Structures 16 (2018) 112–118

Contents lists available at ScienceDirect

Structures

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

Measuring joint opening displacement between model shield-tunnel segments for reduced-scale model tests

Jie Wang, Hongqing Liu, Huabei Liu*

School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, Hubei 430074, China

ARTICLE INFO

Keywords:
Shield tunnel
Reduced-scale model segments
Joint opening
Measurement

ABSTRACT

Joint opening between lining segments in a shield tunnel is a critical parameter for the tunnel performance under different loading conditions. Large joint opening may be an indicator of concrete crushing in the lining and may lead to water leakage. Therefore monitoring the joint opening is an important issue in the model experiments of shield tunnels. However the shield tunnel models in reduced-scale model tests, including centrifuge tests, are small in size and buried in soils, making it quite difficult to monitor the joint opening. In this study, an approach is proposed to measure such opening in reduced-scale model tests. The approach employs a large-range electric strain gage, which is attached across the joint with a free length. The approach was validated and applied to two loading tests of a model shield tunnel made of plexiglass and sliced into six equal segments, which were connected by steel threads simulating the bolts. It was found that the joint opening was proportional to the voltage output of the strain gage, which was independent of the magnitude of the free length. With an appropriate coefficient that was previously calibrated, the joint opening was accurately measured.

1. Introduction

The joint opening displacement between lining segments is an important indicator of the performance of concrete shield tunnel structures. Large joint opening between shield tunnel segments may lead to water leakage, which would affect the operational safety of the tunnel [1]. Therefore monitoring the joint opening displacement is critical during the service life of the tunnel. In addition, it is also necessary to use appropriate approaches to measure the joint opening in model experiments, which generally aim to better understanding the behavior of shield tunnel in complicated loading conditions including earthquake.

In some sense, joint opening is similar to the crack width in various structures. In recent years, many types of sensors have been proposed to detect and measure crack widths. The ease of implementation and quick response characteristic of piezo-ceramics make such a system appropriate for wide application, and Hughi and Marzoik [2], Annamdas et al. [3], and Song et al. [4] used piezo-ceramic sensors to measure the crack width of reinforced concrete structures. Crackmeter measurement is a well-accepted technology in structural health monitoring [5–8]. Bossi et al. [5] designed a SHM network to measure the displacements across major cracks and the rotation of the tunnel segments in real time, Ferri et al. [6] designed a novel crackmeter suited for wireless structural monitoring realized with MEMS strain sensors. Vibrating string sensors with good stability, strong anti-interference ability and relatively low cost to maintenance has been selected as the long-term monitoring sensor for the operational safety of highway tunnel structures [9]. However, it is difficult to apply the aforementioned techniques to measure the joint opening of a model shield tunnel in a centrifuge test. In such a test, the model tunnel is buried in soil, and its size is also rather small.

Fiber optic sensing systems have been successfully developed for many engineering applications including crack detection and application to small scale experiments. Lu et al. [10], Katsuki [11], and Robins et al. [12] presented methods to monitor the crack width by means of optical fiber sensors, which can measure the strain and crack width of concrete structures in real-time. Luca [13] reviewed and discussed the application of distributed optical fiber sensors to geo-hydrological monitoring. Li et al. [14] reviewed the fiber optical sensor health monitoring in various key civil structures and discussed the existing problem in packaging and implementing FOSs in civil structural health monitoring. Chang [15] et al. also applied the fiber optical sensor in the health monitoring of civil infrastructures. Furthermore, Leung [16,17] has developed a novel fiber optic sensors for the detection of cracks and monitoring of their openings in concrete structures. The sensor can be made sensitive to very small crack opening around 0.1 mm. From these studies, it can be seen that the fiber optic sensors can be sensitive to

* Corresponding author.
E-mail address: hbliu@hust.edu.cn (H. Liu).

https://doi.org/10.1016/j.istruc.2018.09.003
Received 29 June 2018; Received in revised form 11 September 2018; Accepted 13 September 2018
Available online 13 September 2018

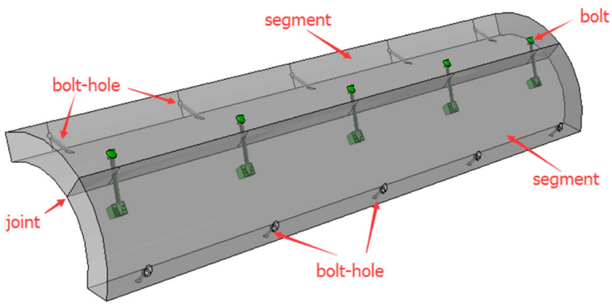
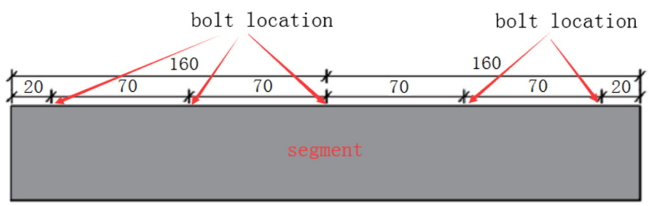
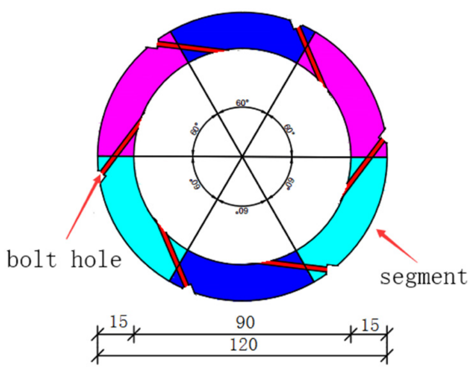


Fig. 1. Schematic diagram of model segments and bolts.



