International Journal of Rock Mechanics & Mining Sciences 66 (2014) 160–168

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Conversion of strain energy in Triaxial Unloading Tests on Marble

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ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form
23 October 2013
Accepted 17 December 2013
Available online 1 February 2014

Keywords:
Strain energy
High geostess
Energy conversion
Triaxial unloading test

ABSTRACT

Axisymmetric triaxial compression loading–unloading tests are conducted on twenty-seven marble specimens with initial confining pressures of 20, 30 and 40 MPa and unloading rates of 0.1, 1.0 and 10 MPa/s. It is found that magnitude of initial confining pressure and unloading rate significantly influence rock failure modes and strain energy conversion (accumulation, dissipation and release) during unloading. The failure mode of rock specimen is gradually changed from shear to tensile with increasing unloading rate. The pre-peak conversion rate of strain energy is increased with increasing unloading rate. This increase trend is enhanced by initial confining pressure. The post-peak conversion rate of strain energy has the similar increasing pattern of the pre-peak one, though it is several to ten times greater. Much strain energy is released after peak strength from the tested specimen and it may account for the occurrence of flying fragments. The higher the unloading rate and/or the initial confining pressure, the more severe the “flying fragment” phenomenon. The characteristics of strain energy accumulation, dissipation and release are investigated in three stages, i.e., elastic compression, pre-peak unloading, and post-peak fracturing. The rule of strain energy conversion for each stage is derived, and triaxial unloading tests and conventional triaxial compression are compared in terms of strain energy and its conversion.

1. Introduction

Rocks under high geostress are commonly encountered during engineering practice, especially in mountainous areas in southwest China [1,2]. Excavations in such rocks are at great risk as unloading would lead to severe rock failure, such as rock burst in deeply buried tunnels, like Jinping Hydropower Station in China [3]. The mechanical behavior of hard rock during unloading under high geostress has been widely investigated by means of laboratory experiment and numerical modeling. He et al. [4] carried out true-triaxial unloading tests to investigate rock burst process of limestone and its acoustic emission characteristics, and indicated that the accumulated energy is rapidly released after peak strength to a complete failure. Conventional triaxial unloading tests were also widely conducted to reveal the characteristics of stress–strain relation, deformation, damage, modulus and strength under unloading conditions [5,6]. These investigations indicated that rock behavior under unloading is different from that under loading. Brittle failure, for example is more pronounced in unloading tests than in loading ones. The laws of thermodynamics indicate that energy conversion is the basic rule of physical processes of materials, and that the damage or failure of materials is accompanied by energy conversion, including accumulation, dissipation and release of energy [7]. Zhang et al. analyzed the energy partitioning in the dynamic fracture process of a short rod rock specimen with the aid of the Split Hopkinson Pressure Bar testing system and a high-speed framing camera [8]. They concluded that the total energy absorbed by a specimen in the dynamic fracture process mainly consists of fracture and damage energy and the kinetic energy of flying fragments. Tsoutrelis and Exadaktylos [9] defined the ratio of the surface energy to the volume elastic strain energy and studied its correlations with rock strength in order to predict the in-situ strength and stability of a rock mass. Hua and You [10] carried out experiments on marble, siltstone and coal with decreasing confining pressure and found that rock fracturing in axial compression absorbs energy, while rock fracturing due to unloading of confining pressure releases energy. They concluded that strain energy is absorbed and stored during the loading stage in rock and the energy is sufficiently large to cause failure when it is released. The density factor of strain energy was also used for investigating heterogeneous behavior of rock under conventional triaxial compression [11]. Wang et al. [12] carried out a study of rock burst within a deeply buried tunnel by numerical methods and concluded that rapid unloading results in rock burst and rapid release of the strain energy.

The specimens from a marble block are studied in the present study by means of conventional triaxial unloading tests at different

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http://dx.doi.org/10.1016/j.ijrmms.2013.12.001

unloading rates and initial confining pressures. The characteristics of strain energy accumulation, dissipation and release are investigated in three stages, i.e., elastic compression, pre-peak unloading, and post-peak fracturing.

2. Test Program

Totally, twenty-seven specimens are prepared from a marble block from the underground powerhouse of Jinping Hydropower Station in China. The tested rock is of grey fine metacrystal calcite marble with strong recrystallization. The crystal grain size is ranging from 0.2 and 0.5 mm. The bulk density of the rock is 2.72 g/cm^3 and the uniaxial compressive strength is 70–80 MPa.

The size of the cylindroid specimen is of 50 mm (diameter) × 100 mm (height). The specimens are put into three groups for being tested under different conditions as listed in Table 1. The experiment is carried out in a MTS815 Flex Test GT apparatus. The axial pressure (σ_1) is applied in a strain-controlled way, for obtaining a full stress pass and avoiding sudden crush of specimen after peak. The unloading rate ν_u and initial confining pressure $\sigma_3{}^0$ are set to be three levels, 10.0, 1.0 and 0.1 MPa/s; and 20, 30 and 40 MPa, respectively. To ensure the failure of rock specimens takes place in the process of unloading, the initial differential stress ($\sigma_1-\sigma_3$) are set as 75 MPa, which is close to the average uniaxial compressive strength of the same rock. Preliminary tests are conducted to determine axial strain rates, which are used later for achieving a stable axial stress (σ_1) during testing (Table 1). Fig. 1 presents a typical path of measured stress with an initial confining pressure $\sigma_3{}^0$ of 30 MPa and unloading rate ν_u of 1 MPa/s. It can be seen that the increase in differential stress ($\sigma_1-\sigma_3$) mainly results from the unloading confining pressure, while the axial stress σ_1 remains almost constant.

