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Investigation into size and strain rate effects on the strength of rock-like materials

Chengzhi Qi [a,*], Mingyang Wang [b], Jiping Bai [c], Xiaokun Wei [a], Hongsen Wang [a]

[a] Research Center for Engineering Structures and New Materials, Beijing University of Civil Engineering and Architecture, Beijing, China
[b] Civil Engineering Institute, PLA University of Science and Technology, Nanjing, China
[c] Faculty of Computing, Engineering & Science, University of South Wales, Pontypridd, UK

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ABSTRACT

Based on a relaxation model, the relationship between spatial and temporal properties of deformation and fracture of rock-like materials is established, the essence of which lies in the finiteness of crack propagation speed and the complex internal structural hierarchy. There exists one-to-one correlation between characteristic length scale and characteristic strain rate, i.e., in order to fracture a sample of size L or activate structural elements of size L, definite strain rate $\dot{\varepsilon}_L$ must be applied, below which a sample of size L would not fracture or structural elements of size L would not be activated. From the viewpoint of structural hierarchy, the size effect may be considered as the realization of the structural surface strength of smaller scale structural elements with the decrease of the sample size. The essence of strain rate effect is that because of the finiteness of crack propagation speed, the increase of strain rate activates the deformation and fracture process of smaller scale elements before the complete fracture of the sample. The dynamic strength of material is the realization of size effect on strength at the activated smaller scale level of solid. Based on one-to-one correlation between characteristic scale level and characteristic strain rate, size effect equation is transformed into strain rate effect equation. This investigation examines the size and strain rate effects on strength of rock-like materials, which would give better understanding of dynamic phenomena of deformation and fracture of rock mass, including the Earth's crust.

1. Introduction

Deformation and fracture of materials are characterized with temporal and spatial features. Temporal features not only give the real time history of deformation and fracture of materials, but also the temporal scales of the process related to the internal structure and physical-mechanical properties of materials. Spatial features present the spatial extension of bodies and the internal structure of materials as well. Similar to Einstein's theory of relativity indicating space and time are closely related to each other, the temporal and spatial properties of deformation and fracture of materials have intrinsic relations.

Generally, research on temporal and spatial features of deformation and fracture of materials has been mainly related to the effects of size and strain rate on strength.

As for size effect on strength, there are two schools of thought[1]: (1) statistical, described by the Weibull theory of random local material strength,[2,3] and (2) energetic (deterministic). The latter examines type I size effect,[4–6] occurring in materials that fail at crack initiation from a smooth sample surface, and type II size effect,[4,5,7,8] taking place in materials with a deep notch or deep stress-free crack formed stably before reaching the maximum load. It is necessary to point out that the type I and II size effect do not correspond to the mode I and II cracks in fracture mechanics.

An appropriate equation for the description of the type I size effect for small to large sizes was given by Bazant et al.[6]

$$\sigma_N(D) = f_r^{\infty}\left[\left(\frac{l_s}{D+l_s}\right)^{rn/m} + \frac{rD_b}{D+l_p}\right]^{1/r} \tag{1}$$

where σ_N is the nominal strength; D is the sample size; f_r^{∞} is the nominal strength of very large size sample; D_b is a deterministic characteristic length interpreted as the thickness of the boundary layer of cracking causing stress redistribution within the cross section; l_p is the material characteristic length representing the size of representative volume element of rock-like material, which is about 2 to 3 aggregate sizes in rock-like materials, and about the same as the minimum possible spacing of parallel cohesive cracks, or as the effective width of the fracture process zone across the direction of propagation; l_s is the second statistic characteristic length, which considers the appropriate asymptotic behavior as $D \to 0$; r is a positive constant; n is dimensions scaling the fracture

* Corresponding author.
E-mail address: qichengzhi@bucea.edu.cn (C. Qi).

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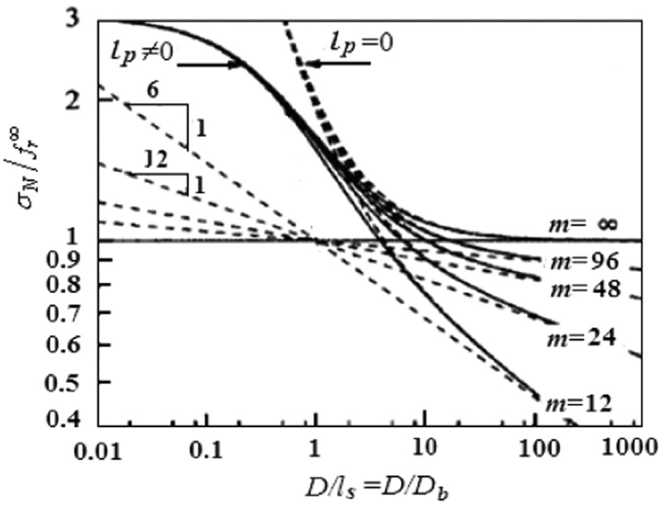

Fig. 1. Size effect of concrete[6].

($n=1$, 2 or 3); m is positive constants called the scaling parameter and Weibull modulus. The general law of size effect of concrete is shown in Fig. 1'[6].

The unique feature of Eq. (1) is the introduction of the reference length scale parameters l_p, l_s and D_b to reflect appropriate asymptotic behavior at small and large sample sizes.

