? It is necessary to associate the energy of the explosion with the parameters of the stress pulse. A series of separate experiments was conducted for this purpose.

In these experiments, the half of the sample width W was varied from 10 to 70 mm, and the velocity of the lateral surface was measured using a laser interferometer (Fig. 2). Actually, explosion of a wire leads to formation of a cylindrical wave, but the sample dimensions allow to use the formula for calculation of the pulse amplitude P in a case of a plane wave [6]:

$$P = 0.5\rho c w, \qquad (4)$$

where ρ is material density, c is velocity of longitudinal waves, w is velocity of the free surface. The duration of the bell-shaped pressure pulse was $T = (2\pm0.1)$ μs.

Thus, the initial amplitude was determined by fitting the experimental values of the stress pulse amplitude at aspiration of the sample width to enough small size (Fig. 3). It was found that the value of the pulse amplitude corresponds to one fifth of the value of the stored energy.



experiment: square points; extrapolation: dashed line

Fig. 3 The attenuation of the pulse amplitude in the gabbro-diabase sample (*U*= 25 kV). W is half-width of the sample (see Fig. 2)..

The stress-wave pattern in the vicinity of the crack tip in the conditions of this experiment can be obtained from a solution of the plane problem. An elastic isotropic plane (x, y) with a semi-infinite crack (y = 0, x<0) is considered. At time t = 0 a concentrated pulse of pressure act on the crack face in the point with coordinates (y = ±0, x = -L) (Fig. 4). Thereby,

$$\begin{aligned} &\frac{\partial \sigma_y}{\partial y} = \rho \frac{\partial^2 v}{\partial t^2} \\ &\sigma_y(x,0,t) = -P\delta(x+L)f(t), x<0 \qquad (5) \\ &\sigma_{xy}(x,0,t) = 0, -\infty < x < \infty \\ &v(x,0,t) = 0, x>0 \end{aligned}$$

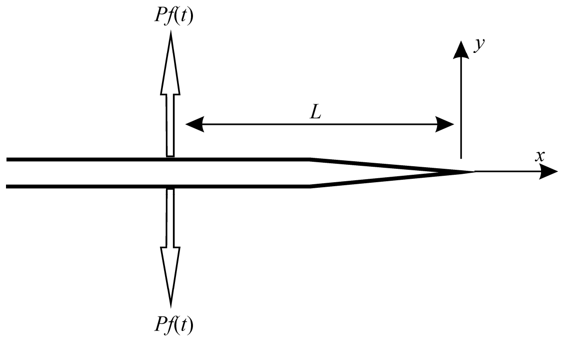


Fig. 4 Statement of the analytical problem

This analytical problem has been solved for loading in the form of the Heaviside step function $f(t) = H(t)$ [7]. We used numerical modelling to avoid bulky calculations and to consider the solution taking into account the real sizes of the sample.

Change of the stress at the crack tip without account of crack propagation is shown in Fig. 5. The arrival of longitudinal wave leads to compression in the crack tip. The rapid increase of stress begins after the arrival of the Rayleigh wave.

