Experimental Investigation on Deformation and Failure of Rock under Cyclic Indentation

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Abstract Indentation induced cracking may have widely encountered in rock engineering, such as drilling and cutting process. It is significant to investigate the deformation and failure process for further understanding the failure mechanism of rock under cyclic indentation. In the present work, we have experimentally investigated the deformation fields on the sample surface via digital image correlation (DIC) technique. It has been found that the force-indentation displacement exhibits hysteresis during the loading-unloading cycles. The energy dissipation and the displacement field in the samples during the process has been analyzed. Furthermore, a median crack has been observed to nucleate running almost parallel to the loading axis when indentation force amounts to a critical value. Experimental analysis reveals that local tensile strain dominates the crack nucleation of rock and the shear strain has an effective influence on crack propagation. In unload-reloading process, crack behavior closure and re-opening is clearly observed by DIC technique. By the displacement distribution along the crack surface, crack opening displacement (COD) and stress intensity factor can be calculated for further fracture analysis.

Keywords Rock, Cyclic indentation, Digital image correlation, Deformation and failure

1. Introduction

Rock fragmentation induced by mechanical tools is an effective technique in mining and civil engineering. Rock cutting by various bits, such as drilling bit, rolling cutter, could be simplified as the cyclic indentation process [1]. Knowledge on deformation and failure process of rock is an important basis for the study of rock failure mechanisms. Therefore, it is necessary to experimentally investigate the damage and fragmentation of rock during cyclic indentation.

Many experimental tests have been conducted in the past decades to investigate the fragmentation of rock. Damage pattern which consists of inelastic zone and a region of multiple cracks is observed in rock under indentation [2]. Laboratory tests, simulating the disk cutter action at the tunnel face by means of an indenter, were carried out to explore the influence of the lateral confinement acting on the rock failure [3]. Acoustic emission (AE) and electronic speckle pattern interferometry (ESPI) techniques were used to detect the events of microcrack nucleation [4]. Numerical methods, such as the finite element method (FEM) [5], rock failure process analysis of two dimensions (RFPA2D) [6], have been developed to simulate the fragmentation process in rocks under indentation. Repeated loading–unloading conditions are widely encountered in practical excavation and drilling engineering. However, affects of cyclic loading on indentation-induced failure remains unclear.

In this work, cyclic indentation tests have been conducted to investigate the deformation and damage evolution of Yunnan sandstone. During the loading-unloading process, images of rock specimens have been sequently captured, from which deformation fields can be obtained by digital image correlation (DIC) processing. Displacement and apparent strain fields calculated by DIC, are used to analyze the deformation, crack initiation, propagation during cyclic loading tests.

2. Experimental setup

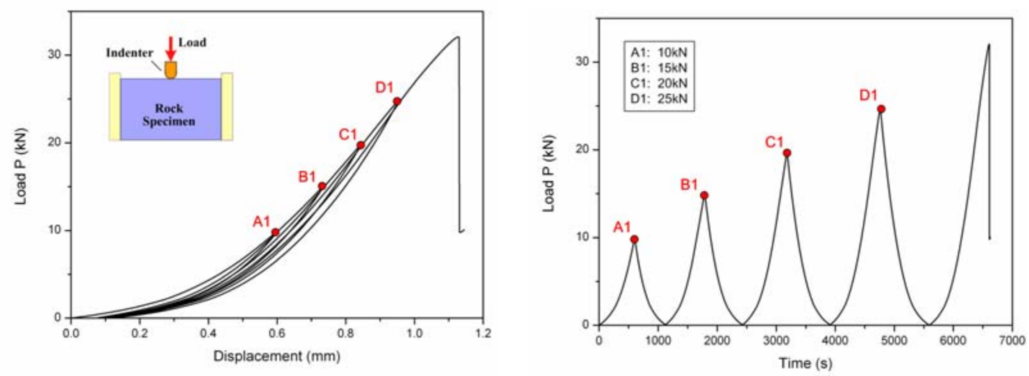
Indentation tests were conducted on Yunnan sandstone plates with a dimension of 150×100×25 mm. Its surface was painted with randomly artificial speckle.Loading system includes electric universal machine (CSS-44100), indenter(diameter Φ=20 mm) and the fixture on which the specimen is mounted. During experiments, the load cell moved down and up with a constant velocity of 0.06 mm/min, the displacements, loads and time from the load cell, were continuously recorded during the experiment.

