CRITICAL SENSITIVITY IN ROCK EXPERIMENTS

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Summary This paper represents an experimental study on catastrophic rupture of a heterogeneous rock. Although rupture shows sample-specific behaviour, a universal sensitivity appears prior to catastrophic rupture. This critical sensitivity provides a valuable precursor for rupture prediction. Furthermore, we extend our previous theoretical model to explore the fluctuations in critical sensitivity in the rock tests.

Introduction

Rupture in heterogeneous brittle media, such as rock, displays catastrophe and sample-specificity [1-4]. Hence, the prediction of rupture is still questionable due to its complexity. Previous analytical works and numerical simulations suggested that critical sensitivity might be a possible common feature prior to catastrophe in these media [2,4,5].

To give the concept of critical sensitivity an experimental validation, a series of experiments has been conducted. 167 gabbro samples were compressed uniaxially and the damage process was observed with acoustic emission. The experimental results show that the response of the samples becomes significantly sensitive to minor variation of controlling variables as approaching the catastrophe. It is found that the results do support the concept of critical sensitivity reasonably.

In addition, we found that the sensitivity observed in experiments displays fluctuations, while the sensitivity obtained from a previous theoretical model [6,7] is monotonic and smooth curve. In order to reveal the mechanism governing the fluctuations in sensitivity, we extend the theoretical model. It is found that the discreteness of the distribution function of the mesoscopic unit's threshold might be a reason for the fluctuations shown in the critical sensitivity.

Experiments

In our tests, rectangular gabbro samples, $5\times5\times13\text{mm}^3$, were loaded uniaxially with a MTS810 testing machine. The loading mode is boundary-displacement control with velocity of 0.02mm/min. The displacement was measured by an extensometer with resolution of $3\mu\text{m}$ and an offset of load 1kN. Acoustic emission technique is an effective method to detect the statistical information of the microcracks in rock in real time [7,8]. In our experiment, two acoustic emission sensors were fixed on two sides of a sample with a specially designed clamp. The AE signals were recorded and processed by an AE21-C system produced by Institute of Computer Technology of Shenyang. The resonant frequency of the sensors is 140kHz and 250kHz, respectively.

Critical sensitivity in rock tests

Figure 1 shows the stress-strain curves for the gabbro samples. The catastrophe appears at the end of each curve. Clearly, it is hard to forecast when catastrophe will occur beforehand. In particular, the strength and the failure threshold show large diversity. This macroscopic uncertainty results in even great difficulty in rupture prediction. Now, we focus on whether critical sensitivity is a common precursor prior to eventual rupture or not. The critical sensitivity means that the response of a system to controlling variable may become significantly sensitive prior to catastrophe. The controlling variable in the present experiments is the boundary displacement denoted by U_b. Here we introduce a dimensionless controlling variable U,

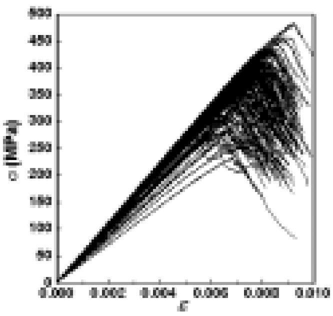


Fig.1 Stress-strain curves of tested gabbro samples

$$U = U_\text{b}/U_\text{c}\,, \tag{1}$$

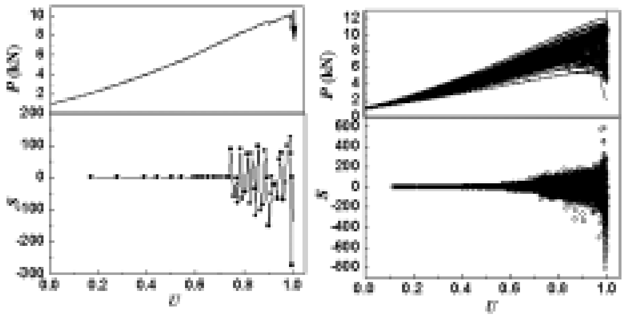
where U_c is the boundary displacement at the catastrophic point of each sample. On the other hand, we adopt the energy release rate R resulting from mesoscopic damage as the response of the system. The definition of R is

$$R = \Delta\Theta/\Delta t\,, \tag{2}$$

where $\Delta\Theta$ is the released energy received by acoustic emission sensors during the time interval Δt. Then, the sensitivity can be defined as

