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Blow-up Regimes in Failure of Rock Specimens

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Abstract. For damage evaluation, the stage of superfast catastrophic failure of a medium and its mechanical behavior in a state of self-organized criticality prior to the onset of a blow-up fracture mode is of great interest for identification of its precursors. In this work, the data of experimental and numerical investigations of mechanical behavior of a medium before its catastrophic failure and the onset of a blow-up fracture mode are presented. Rock samples and ceramic specimens are subjected to three-point bending and uniaxial compression testing. Surface velocities of the loaded specimens are registered using a laser Doppler vibrometer. The blow-up regime duration is measured to be about 10–20 ms. The specimens' mechanical behavior is numerically simulated under experimental conditions, including the regime of catastrophic fracture. The model parameters of damage accumulation are determined from a comparison with the experimental data. A number of features of the material mechanical response before the catastrophic fracture are identified, which could be treated as failure precursors.

INTRODUCTION

Evaluation of durability of objects and structures under loading and reliable prediction of the evolution stages of their deformation, including catastrophic fractures, are among the most important challenges of mechanics and physics of fracture. An essential feature of deformation evolution in loaded solids is the existence of a slow, quasi-stationary stage of accumulation of small-scale damage, hardly pronounced. Stress fluctuations in the vicinity of such micro-scale defects are extremely small and so is their range of action. As long as their concentration is comparatively low, they hardly interact with each other. When it becomes critically high (according to Zhurkov's concentration criterion of crack growth), the cracks begin to interact, bringing the loaded medium into a state of self-organized criticality (SOC), where all the damaging processes become correlated due to the information exchange via the stress microwaves generated by the growing cracks. The process of their coalescence and a transition of fracture to the macroscopic level develop as a superfast catastrophe. One of the main objectives of this work is to investigate this regime.

A MODEL OF DAMAGE ACCUMULATION

In order to describe the catastrophic regime, we propose to use a damage accumulation model relying on the general concepts of the theory of non-linear dynamical systems (NDS). In this case, the rate of damage accumulation in a loaded medium $\mathrm{d}N/\mathrm{d}t$ is a power function of the already accumulated damage N:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = a(\sigma, \lambda)N^{\alpha}, \quad a(\sigma, \lambda) = \frac{(\sigma - \sigma_0)^2}{[\sigma^*(\lambda + 1)]^2 T^*}. \qquad (1)$$

Here σ is the operating local stress, parameter $a = a(\sigma, \lambda)$ depends on the stress and Lode parameter λ, determining the type of the stress state [1], T^* is the model parameter having the dimension of time, it represents a compression

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of the calculation time with respect to the real time and is selected beforehand for the stress waves, generated by the local variations in the stress-strain state (SSS) within comparatively small changes in the loading conditions, to propagate through the specimen 1–2 times, ensuring an information exchange among all deformed structural elements. Upon the existence of this information exchange only the processes of self-organization and SOC states are possible in the medium, which provides a consistent cooperative response of the medium to loading and a transition of the evolution process into a superfast catastrophic regime. Parameter $\alpha = 2$, or close to 2, which results in a hyperbolic law of damage accumulation with increasing time [2]. Power laws of this type are fundamental properties of evolution of a large number of dynamical systems [3].

Expression (1) can be reasonably expressed in terms of the measure of damage $d = N/N^*$, where N^* is a certain critical value of the number of disturbances for $D = 1$. The damage varies within the range $0 \le D \le 1$, at $D \to 1$ the medium fails. Following (1), we obtain the measure of damage given by

$$D = \int_0^{t^*} \frac{(\sigma - \sigma_0)^2 D^\alpha \mathrm{d}t}{[\sigma^*(\lambda+1)]^2 (N^*)^{1-\alpha} T^*}. \quad (2)$$

