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Experimental and analytical study on longitudinal joint opening of concrete segmental lining

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ABSTRACT

Longitudinal joint opening is a common distress in shield tunnel operation. Existing longitudinal joint models are mainly developed for the design of segmental lining, but the real behavior of longitudinal joints in operational tunnels may exceed the normal design range. The aims of this paper are to study the development of longitudinal joint opening with bending moment under different axial stress levels, and investigate the longitudinal joint opening in the Ultimate Limit State (ULS). Firstly, full-scale tests on the longitudinal joints that are adopted in the Shanghai Metro Line No. 13 are conducted. The longitudinal joints are continuously loaded until completely damaged. Secondly, based on the test observations, a progressive model is proposed to predict the mechanical behavior of the joint. The proposed model is then verified by the test results. Lastly, using the proposed model, the influences of the axial stress level, bolt pretightening force, concrete delamination depth and bolt corrosion depth on the mechanical behavior of the joint are investigated. The following conclusions are drawn from the analysis: (1) Longitudinal joint opening is highly dependent on the axial stress level. For the joint subjected to the same bending moment, the larger the axial load, the smaller the joint opening. (2) Generally, the joint opening decreases with the increasing of bolt pretightening force, and increases with the increasing of concrete delamination depth and bolt corrosion depth. (3) The joint opening in the ULS increases with the increasing of axial load for the sagging moment case, and decreases for the hogging moment case. The structural state based on joint opening and the effects of joint configuration are also discussed.

1. Introduction

Shield-driven tunnels are widely adopted in the development of underground spaces for transportation and utility networks in soft soils. The health condition of a shield tunnel generally deteriorates with the operation time because of internal factors (e.g., material degradation), and external factors (e.g., nearby constructions, differential settlement in soft ground, train vibration, unexpected loading at the ground surface). Longitudinal joint opening is a common distress in shield tunnel operation, and it can be a main cause of water leakage, which is another detrimental distress in shield tunnel operation. Longitudinal joint opening width is also an indicator for the deformation of segmental lining, and it can be used to assess the safety of tunnel structure (Wang and Zhang, 2013; Yu et al., 2013). For example, the allowable upper limit for joint opening is 2–4 mm based on the Shanghai foundation design code (DGJ08-11, 2010). Therefore, the development of longitudinal joint opening with internal forces and the determination of longitudinal joint opening width in the Ultimate Limit State (ULS) are important issues for tunnel maintenance and operation.

Earlier attempts to consider the influence of longitudinal joints on tunnel lining behavior were based on the increase of the lining flexibility. The tunnel lining was simplified as a uniform rigidity ring, and the effect of longitudinal joints was taken into account by applying a reduction factor to the bending stiffness of the tunnel lining (Muir Wood, 1975; JSCE, 1977; Blom, 2000). A main drawback of this method is that the joint opening cannot be obtained.

Recent models consider the longitudinal joints behavior by means of rotational springs located at joint places, and the stiffness of the rotational springs is considered as a constant for simplicity (ITA, 2000; JSCE, 2000; Lee and Ge, 2001; Koyama, 2003; Ding et al., 2004; El Naggar and Hinchberger, 2008; Teachavorasinskun and Chub-uppakarn, 2010). The joint opening can thus be derived

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from the predicted spring rotation angle. As pointed by many studies (e.g., Zhu 1995; Blom, 2000; Zhong et al., 2006), the longitudinal joint present a complex nonlinear behavior due to its incapacity to transfer tensile stress, and the stiffness decreases significantly after the joint is opened (i.e., a loose of joint contact at one side of the joint). Joint structural tests show that the rotational stiffness is higher when a joint is subjected to a sagging moment (i.e., positive bending moment) than when it is subjected to a hogging moment (i.e., negative bending moment) (Zhu, 1995; Lee and Ge, 2001; Do et al., 2013). According to the test results, rotational stiffness under a hogging moment was approximately 1/2–1/3 of the stiffness under a sagging moment. As a result, a rotational spring with either bilinear (e.g., Blom, 2000; Koyama, 2003; Zhong et al., 2006) or nonlinear (Zhu, 1995) constitutive model is proposed to describe the relationship between joint rotational angle and bending moment. However, structural tests also show that the joint behavior is dependent on the axial stress level (Zhu, 1995; Blom, 2000; Koyama, 2003; Zhong et al., 2006; Arnau and Molins, 2011). For the same joint, different axial stress levels provide different rotational behaviors. Therefore, the predicted joint opening may not be accurate if the effect of axial stress levels on joint behavior is neglected. In addition, the joint opening in the ULS cannot be accurately predicted using existing models because of the complex nonlinear behavior of the joint.

