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Rate dependent critical strain energy density factor of Huanglong limestone

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ABSTRACT

Critical strain energy density of rock can be defined as a fundamental parameter in rock fracture mechanics, an intrinsic material property related to resistance to crack initiation and propagation. By means of the three-point bending experiments, the critical strain energy density factor of Huanglong limestone was measured over a wide range of loading rates from 8.97×10^{-4} MPam$^{1/2}$ s^{-1} to 1.545 MPam$^{1/2}$ s^{-1}. According to the approximate relationship between static and dynamic critical strain energy density factor of Huanglong limestone, relationship between the growth velocity of crack and magnitude of load is obtained. The main conclusions are summarized as follows: (1) when the loading rate is higher than 0.0279 MPam$^{1/2}$ s^{-1}, the critical strain energy density factor of rock increased markedly with increasing loading rate. However, when loading rate is lower than 0.0279 MPam$^{1/2}$ s^{-1}, the critical strain energy density factor slightly increased with an increase in loading rate. It is found from experimental results that the critical strain energy density factor is linear proportional to the exponential expression of loading rate, (2) for Huanglong limestone, when the growth velocity of crack is lower than 100 m/s, value of the maximum load was nearly a constant. However, when the growth velocity of crack is higher than 1000 m/s, value of the maximum load dramatically increases with increasing the crack growth velocity, and (3) the critical SED of Huanglong limestone is higher as the loading rate is higher.

1. Introduction

SED and energy release rate G and stress intensity factor K and path-independent integral J can defined as a parameter in characterization of mechanical behavior of rock materials. However, energy release rate G and stress intensity factor K are applied essentially to linear elastic systems while path-independent integral J to non-linear but still elastic systems. The fact is that both energy release rate G and path-independent integral J are negative for non-homogeneous systems. Therefore, energy release rate G and path-independent integral J and stress intensity factor K can not be applied to localized physical systems, such as deformation localization of rock.

SED theory proposed in [1–4] has been successfully applied to a variety of engineering problems for different materials and at different scales. For example, SED theory is successfully used to investigate the deformation localization of rock subjected to compressive and tensile loads [5–7]. Therefore, critical strain energy density of rock can be considered to be a fundamental parameter in rock fracture mechanics, an intrinsic material property related to resistance to crack initiation and propagation.

Great efforts had already been made to thoroughly investigate and test the dynamic fracture toughness of rock. Three methods for measuring rock fracture toughness have been suggested by the ISRM so far [8,9], such as three-point chevron bend specimens (CB), short rod specimens (SR), straight-through cracked three-point bend round beam specimens (SB) and cracked chevron notched Brazilian disc specimens (CCNB). However, critical strain energy density factor of rock is not investigated by laboratory tests.

In the paper, by means of the three-point bending experiments, the critical strain energy density factor of Huanglong limestone was measured over a wide range of loading rates from 8.97×10^{-4} MPam$^{1/2}$ s^{-1} to 1.545 MPam$^{1/2}$ s^{-1}. It is found from experimental results that the relationship between critical strain energy density factor and loading rate is defined. According to the approximate relationship between static and dynamic critical strain energy density factor of Huanglong limestone, relationship between load and the crack growth length at different growth velocity of crack are analyzed.

2. Experimental method

The Huanglong limestone test specimen is from Lead–Zinc mine in Nanjing. The values of mechanical parameters of Huanglong limestone are summarized as follows: Young's modulus E = 26.911 GPa, Poisson's ratio ν = 0.151, weight density ρ = 2730 Kg/m^3. The specimens in this study, a cylinder ϕ = 50 mm × 200 mm, were machined strictly according to the requirement of the ISRM suggested methods [8]. Moreover, using metal milling cutter, a

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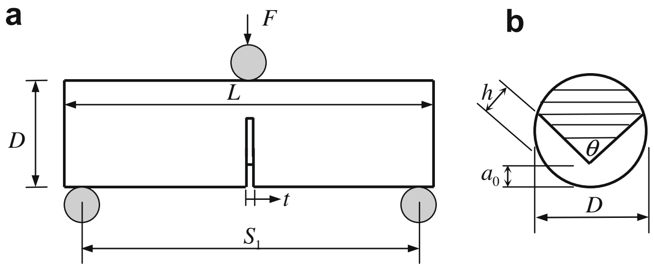

Fig. 1. Sketch of three-point chevron bend specimens (CB). (a) Edge crack beam, and (b) cross section.

chevron notch is prefabricated at the center of round bar. As depicted in Fig. 1, the specimen dimensions are detailed as follows: $D = 50$ mm, $L = 200$ mm, $S = 166.6$ mm, $\theta = 90°$, $a_0 = 7.5$ mm, $t = 2$ mm, $h = 12.6$ mm.

All the tests are performed on an INSTRON1342 servo-control machine in Chongqing University. Load was applied at six different loading rates, which is controlled by load point displacement (LPD) δ_F. The loading rates are 0.1 mm/s, 0.04 mm/s, 0.01 mm/s, 0.004 mm/s, 0.0004 mm/s and 0.0001 mm/s, respectively. A total of 30 specimens were tested in this survey. The tests were conducted in six groups, there were five sets of tests in the each group. During the process of loading, crack opening displacement (COD) is recorded by clip gauge at the same time, as shown in Fig. 2.