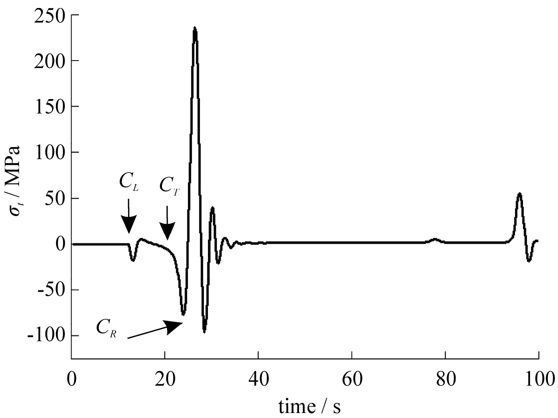


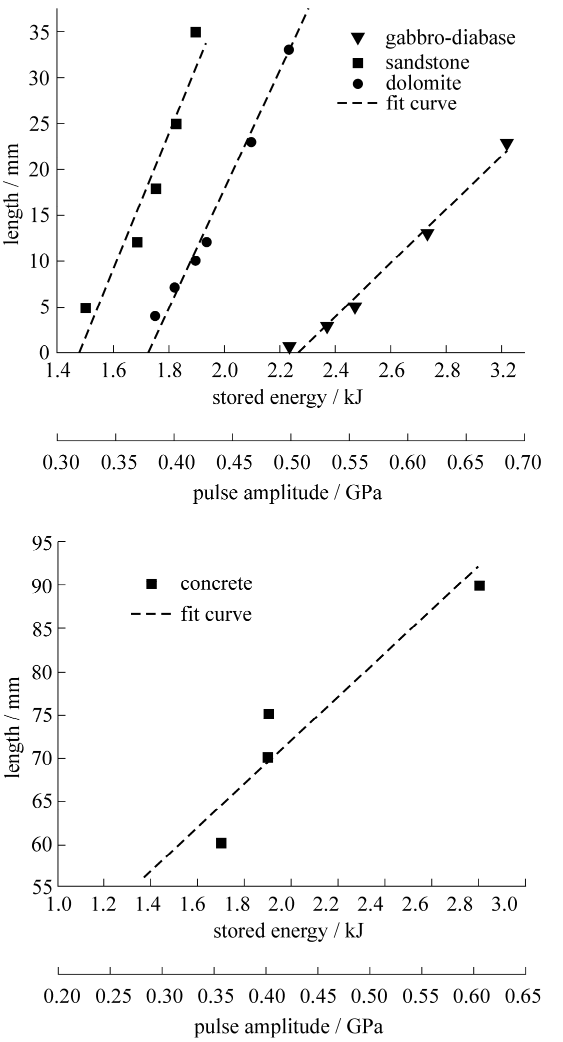
Fig. 5 Simulation of the stress-wave pattern at the crack tip

3 Results

The experimental results are presented in Figure 6. The dependences were obtained by extrapolation the experimental points to zero length (or minimum visible length) of the crack. The amplitude corresponding to zero length of the crack is threshold amplitude. For example, the threshold for sandstone is 0.32 GPa. Thus, fracture will not occur when a pulse with duration T < 2 μs and amplitude of P < 0.32 GPa.

It is important to note that we must always bear in mind the scale of observation. This means that we must agree on “what is fracture?” at the stage of the problem formulation. For example, in our case, it is a crack visible with the naked eye. However, we could look for an initial crack with a microscope or to accept its minimum allowable length. All these are different scales of failure, which require different contributions of energy.

The angle between the *Y*-axis and the curve is the fracture energy $d\xi / dl$. In our example, the estimation of quantitative values of the energy consumption can contain large errors due to the indirect determination of the input energy. However in [8], it is shown that the energy required for fracture depends on the pulse duration and can greatly exceed the Griffith surface energy.



points: the result of the experiments; dashes: the linear extrapolation

Fig. 6　The crack length vs. the stored energy of the capacitor

The analysis of the fracture surface of concrete has shown that there are several ways of crack extension: through the matrix, between the inclusion and the matrix, through inclusion. Each way requires the various contribution of energy. Determination of fracture energy in a case of composites requires further research, since threshold loads can differently affect on the elements of the composite material.

4　Conclusions

Strength characteristics of a material depend on threshold parameters of the impact. This paper presents an example of defining the threshold pulse amplitude and duration in simple experiments. It is shown that failure of the considered rocks and concrete has threshold character.

The analysis of the results shows the possibility of application of electric explosion of conductors to study dynamic strength parameters of materials, including rocks and concrete.

The crack length was measured as a function of explosion energy. The threshold value of the pulse amplitude for a given duration was defined by extrapolation of the experimental points to zero length of the crack. This approach makes it possible to determine not only the threshold characteristics of an impact, but also effective fracture surface energy.

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导致混凝土和岩石断裂的脉冲载荷的阈值特性

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摘要: 定义了冲击阈值参数, 给出了 2 μs 短脉冲加载下混凝土和岩石裂缝扩展的实验结果, 裂纹表面加载采用电爆炸方法实现. 依据裂纹长度依赖于储能的关系, 定义了给定脉冲宽度的载荷阈值. 提出了采用此方法定义断裂有效表面能的理论可行性.

关键词: 阈值脉冲; 裂纹扩展; 导体电爆炸; 断裂能量; 混凝土; 岩石

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