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Study on deformation localization of rock by white light digital speckle correlation method

岩石变形破坏局部化的白光数字散斑相关方法研究

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Abstract: The principle of white light digital speckle correlation method (DSCM) is presented in this paper, and deformation localization of rock and coal is discussed by using white light DSCM. The starting point of deformation localization is gauged, and the evolution process of localization is demonstrated, and for the first time, the width of deformation localization is obtained by experiment. By experimental and theoretic analysis, the results of investigation indicate that the white light digital speckle correlation method is very useful in studying the non-homogenous evolution process of rock, and by this method, the microscopic parameter of rock can be gauged.

Key words: rock; deformation localization; white light digital correlation speckle method

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摘 要: 介绍了白光数字散斑法的基本原理,并采用白光数字散斑相关方法研究了煤岩的变形局部化,通过实验测定了煤岩变形局部化的开始时刻、演化过程,首次获得了局部化带的宽度,为研究岩石非均匀变形的演化过程、测定岩石的细观本构参数提供了一种新的手段。

关键词: 岩石; 变形局部化; 白光数字散斑相关方法

1 Introduction*

In recent years, numerous and extensive studies on deformation localization have appeared in the literatures. Scientists have found that a vital characteristic of rock failure is non-homogeneous deformation, and the deformation is apt to concentrate on a certain region when rock material is undergoing compressive and tensile load. In order to investigate the deformation localization of rock, Zhengjie etc.[1] studied the deformation localization of Jinan Huilu rock by optical-elastic stick-bearing method. Berthaud[2,3] studied the deformation localization of brittle rock material by laser speckle method. However, studying the deformation localization need adequate and holographic speckle field, the above-mentioned two methods do not meet this requirement well, therefore, in this paper we adopt a new optical gauge method—white light digital speckle correlation method. A white light source is used in this experiment, thus the optical setup is much simple. Meanwhile, this method is not constrained by environment and then is suitable to the measurement of rock structure in field.

2 Basic principles

With the improvement of science and technique, the metrology is developed and applied very quickly, especially the optical metrology. Optical metrology is one of new measuring technique of deformation localization, and speckle and moiré methods have been widely applied to various research works, due to the advantages of non-contact, full-field, and high precision. However the tedious photographic processing procedure makes it difficult to apply in many aspects. On the other hand, the complex optical arrangement, high requirement of vibration isolation and limited measuring scope are also the reasons of obstruction to its application. A new technique called digital speckle correlation method (DSCM) was developed in 1982 by I. Yanguch, W. H. Peter and W. F. Ranson[4] respectively. The main concept of DSCM is to compare two random speckle patterns that characterize the object to be measured before and after the displacement using the search algorithm for the maximum correlation coefficient criterion, and can be obtained according to the position change of the point. Moreover, the DSCM can get the distribution of displacement and strain by studying the distribution of the digital gray field, and this method needn't conduct complex pre-processing and its light route is very simple. DSCM can use laser or white light as its light source. We adopt white light as light source for DSCM to conduct experiment, and experiments indicate that the white light DSCM can meet the requirement of large deformation field measuring. For grabbing the high quality speckle patterns, we adopt artificial speckle field, which spray glass particle painted on the surface of samples to conduct experiment.

In order to realize the sharp and unimodal properties of the correlation coefficient and to find the accurate position of maximum C which shows how closely the two subsets are related, we adopt a novel equation to calculate the intensity distributions of the two subsets $f(x_i, y_i)$, $g(x_i^*, y_j^*)$, and the correlation equation[5,6] is

$$C = \frac{\sum_{i=1}^{m}\sum_{j=1}^{m}[f(x_i, y_j) - \bar{f}][g(x_i^*, y_j^*) - \bar{g}]}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m}[f(x_i, y_j) - \bar{f}]^2}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m}[g(x_i^*, y_j^*) - \bar{g}]^2}} \quad (1)$$

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where $\bar{f}$ and $\bar{g}$ are the average values, and m is the size of subset in pixel. The point pairs of maximum C imply the same point on the object before and after loading. Except the pixel level search, a sub-pixel level search must be completed to obtain a 0.01 pixel displacement measurement precision. Then displacement of the object can be measured through comparing all the point pairs in these two speckle images.