CCD camera with 1004×1003 pixels, a Matrox meteor Ⅱimage capture, a frame grabber and two white lights are used to capture images of the specimen. The observed area of specimen surface is 57×57mm. Sequential images were captured by a digital image system at a rate of 1 frame/s. Digital image correlation (DIC) is a powerful tool to measure the full field displacement distribution on the surface of specimens [7-9]. Then the displacement field can be used to derive the strain field by smoothing difference with numerical methods [10].Deformation information of specimen surface obtained by DIC, is used to characterize the damage and fracture process of rock.

3. Experiment

Samples of Yunnan sandstone were subjected to increasing-amplitude cyclic indentation experiments to investigate the evolution of deformation and fracture as rock approaches failure. The typical Load-displacement and Load-time curves are shown in Fig.1. The peak load of the first cycle is 10 kN (~30% peak load) and is increased by 5 kN in the subsequent cycles until the sample failed. The loading curves are usually not coincidence with the unloading curves and hence they form hysteresis loops which indicate that residual displacement develops.

The residual deformation exists not only at end of each cycle, but virtually at any load level during loading-unloading stage. It can be verified upon examining the load-displacement curves during different loading cycles but at the same load level. For instance, Fig.2 shows that during cycle 1 and 2 at the same load of 5 kN, the loading and unloading points A01, A11, B01, B11 are not coincident with each other on the load-displacement curves. To look into the displacement field in the indented sample, Fig.3 demonstrates DIC contours corresponding to points A01, A11, B01 and B11 designated in Fig. 2. One may find that the sequence of the severity of the vertical deformation at those points are A01, A11, B01 and B11, which is in good agreement with overall force-indenter displacement curves, but the horizontal displacement field at those points seems not to follow that simple sequence.



(a) (b)

Fig.1 Load-displacement and load-time curves of cyclic indentation tests.

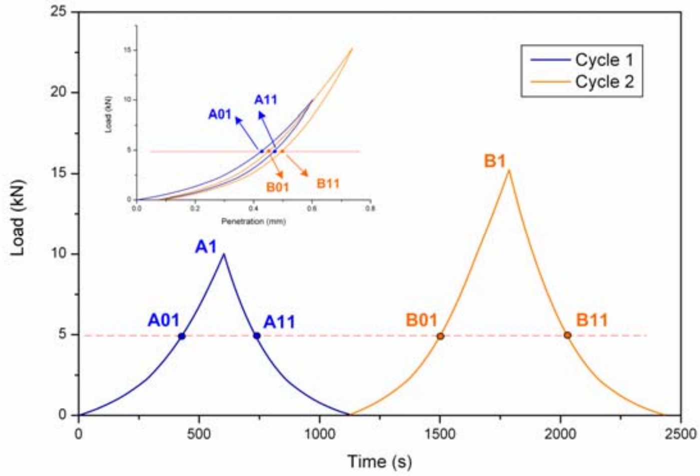


Fig.2 Mechanical response in the first two cycles

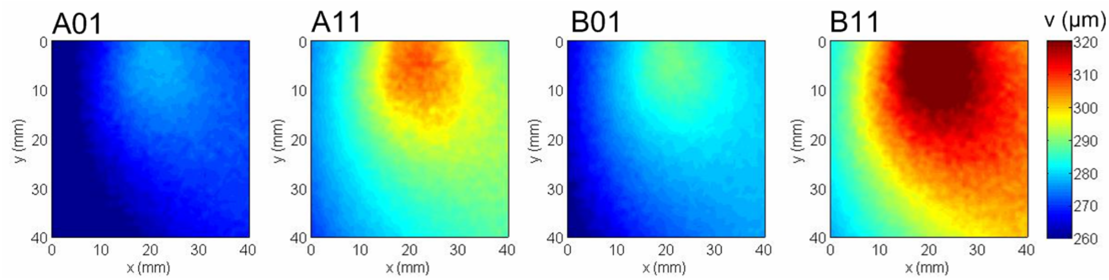


Fig.3 Vertical displacement fields at selected points with the same load P=5 kN.