This straightforward model contains only two phenomenological parameters having a simple meaning: σ_0 is the stress threshold, having overcome which the damage begins to accumulate, at $\sigma < \sigma_0$ $D = 0$, and $C = (\sigma^*)^2 (N^*)^{1-\alpha}$ is the phenomenological parameter selected from the experiments. It determines the rate of damage accumulation in the medium. The upper limit of the integral t^* determines the local life span of the medium as a function of the level of operating local stresses. Multiplier $(\lambda + 1)$ regulates the damage accumulation rate as a function of the type of the stress state $(-1 \le \lambda \le 1)$. In the regions of shear λ approximates zero, in the regions of shears-compressions $0 < \lambda \le 1$, while in the region of shears-tensions $-1 < \lambda < 0$. Thus, the rate of damage accumulation in the areas with prevailing tensile shears is considerably higher than that in the regions with prevailing compressive shears (in tensile regions $\lambda \to -1$, and multiplier $(\lambda + 1) \to 0$) [4].

EXPERIMENTAL RESULTS AND NUMERICAL SIMULATION DATA

The experiment on loading small-sized (marble and artificial marble) specimens was performed in a DVT GP D NN tensile compression testing machine (Devotrans, Inc.). The specimens measuring 15×15×15 mm were subjected to uniaxial compression at a constant load up to their macroscopic fracture. This allowed determining the specimen life span as a function of applied load with a concurrent registration of the surface velocities, including those during the superfast catastrophic stage. To do so, we used a laser Doppler vibrometer (Polytec, Inc.) (OFV-505 laser sensor head and OFV-5000 controller with VD-09 decoder). The method of laser Doppler vibrometry allows measuring the velocity within the laser beam spot parallel to the direction of lasing. The laser in the experiment was adjusted perpendicular to the lateral surface of the specimen, so the experimentally obtained velocity values corresponded to the normal component of the lateral surface velocity. The time resolution during the experiments was 20.83 μs (at the recording frequency 48 kHz), the precision of measurements allows for registering as small velocity as 0.1 μm/s and the laser spot diameter in the gage site was about 50 μm.

Shown in Fig. 1 is a typical time dependence of the free surface velocity during the transition from a quasi-stationary stage of damage accumulation to a catastrophic macroscopic fracture. The last stage before fracture is worth noting. It is evident that the lateral surface displacement velocity in the stage of catastrophic fracture rapidly increases by three orders of magnitude. Actually, only the last 100 ms of the deformation the velocities exceed the noise by a factor of 2–3 and could be taken into consideration (Fig. 1a). This stage corresponds to the SOC state and SSS evolution in the blow-up regime. The last 20 ms before failure at the point of time 98.0198 s (Fig. 1b) could be conventionally treated as the development of fracture as a macrocatastrophe. During the entire quasi-stationary stage (from 0 to 97.9 s), the noise from the external impact is comparable in amplitude with the useful signal, that is why this stage was not included into analysis (Figs. 1c and 1d).

The time dependence of the normal velocity in the point of the surface parallel to the compressive axis, which was obtained in the specimen compression experiments, is shown in Fig. 2a in comparison with the theoretical curve for the measure of damage D calculated according to (2). There is a virtually ideal coincidence of the theoretical and experimental curves for the value of $\alpha = 1.875$, somewhat lower than 2, which is characteristic for such power dependences determining the evolution of dynamical systems. The model parameter C was found from the condition of the fit of the calculated damage curve with the experimental dependence for the surface velocity, which was normalized with respect to unity at the moment of fracture. Life span t^* was determined from the experiment.