3. Results and interpretation

3.1. Effect of loading rate on the critical strain energy density factor

Fig. 3 illuminates the relationship between load and crack opening displacement. Initially, specimens follows a period of linear ascending, the load reaches its maximum, which corresponds to the initiation of the crack. Then the load must go down, since the dimensionless strain energy density factor is rising, the crack propagates unstably at this stage. The load soon reaches the local minimum value P_{min}, which corresponds to the critical crack opening displacement. Moreover, it can be observed from Fig. 3 that the maximum load is higher as loading rate is higher.

Maximum load, critical time at the peak, crack opening displacement and load point displacement are shown in Table 1. From Table 1, three main conclusions are summarized as follows: (1) when the loading rate is higher than 0.004 mm/s, the maximum load increases markedly with increasing the loading rate. However, when the loading rate is lower than 0.004 mm/s, the maximum load slightly increases with increasing the loading rate, and (2) crack opening displacement and load point displacement at the peak slightly varied with loading rate, which seem to be dispersive at different loading rate.

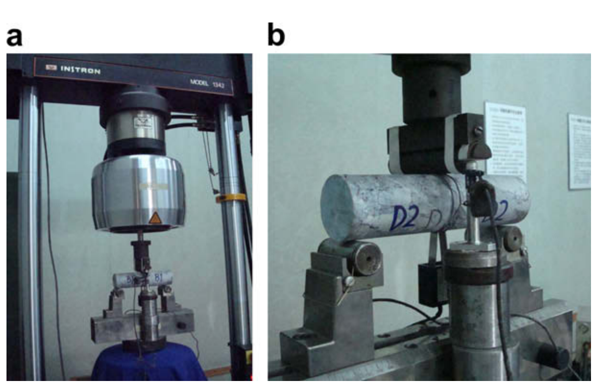

Fig. 2. Photograph of three-point bending test. (a) Beam specimen, and (b) near view.

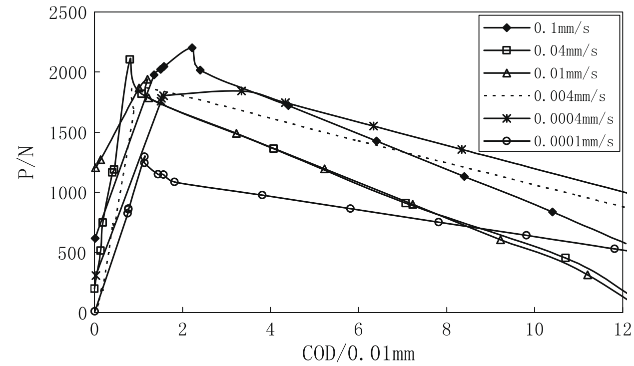

Fig. 3. A test record of load-displacement for three-point chevron bend specimens of Huanglong limestone.

Table 1
Experimental results of maximum load and crack opening displacement and load point displacement.

Loading rate v_1 (mm/s)	Load point displacement at the peak δ_F (mm)	Crack opening displacement at the peak (0.01 mm)	Critical time at the peak t_m(s)	Maximum load P(N)
0.1	0.131	2.22	1.3278	2201.244
0.04	0.123	0.80	3	2103.850
0.01	0.051	1.21	5.1608	1940.191
0.004	0.251	0.98	63	1883.000
0.0004	0.156	3.34	390.9608	1842.096
0.0001	0.134	1.14	1347	1296.461

According to works in [1–3], for the isotropic and homogeneous material, the relationship between the strain energy density factor S and the mode I stress intensity factor K_I can be written as

$$S = a_{11}K_I^2 \tag{1}$$

where $a_{11} = \frac{1}{16\pi G}[(3 - 4v_0 - \cos\theta)(1 + \cos\theta)]$, K_I is the mode I stress intensity factor.

For the isotropic and homogeneous material, the relationship between the critical strain energy density factor and the mode I critical stress intensity factor can be written as

$$S_c = \frac{(1 + v)(1 - 2v)}{2\pi E}K_{IC}^2 \tag{2}$$

where S_c is the critical strain energy density factor, K_{IC} is fracture toughness.

Eq. (2) can not be applied to the anisotropic and non-homogeneous materials. Energy release rate G and path-independent integral J and stress intensity factor K are not suitable for the anisotropic and non-homogeneous materials. For the anisotropic and non-homogeneous material such as rock, the critical strain energy density factor can be derived from three-point chevron bend test and the area under the uniaxial stress–true strain curve of anisotropic and non-homogeneous rock material. Therefore, one can replace $\frac{(1+v)(1-2v)}{2\pi E}$ by $f(E, v)$ at a given strain rate. Then, critical strain energy density (SED) factor of three-point chevron bend specimen can be determined as follows

$$S_c = f(E, v)\left(\frac{A_{min}P_{max}}{D^{1.5}}\right)^2. \tag{3}$$

The SED theory predicts failure by fracture and/or yielding, it is based on the following hypotheses [1–3]:

(1) The location of fracture initiation is assumed to coincide with the maximum of minimum of (dW/dV) or $(dW/dV)_{min}^{max}$.