Tunnelling and Underground Space Technology 78 (2018) 76–83

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Thermal radiation characteristics of stress evolution of a circular tunnel excavation under different confining pressures

Shuren Wang[a,d,*], Dejian Li[b,1], Chunliu Li[c,1], Chengguo Zhang[d,1], Yanbo Zhang[e,1]

[a] International Joint Research Laboratory of Henan Province for Underground Space Development and Disaster Prevention, Henan Polytechnic University, Jiaozuo 454003, China

[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Beijing 100083, China

[c] Institute of Urban Construction, Hebei Normal University of Science & Technology, Qinhuangdao 064003, China

[d] School of Mining Engineering, University of New South Wales, Sydney, NSW 2052, Australia

[e] College of Mining Engineering, North China University of Science and Technology, Tangshan 063009, China

ARTICLE INFO

Keywords:
Similar experiment
Infrared radiation
Circular tunnel
Stress evolution
Confining pressure

ABSTRACT

The infrared thermography has been tested herein for the study of the thermal radiation characteristics of stress evolution induced by a circular tunnel excavation during the biaxial compression tests of the similar material, together with the uniaxial compression test for the cylindrical specimen of the same material. The results showed that the stress curve of the cylindrical specimen displayed some larger fluctuations while the average infrared radiation temperature (AIRT) curve decreased with time. The correlations between the axial stress of the cylindrical specimen and its surface thermal radiation temperature presented distinctly two stages, namely negative nonlinear correlation in the front-peak curve and linear correlation in the post-peak curve. The cylindrical specimen demonstrated a tensile failure mode and showed the cooling effect. Under biaxial uniform compression, the temperature field and the stress field of the surrounding rock displayed a homogeneous state after the circular tunnel excavation. Maintaining the horizontal load constant and continuing to increase the vertical load, the thermal radiation temperatures on the specimen surface demonstrated a significant change after the circular tunnel excavation, which verified the consistency of the dynamic evolution process of the temperature field and the stress field during the circular tunnel excavation. The results obtained in the study lay the foundations for future studies focusing on the utility of the infrared thermography in the similar engineering.

1. Introduction

It is often difficult to perform the stress measurement directly, so the non-destructive and noncontact scanning, namely the thermal infrared imaging technology has been widely applied to various aspects in the world. For example, Taras et al. (2003) examined the coupled thermal, mechanical and diffusive processes in two-layer semitransparent composite subjected to thermal infrared radiation. Ploteau et al. (2007) aimed at presenting the development, construction, calibration and test of flux meters designed to make in situ measurements of infrared radiation in industrial furnaces. Bideau et al. (2009) developed a numerical model to predict temperature and vulcanization profiles in the material thickness. Park (2010) applied the thermal infrared camera to detect the increase of temperature and the distribution of thermal abnormalities at the three phases of rock failure, before, at the moment and after failure under uniaxial loading, for different specimens obtained in Korea. Lai et al. (2013) studied the durability of externally-bonded concrete beams by monitoring the intermediate cracking processes. Baron et al. (2014) presented a new approach for mapping open cracks and tension fractures within rock slope instabilities and rock cliffs, which resided in high-resolution ground-based and airborne infrared thermography. Naouar and Sougrati (2014) adopted the infrared thermography as a sounding method to estimate the change in temperature, or thermal contrast induced by the presence of a defect in a specimen. Khana et al. (2015) aimed to demonstrate the implementation of the infrared thermography method for the non-destructive evaluation of concrete masonry structural components by a numerical and experimental study. Mineo and Pappalardo (2016) used a new test for the indirect assessment of porosity through infrared thermography and studied the cooling behavior of rock samples in laboratory. The

* Corresponding author at: International Joint Research Laboratory of Henan Province for Underground Space Development and Disaster Prevention, Henan Polytechnic University, Jiaozuo 454003, China.

E-mail address: shurenwangs@163.com (S. Wang).

[1] These authors contributed equally.

https://doi.org/10.1016/j.tust.2018.04.021
Received 29 June 2017; Received in revised form 23 November 2017; Accepted 10 April 2018
0886-7798/

infrared thermography was employed by Pappalardo and Mineo (2017) for the infrared analysis of the basaltic rock specimens to highlight differences and peculiar features related to their structure.

In recent decades, to overcome the disadvantage that the strain gauges pasted on the specimen surface fail due to a greater deformation fracture for the brittle and quasi-brittle media such as rock, extensive researches have been conducted by applying the thermal infrared imaging technology to the rock and similar material in China. For example, based on the thermal infrared radiation (TIR) detection during uniaxial loading tests, Wu et al. (2002) found that the TIR-anomaly characteristics of rock surface reflect the features of rock deformation or rock failure. Guo et al. (2006) obtained infrared radiation isothermal fringes through the thermal infrared images subtraction and data interpolation to detect the photoelastical material. According to the thermodynamics theory and physical micro-properties of solid materials subjected to external loading at room temperature, Wang et al. (2009) deduced a formula of calculating temperature difference of infrared radiation in terms of the sum of three principal strains to quantitatively investigate the infrared radiation characteristics in the test. Zhang and Liu (2011) conducted the TIR variation features research on a selected rock with a hole by using uniaxial loading system and thermal imager. Gong et al. (2013) conducted experiments on roadway excavation in large-scale geological physical models and captured the structural behavior of the differently inclined rock strata based on infrared thermographic technique. Zhang and Liu (2014) suggested that the infrared imaging technology could detect part of rock painting stalactite disease, and finite element theoretical simulation was an effective means to study the rock painting stalactite disease. Sun et al. (2017a, 2017b) conducted the thermography analyses of floor heave after the deep roadway excavation in 10° inclined strata and investigated the occurrence of rock burst in a rock specimen by using the thermal infrared imaging technology.