The detailed test procedures are as follows:

Step 1: Increase hydrostatic pressure to the level of designed initial confining pressure ($\sigma_3{}^0$). The stress path of this stage is presented by line *OA* in Fig. 1.

Step 2: Increase axial pressure (σ_1) to achieve a differential stress of 75 MPa, while the initial confining pressure ($\sigma_3{}^0$) remains unchanged (Line *AB* in Fig. 1).
Step 3: Reducing confining pressure (σ_3) at the pre-specified rate (Table 1) until the peak strength of the specimen (Line *BC* in Fig. 1).
Step 4: After the peak strength (Point *C*), the confining pressure is unloaded continuously to zero to finish the test, while the rate of axial strain is maintained (Line *CD* in Fig. 1).

Table 1
The tested specimens.

Unloading rate of confining pressure (ν_u, MPa/s)	Axial displacement rate for loading (mm/min)	Initial confining pressure ($\sigma_3{}^0$, MPa)	Specimen number[a,*]
0.1	0.001	20	S20-1, S20-2, S20-3
		30	S30-1, S30-2, S30-3
		40	S30-1, S30-2, S30-3
1	0.1	20	M20-1, M20-2, M20-3
		30	M30-1, M30-2, M30-3
		40	M40-1, M40-2, M40-3
10	1	20	F20-1, F20-2, F20-3
		30	F30-1, F30-2, F30-3
		40	F40-1, F40-2, F40-3

[a] S20-1 stands for the first specimen tested under the confining pressure of 20 MPa, unloading rate of 0.1 MPa/s (slow). M—moderate unloading rate (1 MPa/s), F—fast unloading rate (10 MPa/s).

[*] S20-1 stands for the first specimen tested under the confining pressure of 20MPa, unloading rate of 0.1MPa/s \(slow\). M – moderate unloading rate \(1MPa/s\), F – fast unloading rate \(10MPa/s\).

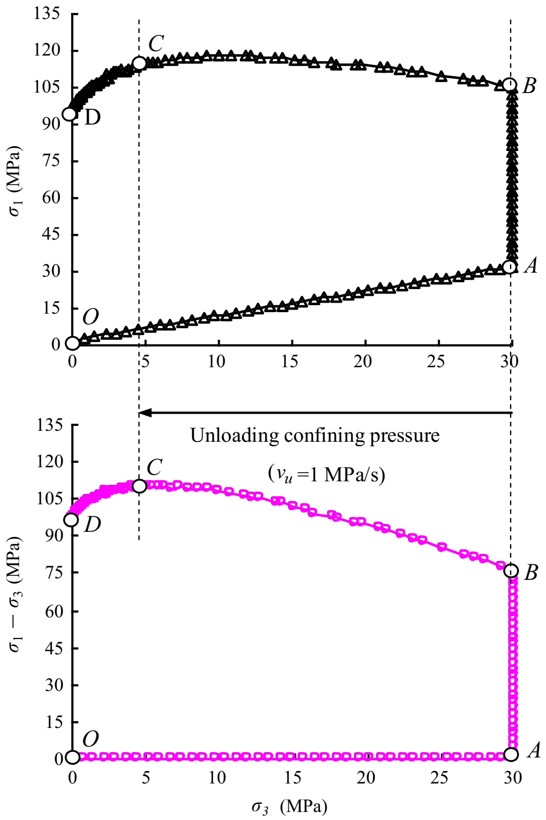

Fig. 1. Typical stress path measured during unloading tests (Specimen M30-1 as example).

3. Conversion of Strain Energy

3.1. Calculation of strain energy

The calculation of strain energy under unloading condition can be done by using the same method for conventional triaxial compression test, for the specimen is always kept at triaxial compression state during the test, though the confining pressure is reduced all the way. Both σ_1 and σ_3 do positive work to the specimen during the process of loading hydrostatic pressure (Line *OA* in Fig. 1). Furthermore, the axial stress σ_1 keeps doing positive work until the maximum differential stress ($\sigma_1-\sigma_3$) is achieved (Line *AB*). During unloading, the confining pressure σ_3 does negative work, due to the radial dilation of the specimen. In other words, the strain energy of the specimen is accumulated due to deformation by axial compression, while some of it is consumed due to radial dilation. Therefore, the total strain energy U can be expressed by:

$$U=U_1+U_3+U_0 \tag{1}$$

where U_1 is the absorbed strain energy due to axial compression by σ_1 after hydrostatic pressure (Point *A* in Fig. 1), U_3 the