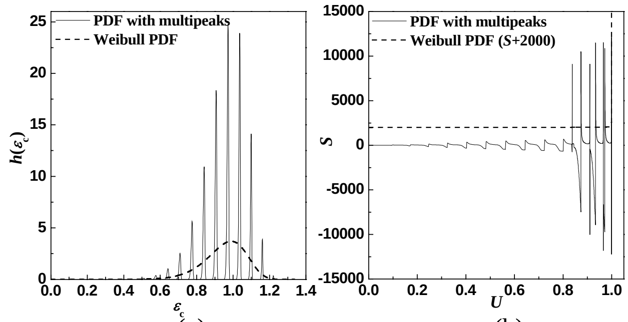
$$S = \frac{U}{R}\frac{\Delta R}{\Delta U}\,. \tag{3}$$

where ΔR is the increment of energy release rate corresponding to the increment of dimensionless boundary displacement ΔU. Figure 2(a) shows the sensitivity S calculated from the data of acoustic emission for a sample in the experiments. At the initial stage, S keeps in low level, which means that the system is in the state with low sensitivity. However, S increases significantly near the catastrophic transition point $U = 1$. This implies that the system becomes highly sensitive prior to catastrophe point. Figure 2(b) shows the sensitivity S for 131 samples. Noticeably, the series of S are different from sample to sample, but, more importantly, there is a common trend in S for all samples, namely S increases significantly near the catastrophe transition point. This is an experimental evidence of critical sensitivity prior to rupture in heterogeneous rock.



(a) (b)

Fig.2 Sensitivity observed in experiments
The arrows indicate the catastrophic rupture point.
(a) for a single sample, (b) for 131 samples



(a) (b)

Fig.3 (a) Threshold distribution function of mesoscopic units
(b) Sensitivity observed in theoretical models

Mechanism of the fluctuations of sensitivity in the experiments

However, the sensitivity shows fluctuations, and in particular, may become negative (Fig2), why? A theoretical model is proposed to explain the phenomenon. The rock sample and the MTS tester, be simplified as an elastic part, are in series and driven by boundary displacement U_b quasi-statically. The rock sample can be thought to be a driven, nonlinear threshold system [5,6], where the mesoscopic strain threshold ε_c follows a distribution function (PDF) $h(\varepsilon_c)$. Then, analytical expressions of the response of the system can be derived according to the mean field approximation.

In the case that $h(\varepsilon_c)$ is Weibull distribution function [9], the sensitivity is monotonic and smooth curve (Fig3 (b) dashed line). However, the distribution function of real materials may present complicated structure and can't be modeled by a continuous single-peak function. So we assume that it is a function with multi-peaks (Fig3 (a) solid line). If so, the sensitivity displays fluctuations (Fig3 (b) solid line), which is similar to the sensitivity in experiments (Fig2). So, the multi-peak structure of the distribution function might be the reason for the fluctuations shown in the critical sensitivity.

Discussions

Our experiments on gabbro indicate that critical sensitivity is a precursor prior to rupture. This highlights the essence of the rupture in heterogeneous media and can provide a clue to prediction of catastrophic rupture. The comparison between theoretical and experimental results shows that the multi-peak structure of the distribution function of mesoscopic strain threshold might be a reason for the fluctuations shown in the critical sensitivity.

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References

[1] Bai Y.L., Lu C.S., Ke F.J. and Xia M.F.: Evolution Induced Catastrophe. *Phys. Lett. A* 185:196-199, 1994.

[2] Xia M.F, Ke F.J. and Bai Y.L.: Threshold Diversity and Trans-scale Sensitivity in a Nonlinear Evolution Model, *Phys. Lett. A* 236: 60-64, 1997.

[3] Wei Y.J., Xia M.F., Ke F.J., Yin X.C. and Bai Y.L.: Evolution Induced Catastrophe and Its Predictability. *Pure Appl. Geophys* 157:1945-1957, 2000.

[4] M.F. Xia, Y.J. Wei, F.J. Ke and Y.L. Bai: Critical Sensitivity and Trans-scale Fluctuations in Catastrophe Rupture. *Pure Appl. Geophys.*159: 2491-2509, 2002.

[5] Zhang X.H., Xu X.H., Xia M.F. and Y.L. Bai: Critical Sensitivity in Driven Nonlinear Threshold Systems. *Pure Appl. Geophys.* 161, 2004 (accept).

[6] Zhang X.H., Rong F., Jia Z.K., Ke F.J., Xia M.F. and Bai Y.L.: Coupling Effects of Heterogeneity and Stress Fluctuation on Rupture. *Theor. Appl. Fract. Mech.*, 2004 (accept).

[7] Zietlow W.K. and Labuz J.F.: Measurement of the Intrinsic Process Zone in Rock Using Acoustic Emission. *Int. J. Rock Mech. Min. Sci.* 35: 291-299, 1998.

[8] Rudajev V., Vilhelm J. and Lokajíek T.: Laboratory Studies of Acoustic Emission prior to Uniaxial Compressive Rock Failure. *Int. J. Rock Mech. Min. Sci.* 37: 699-704, 2000.

[9] Weibull W.: A Statistical Distribution Function of Wide Applicability. *ASME Trans. J. Appl. Mech.* 18: 293-297, 1951.