(a)



(b)

Fig. 2. Schematic diagram of the dimensions of the modelled tunnel (unit: mm): (a) side view (b) cross-section view.

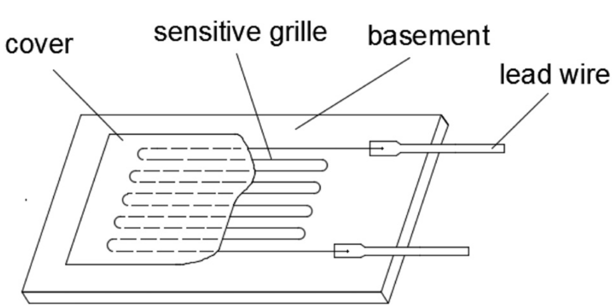
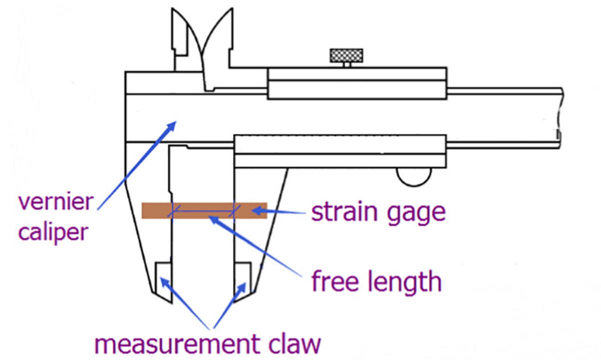
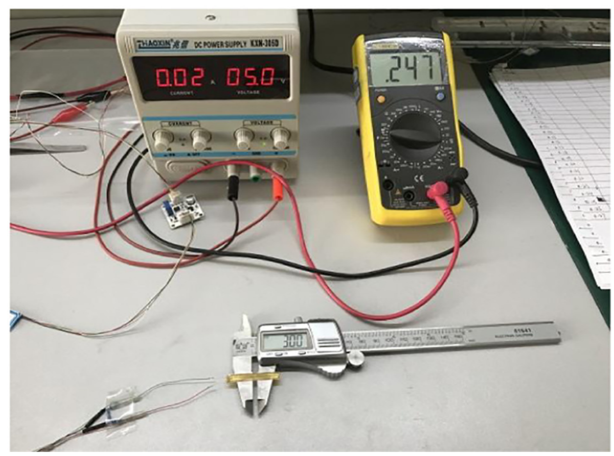


Fig. 3. Structure of electric-resistance strain gage.



(a) The schematic diagram



(b) The practice diagram

Fig. 4. Illustration of the concept verification and calibration.

detect the crack and exactly measure the very small crack width in a dynamic range. However, optical fibers are fragile and are subjected to breakage especially during installation to the host structures. In addition, the cost is relatively high.

The strain gages have a broad application in local small strain measurement and crack detection. Goto et al. [18] developed a device by strain gage to investigate the stiffness of soils and the device can measure strain levels ranging from 10^{-6} to 10^{-2}. Zhang et al. [19] adopted the Hole-drilling strain-gage method for measuring working strains in concrete structures. Roesler and Baenberg [20] used strain gages to detect the static and fatigue cracks on concrete structures. Salem and Ghosn [21] used strain gages to estimate the crack length. Vospernig et al. [22] applied strain gages to detect the crack. The above studies revealed that strain gages have a relatively wide range in local strain measurement, and they can detect the crack and even estimate the crack length. However, when it is needed to exactly measure the crack opening displacement, few existing approaches have applied strain gages for this purpose. This manuscript put forward a method by using strain gages to exactly measure the joint opening displacement between model shield-tunnel segments for reduced-scale model tests.

In a reduced-scale or centrifuge model tests of shield tunnels, the model tunnel is usually manufactured by microconcrete, gypsum, aluminum, and plexiglass, among other materials. Kiani et al. [23] used asbestos-reinforced cement pipes to model the tunnels, and the joints were connected by pins. Liu et al. [24] used gypsum to simulate the tunnel tube. However, because of the difficulty in the preparation of microconcrete or gypsum, the shield tunnel model is generally made of aluminum or plexiglass. As the elastic modulus of aluminum is close to the concrete, in a centrifuge test, the wall of the aluminum tube model is very thin, which makes it difficult to divide the tube into segments that should be connected by bolts. Sun [25], Liu and Nezili [26], and Adalier et al. [27] all employed aluminum tubes to model shield tunnels without considering the influences of the joints. Plexiglass tube, on the other hand, may be sliced into segments to better model prototype shield tunnels. Huang et al. [28] used polyethylene (PE) tubes to model shield tunnel segments, which were connected by screws to model the