When $n/m << 1$, Eq. (1) satisfies three requirements: (1) for small sizes, it asymptotically becomes the following equation

$$\sigma_N(D) = f_r^\infty \left[1 + \frac{rD_b}{D + l_p} \right]^{1/r} \tag{2}$$

and (2) for larger sizes, $D >> l_s$ (and for $l_s \geq l_p$), Eq. (1) asymptotically represents the Weibull size effect:

$$\sigma_N(D) = f_r^\infty (l_s/D)^{n/m} \to D^{-n/m} \tag{3}$$

and (3) For $m \to \infty$, Eq. (1) asymptotically approaches the deterministic energetic formula

$$\sigma_N(D) = f_r^\infty \left[1 + \frac{rD_b}{D} \right]^{1/r} \tag{4}$$

One of the unique temporal features of deformation and fracture of materials, including rock-like materials, is the strain rate sensitivity to material strength. Some experimental data of strain rate dependence on strength are shown in Fig. 2.'[9] The general law of strain rate sensitivity to rock strength is shown in Fig. 3.'[10] In the lower strain rate range identified as Regime I in Fig. 3, the material strength increases slowly with the increase of strain rate. In the intermediate strain rate range in Regime II, the strain rate sensitivity is characterized by a rapid strength increase when the strain rate exceeds a threshold level. At very high strain rate in Regime III, the strength dependence becomes weak again, similar to the dependence in Regime I. This phenomenon has been intensively examined by many scientists.[11–24] The distinctive feature of any dynamic loading process in comparison with a static one is the appearance of inertial effect in dynamic loading process which induces overloading (strength enhancement) in solid material. But the final level of overloading is eventually determined by the proceeding in solid material kinetic fracture process (stress relaxation process), i.e., by the time from the beginning of loading to the moment of failure which can be characterized by viscosity. On the basis of the results obtained by the above-mentioned scientists, Qi et al.[25] proposed a model which has stimulated debate between the coexisting thermally activated and macro-viscous mechanisms. The dependence of viscosity on strain rate is

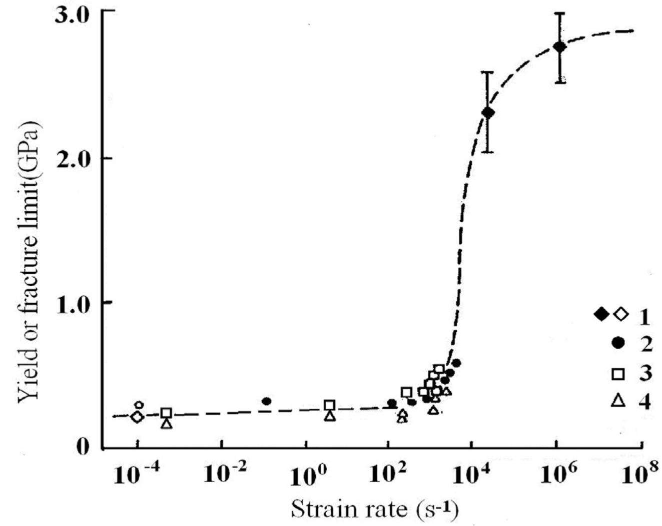

Fig. 2. Strain rate dependence on strength of dolomite (1), Limestone (2), granite (3), basalt (4)[9].

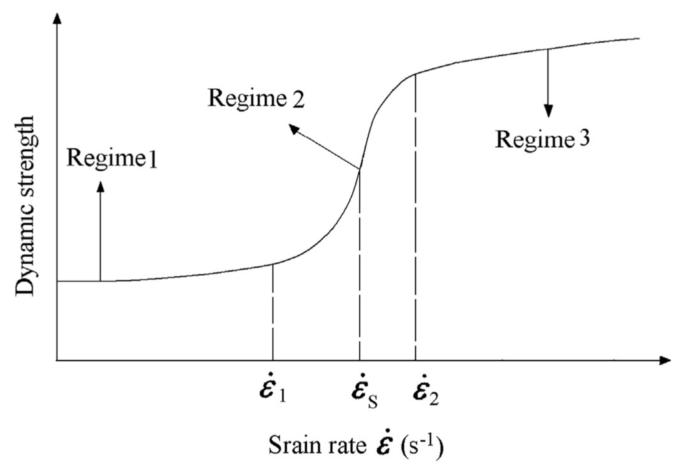

Fig. 3. Dynamical strength vs. strain rates of brittle materials ($\dot{\varepsilon}_1 \approx 10^0$–$10^2$ s^{-1}, $\dot{\varepsilon}_s \approx 10^3$ sec^{-1}, $\dot{\varepsilon}_2 \approx 10^4$ s^{-1}).[10]

obtained by investigating viscosity at different internal structural scales of rock mass. According to this model the dependence of dynamic strength σ_Y of rock-like materials on strain rate $\dot{\varepsilon}$ may be given by

$$\sigma_Y = \frac{1}{\gamma}\left(U_0 + kT \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) + \frac{b(\dot{\varepsilon}/\dot{\varepsilon}_s)^{n_1}}{(\dot{\varepsilon}/\dot{\varepsilon}_s)^{n_1} + 1} \tag{5}$$

where U_0 is the activation energy; γ is the activation volume; k is the Boltzmann's constant; T is the absolute temperature; $\dot{\varepsilon}_0 = \varepsilon_0/\tau_0$ represents the maximum possible strain rate in the material with ε_0 being the limit of deformation at failure, τ_0 being a temporal parameter in the order of Debye's vibration period of atoms (about 10^{-12} s); b is the maximum possible magnitude of the contribution from macro-viscous mechanism; $\dot{\varepsilon}_s$ is an approximation parameter, controlling the inflexion point of the curve; n_1 is model parameter for the shape of the curve.

Is there any relationship between size and strain rate effects? Under dynamic loading condition, a study carried out by Kipp et al.[15] showed that, with the increase of strain rate the size of activated blocks decreases (see Fig. 4). It can be seen from Fig. 4 that all the curves at different strain rates collapse into the static size effect curve at small sample size, indicating that the apparent dynamic strength of solid is simply the demonstration of the