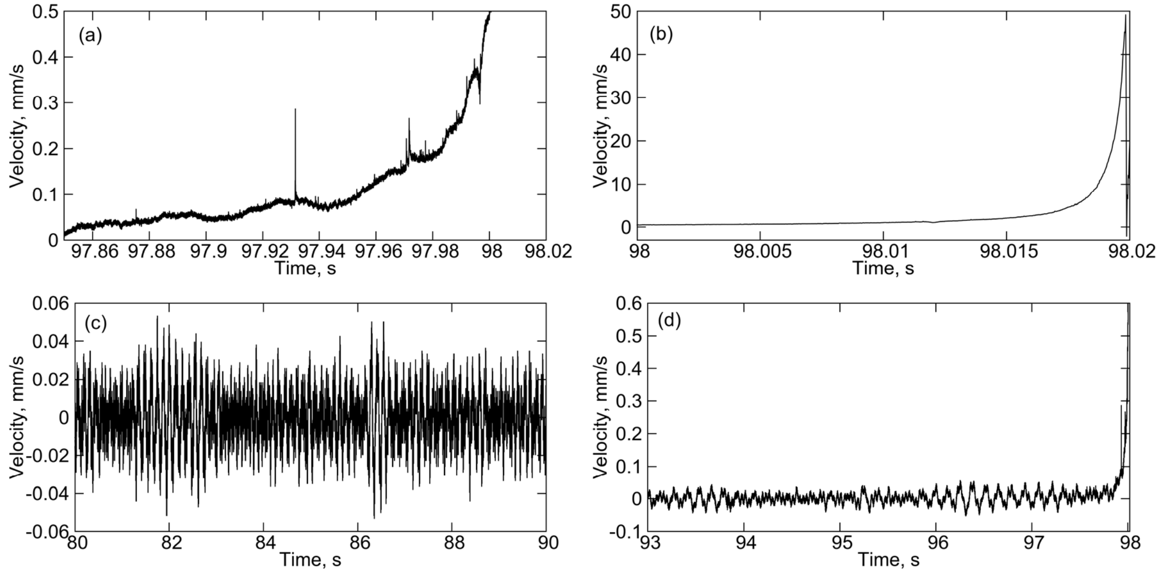

FIGURE 1. Temporal dependence of the free surface velocity of the specimen under compression in different deformation stages

The transition of the failure into the catastrophic regime could be more reliably determined in half-logarithmic coordinates (Fig. 2b).

The investigation of G. Kocharyan and co-workers [5, 6] on the experimental study of the regimes of inter-block slip along a specially prepared layer of granulated material filler also included the study of a slip mode referred to as a dynamic slip phenomenon. The duration of dynamic slips, characterized by a catastrophic drop of the shear force, was varied within the range from 40 to 80 ms, which is quite close to the durations measured in the present work.