To sum up the above mentioned literatures, we found that the thermal infrared imaging technology could be applied for detection of the failure process of concrete, coal, metal, and other materials. Although this technique had been widely used in several scientific fields, its direct application for rock mechanics purposes was still under development. Moreover, it was not perfect enough about the dynamic evolution process of the temperature field and the stress field after a tunnel excavation. So it is necessary to conduct the further study for observation of thermal radiation characteristics of stress evolution induced by a circular tunnel excavation and revealing the correlation curve of the loading stress and the thermal infrared temperature on the surface of the specimen using the infrared thermography.

2. Description of the problem

The thermal infrared imaging technology, as a method of observation surface temperature change of the test material, based on the correlation establishment between the radiation temperature and the stress variation, the temporal phases and the spatial evolution characteristics of the thermal radiation and the stress variation could be obtained in real time (Tan et al. 2005). Therefore, it was of an important meaning to research the stress measurement of the test materials.

As shown in Fig. 1, there is stress redistribution in the surrounding rock after the circular tunnel excavation. Suppose that r_0 is the radius of the circular tunnel, r is the distance from A to the center O. The vertical stress is p_0, the horizontal stress is λp_0, and λ is the coefficient of lateral pressure. In general, according to G. Kirsch's solutions (Wang et al. 2015), the tangential stress σ_θ, radial stress σ_r, and shear stress $\tau_{r\theta}$ of point A in the elastic state will satisfy the following formulae:

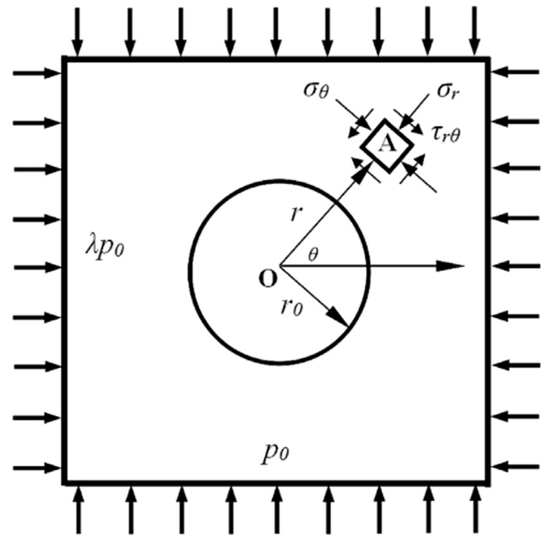

Fig. 1. The computational model.

$$\begin{cases} \sigma_r = \frac{p_0}{2}\left[(1+\lambda)\left(1-\frac{r^2}{r_0^2}\right)-(1-\lambda)\left(1-4\frac{r^2}{r_0^2}+3\frac{r^4}{r_0^4}\right)\cos 2\theta\right] \\ \sigma_\theta = \frac{p_0}{2}\left[(1+\lambda)\left(1+\frac{r^2}{r_0^2}\right)+(1-\lambda)\left(1+3\frac{r^4}{r_0^4}\right)\cos 2\theta\right] \\ \tau_{r\theta} = -\frac{p_0}{2}\left[(1-\lambda)\left(1-2\frac{r^2}{r_0^2}-3\frac{r^4}{r_0^4}\right)\sin 2\theta\right] \end{cases} \tag{1}$$

So the reliability of the infrared thermography results can be verified by the G. Kirsch's solutions, and the results will provide the technical reference for the real-time detection of the stress field changes of the rock specimens by using the infrared radiation imaging technology.

Based on G. Kirsch's solutions, the biaxial compressive tests of similar material were conducted for observation of thermal radiation characteristics of stress evolution induced by a circular tunnel excavation using infrared thermography. Two different shape samples were selected to complete the tests in the paper.

For obtaining the correlations between the axial stress of the specimen and its surface thermal radiation temperature, the cylindrical specimen of the similar material was conducted to the uniaxial compression test. Then, in order to establish the relationship between the rock stress and the infrared radiation temperature after the circular tunnel excavation under different confining pressures, the similar materials test of a circular tunnel loaded by biaxial compression was carried out by the infrared thermography technology.

3. Methodology

3.1. Test specimens

As shown in Figs. 2, 3 and 4, the white cement was selected as the specimen material. Square plate specimen with a hole diameter 30 mm, whose dimensions were length × height × thickness = 110 × 110 × 30 mm^3, was made in accordance with the water-cement ratio of 0.8: 1. And the same material standard cylindrical sample with diameter 50 mm and length 100 mm was made, which two ends were polished, with tolerance of parallelism being less than 0.01 mm. The square plate specimens were divided into two groups, each group with four samples, and this is the same for the cylindrical samples. The physical and mechanical parameters of two test specimens were listed in Table 1.