3 Experimental result and analysis

In order to study the deformation localization in the laboratory, we collect natural rock materials to conduct a series of experiments. Shandong Huafeng sandstone, Three Gorges area granite are used as rock samples and Beijing Da'anshan coal as coal samples. Before experiment, glass microballoon paint, which is suitable for many materials for deformation measurement, was sprayed on a smooth surface of each sample. After three days, these samples may be used to conduct experiment. For the sake of obtaining the complete stress- strain curve of rock material, the high rigidity servo-controlled testing machine is selected to conduct the experiment[7,8].

3.1 Sandstone

The dimension of sandstone sample is 5 cm × 5 cm × 10 cm, and the viewing scope is 49 mm × 49 mm. The complete stress- strain curve of rock is shown in Fig. 1. As the loading increases to 31 percent of rock's peak strength, that's to say the loading step is 4, and we can see that the deformation is homogenous, which is shown in Fig. 2. When the loading is 90.3 percent of rock's peak strength (at the 19^{th} loading step), there appears the signal of deformation localization. When the loading force is reduced to 90.3 percent of peak strength, the deformation localization region is formed apparently. But the position of localization has changed greatly and the region is not stable, and the region vibrates obviously as well. However, when the loading is reduced to 70 percent of peak strength (the 28^{th} loading step), the deformation localization region is formed completely and the region is stable which is presented in Fig. 3. From now on, the width of deformation localization region is keeping stable as the loading is applied continuously, in the end, the rock will be damaged along this region, and the crack of the damaged rock is shown in Fig. 4.

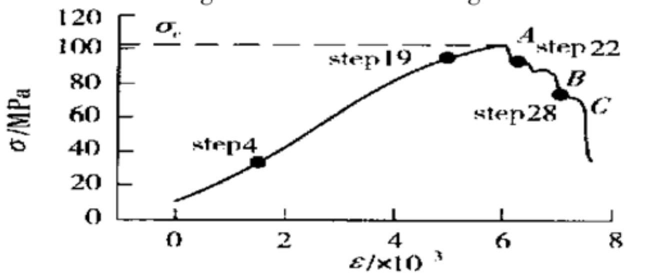

Fig. 1 The complete stress- strain curve of sandstone

From Fig. 3, the slope localization bandwidth of rock is 40 pixels which is measured by experiment, so the width of rock localization band is:

$$W_r = 40 \times 49/512 = 3.828 \text{ mm}$$

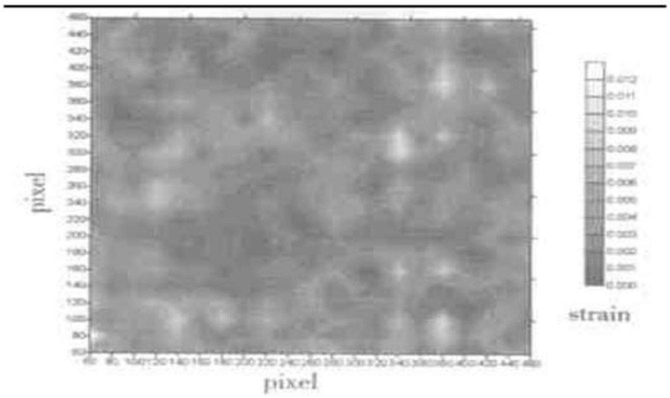

Fig. 2 The maximum shear strain distribution image of sandatone under the 1- 4^{th} loading step

Where W_r is the width of sandstone localization band.