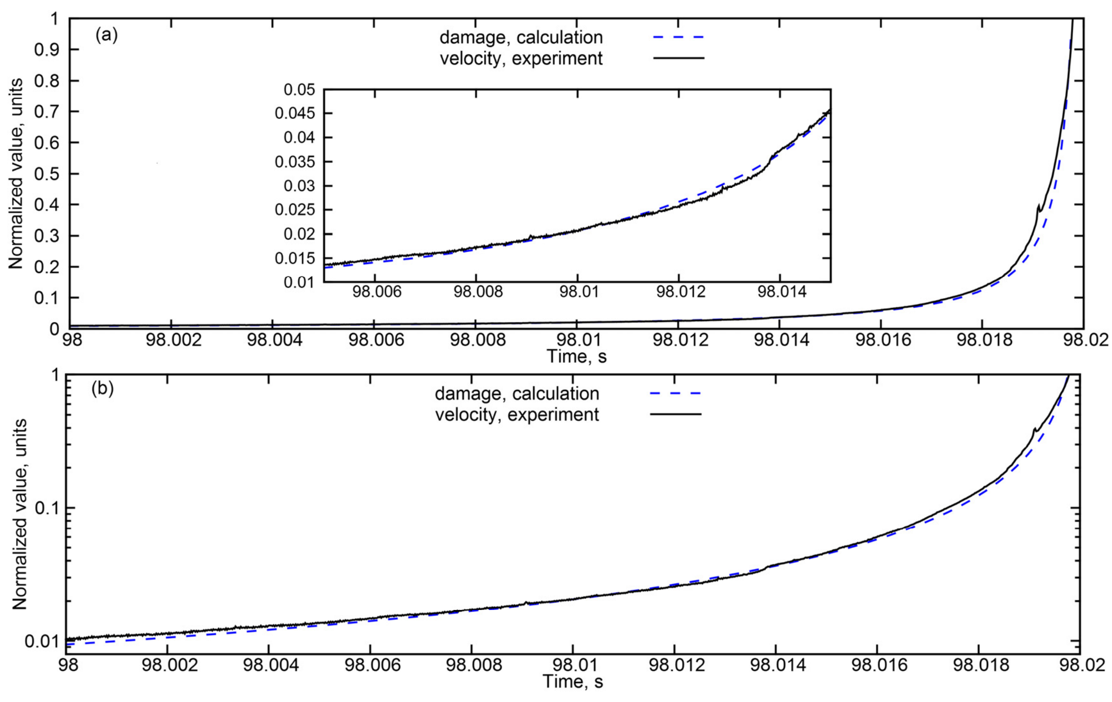

FIGURE 2. Catastrophic stage of SSS evolution in terms of the lateral surface velocity (experiment) and damage (calculation) (a), transition of the failure into a blow-up regime in log scale (b)

If we take the catastrophic stage duration in this work to be 20 ms, then large values of the time of catastrophic stage of softening of the block interlayer in the Kocharyan's experiments would have been determined by a higher interlayer viscosity and the constrained conditions of its deformation due to the heavyweight block and the load applied to it normally, while the lateral surfaces of small-sized brittle specimens in our present experiments were left free. As was demonstrated earlier [4], the constraints of deformation would increase the blow-up duration by several times or even orders of magnitude, sharply changing the fracture pattern in time.

It could be seen from a comparison of the theoretical curves and the experimental data that a simple model of damage accumulation relying on the description of fracture from the standpoints of the theory of evolution of NDS provides a very good agreement with the experimental data.

CONCLUDING REMARKS

In the experiments on investigation of life span of small-sized specimens of marble and artificial marble as a function of applied loading, two stages of damage accumulation and specimen fracture have been identified—a lengthy quasi-stationary phase and a superfast catastrophic stage occupying no more than a thousandth fraction of the total life span, t^*. The catastrophic stage, as a blow-up fracture mode, has been conventionally defined as a deviation from the slow, practically linear, microdamage accumulation in the quasi-stationary stage. Its duration has been estimated to lie within 100–70 ms. The duration of a sharp increase in the surface velocity, where its amplitude exceeds that in the quasi-stationary stage, has been found to be 10–20 ms. The velocity amplitudes for the lateral surface in the quasi-stationary stage were as low as noise, which is due to the instrument sensitivity. To determine the time of fracture transition into a blow-up stage is the primary objective in the study of the mechanisms of fracture focus formation and evolution of SSS in the course of deformation. Reaching this objective would help predicting the onset of a catastrophic fracture stage. We believe the pattern of flicker-noise, caused by multiple microscopic fracture events, to be a sufficiently reliable characteristic capable of differentiating the stages of SSS evolution. The variations in the statistical flicker-noise parameters could be treated as precursors of the fracture transition into a catastrophic phase [7].

It has been shown that a simple model of damage accumulation, relying on the concept of a power-law dependence of accumulated faults on their number, can provide a very good description of both the averaged trend of variations in the specimen and the catastrophic fracture stage. For short times where the loaded specimens maintain their durability as a function of load, the model calculations of fracture demonstrate an excellent agreement with the experiments. Thus, a study of the deformation process and fracture of a high-strength medium as a typical NDS evolving in the field of operating stresses is quite promising in terms of developing new methods for prediction of catastrophic fracture. The damage accumulation model described with the parameters identified by experiments similar to outlined here could also be useful for other numerical methods and computational approaches to mimic the features of failure of rocks and engineering materials [8, 9].

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