It is well known that when the indentation force attains at a critical value, crack will nucleate and propagate in the sample that may lead to the final failure. By using the DIC technique, apparent strains at final stage of loading-unloading cycle are presented in Fig.4.Upon reloading to point D01 with load P=20 kN, tensile strain appears beneath the indenter and its maximum magnitude is about 0.6% located in the local region (Fig.5 D01 ε_x). Apparent shear strains were recognized by the contrast of red and blue regions, indicating concentration of shear strains in the central part of the specimen.

At D1 for load P=25 kN, the tensile strain concentrates in a very narrow belt, the value is far larger than those at other load level. Giving the sharp gradient of displacement, it can be concluded that a crack has nucleated there. During the unloading period the peak of apparent strain is lower Fig.5 D2). It indicates that no additional new crack appears but only the existed crack begins to close. The value of ε_x is smallest at point D2 (load=0kN).

With increased subsequent loading, the crack develops both in length and opening. The significant increase was found in D21 (Load=25kN), apparent strains at the crack surfaces were obviously greater than D1. Afterwards, on continuous development of the cracking, the fracture eventually went through the specimen. After the test, it was observed that the crack identified by DIC developed along the path of the final failure.

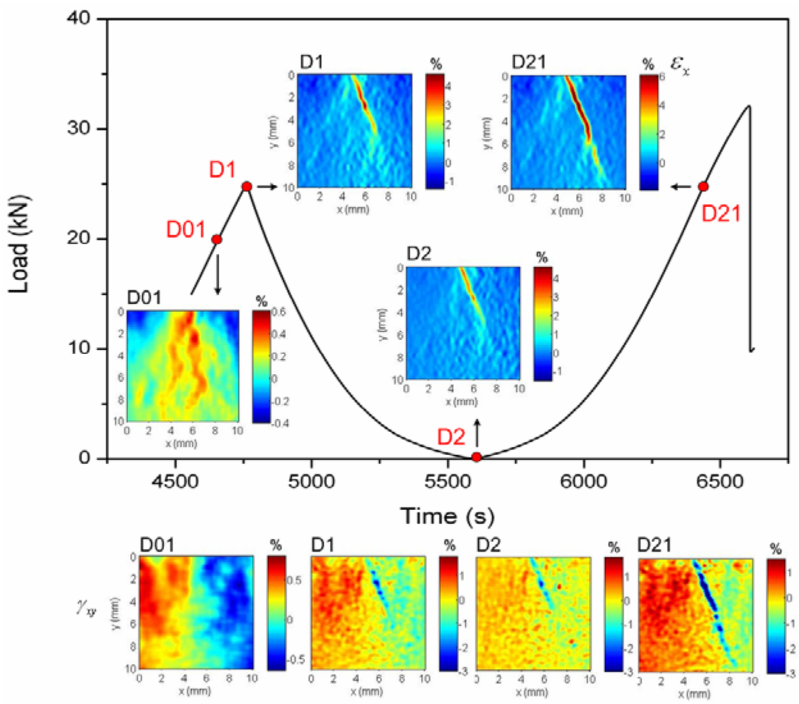


Fig.4 Distribution of the apparent strains ε_x and γ_{xy} during the final unloading and reloading stage

4. Conclusion

Cyclic indentation tests have been conducted in conjunction with the nondestructive technique of DIC to study the deformation and failure of rock samples. It has been found that DIC is an efficient method in tracing the deformation behavior and identifying the onset of the crack in rock.

By analysis of the experimental results, it has been detected that tensile strains concentrate beneath the indenter just before cracking, and a crack nucleates when the indentation load exceeds a critical value. The closure and propagation of the crack during unloading-reloading can be well described by the apparent strain fields.

Acknowledgements

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