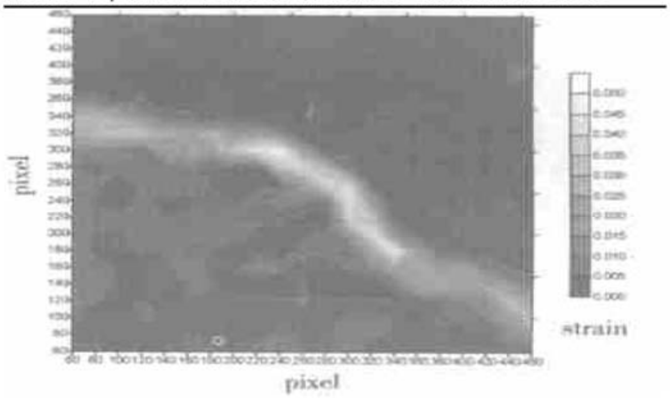

Fig. 3 The maximum shear strain distribution image of sandstone under the 27- 28^{th} loading step

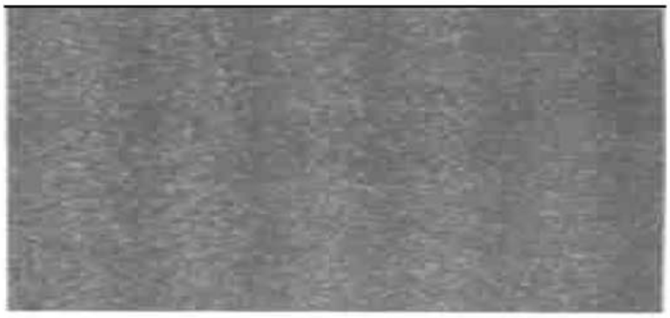

Fig. 4 The speckle image of sandstone macroscopic failure

3.2 Coal

The dimension of coal sample is 5 cm × 5 cm × 10 cm, and the viewing scope is 40 mm × 40 mm. Fig. 5 is the complete stress- strain curve of coal. When the loading is 60 percent of coal's intensity strength, the deformation of coal is homogenous and there is no signal of localization. By several experiments, we find that the stable deformation localization is formed just on the point of the peak strength and the loading of the 7^{th} loading step is just the peak strength of coal, which is shown in Fig. 6. The deformation width of the localization region is as 20 times wider than that of the outside region. At last, the coal will be damaged as the same way as that of the rock, which can be observed in Fig. 7.

From Fig. 6, the slope localization band width of coal is 60 pixels, so the width of coal localization band is:

$$W_c = 60 \times 40/512 = 4.6875 \text{ mm}$$

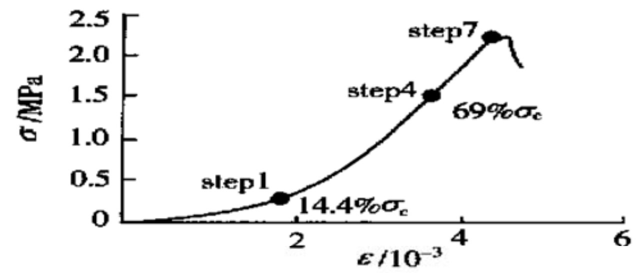

Fig. 5 The complete stress– strain curve of coal

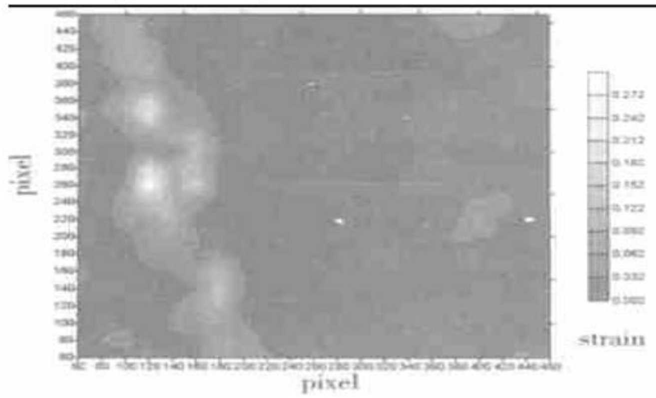

Fig. 6 The maximum shear strain distribution image of coal under the 4– 7th loading step