The objective of this paper is to investigate the development of longitudinal joint opening with both sagging and hogging moment under different axial stress levels, and investigate the longitudinal joint opening in the ULS. Considering the joint opening in the ULS has not been obtained in the previous tests (e.g., Zhu, 1995; Lee and Ge, 2001; Ding et al., 2004; Zhong et al., 2006; Teachavorasinskun and Chub-uppakarn, 2010), we first conducted full-scale tests on the longitudinal joint that is adopted in the Shanghai Metro Line No. 13. The longitudinal joint is continuously loaded until it is completely damaged. Then, we propose a progressive model to simulate the joint opening behavior based on the test observations. The joint model is verified by the test results. Finally, a parametric study on the influences of axial stress level, bolt pretightening force, and material degradation (i.e., concrete delamination depth and bolt corrosion depth) on the joint opening is performed based on the joint model.

2. Full-scale longitudinal joint tests

The lining structure of Shanghai Metro Line No. 13 is studied in this paper. The external diameter of the tunnel lining is 6.20 m, and the inner diameter is 5.50 m. The ring width and thickness are 1.20 m and 0.35 m, respectively. Each ring consists of one key segment (K), two adjacent segments (L_1 and L_2), two standard segments (B_1 and B_2), and one counter key segment (D), as shown in Fig. 1. Each longitudinal joint has two bolt pockets with embedded steel cushions in both sides. The longitudinal joint is connected by two completely pass-through bolts with a diameter of 30 mm and a length of 485 mm. When the segment is placed in position, bolts are inserted into the pockets and tightened on both ends with grommets and nuts. The longitudinal joint also includes a gasket for waterproofing, and a guidance rod to allow the segment to be guided into its position during the assembly stage. The guidance rod also functions as a shear pin. The concrete type is C55. The bolt grade is 5.8, which means its tensile strength is 500 MPa and its yield strength is 400 MPa.

The specimens used in the tests, including the segments, bolts, and gaskets, are the same as the actual tunnel lining. The segments are fabricated in the same factory as the tunnel lining to ensure they are of identical quality. A schematic diagram of the specimen and the details of the longitudinal joint are shown in Fig. 2.

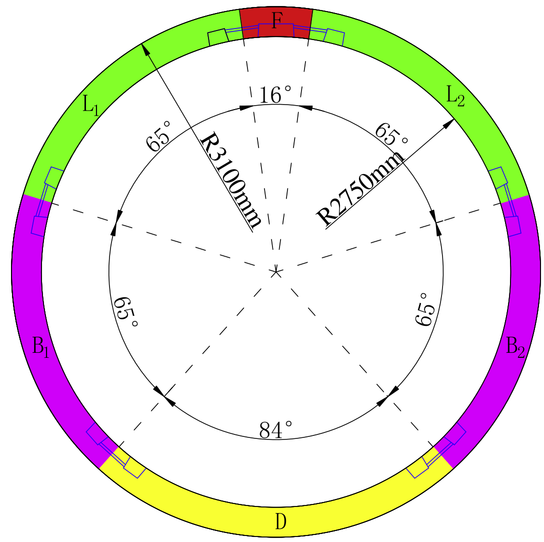

Fig. 1. The structure of tunnel lining.

2.1. Test set-up

The longitudinal joint was tested on the TJGPJ2000 facility in Tongji University. The size of the facility is approximately 4 m in width, 3 m in height, and 3 m in depth. The facility consists of self-balancing frames, steel supports for segment, horizontal and vertical motor servo loading systems, and an operating system, as shown in Fig. 3.

The horizontal loading system consists of four 1000 kN hydraulic jacks. The vertical loading system consists of two 750 kN hydraulic jacks and one 1500 kN hydraulic jacks. The maximum travel ranges for the horizontal and vertical hydraulic jacks are 15 cm and 20 cm, respectively. A series of tests on the mechanical response of shield tunnel linings, such as bending tests on segment joints, shear tests on radial or circumferential joints, and tests on the moment transfer coefficient between the lining rings can be conducted using this facility by adjusting loading modes.

To obtain the full behavior of the longitudinal joint, the joint subjected to both sagging (positive bending) and hogging (negative bending) moments were conducted. The horizontal and vertical hydraulic jacks were applied on the segments to simulate the axial forces and bending moments. The joint subjected to the sagging moment case is illustrated in Fig. 3. For the hogging moment case, the segments and the steel supports were flipped upside down.

2.2. Loading

The horizontal loads were estimated based on a calculation of axial forces of a tunnel with an overburden depth of 20 m using the beam spring model (Koyama, 2003). Calculation results show that the axial force in the maximum hogging moment area is approximately 1.2 times that in the maximum sagging moment area. Therefore, the horizontal load was applied to 900 kN and then remained unchanged for the sagging moment case. For the hogging moment case, the horizontal load was applied to 1080 kN and then remained unchanged. The vertical load was then applied at a rate of 20 kN/min until the joint was completely damaged for both cases.

2.3. Monitoring

The joint opening was measured by four deformation gauges (V1–V4) instrumented on the segment external and internal edge,