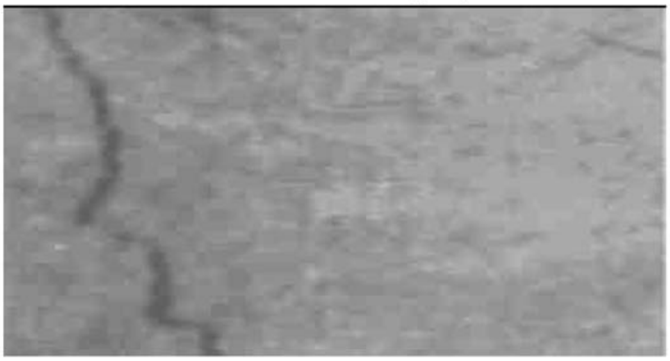

Fig. 7 The speckle image of coal macroscopic failure

Where W_c is width of coal localization band.

3. 3 Granite

Moreover, granite, which was taken from Three Gorges area, is experimented in laboratory. The dimension of granite is 5 cm × 5 cm × 10 cm. The resolution of imaging system in this experiment is 0. 057 mm/pixel with the field of view 42 mm × 42 mm in the center of sample surface. A CCD camera with a zoom lens takes speckle images. The uniaxial compression is performed by incremental steps and speckle image is recorded at each step. Load-displacement curve and sampling points are shown in Fig. 8. After reaching the peak of load curve, the specimen loading decreases with the increasing of the displacement. When it decreases to about 70% of the peak load (increment 7– 8 in this experiment) , localization is initialized. Shear strains in localization zone are about 20 times of those in homogenous zone. Fig. 9 is the distribution of shear strain of increment 7– 8.

4 Conclusions

The white light DSCM is used to study the deformation localization phenomenon of brittle rock material, and the results of the experiment prove that this method is precise and valid in measuring the displacement of brittle material deformation. The strain in localization band is as 20 times wider than that in the outside region. For the first time, this paper measures the width of rock localization band by experiment.

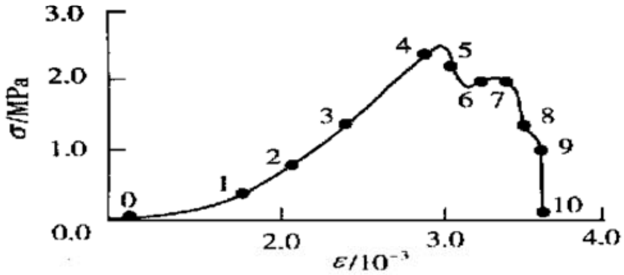

Fig. 8 The complete stress– strain curve of granite

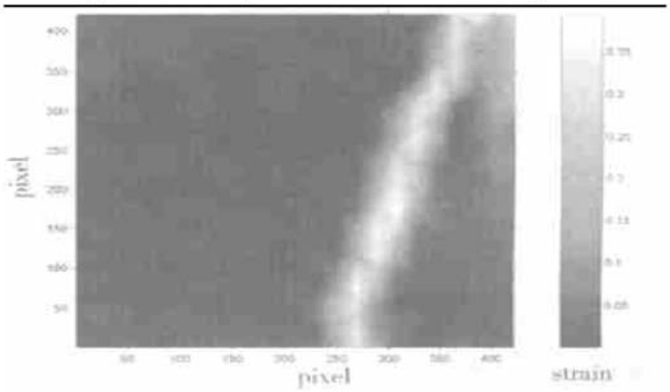

Fig. 9 Distribution of shear strain of increment 7– 8

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