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Full-scale tests on bending behavior of segmental joints for large underwater shield tunnels

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ABSTRACT

This paper presents an experimental and numerical study on the bending behaviour of segmental joints for large underwater shield tunnels. A series of full-scale tests of segmental joint for underwater shield tunnel are carried out to investigate the bending performance under compression-bending loads. And comparative numerical simulations are conducted to compare with the test results and analyze the occurrence and development process of joint failure. The results indicate that the joint opens linearly and deforms nonlinearly after the visible concrete cracking occurred, the shape of joint interface is a curved surface during joint opening. The time when the bolt becomes stressed depended on axial force, and the bolt stress increased linearly with the growth of bending moment. Joint bending stiffness can be divided into three stages according to turning point of 'visible concrete cracking' and 'bolt yield', large axial force has a great influence on keeping it. The joint waterproof material could hardly promote the bending stiffness and capacity of segmental joint for its small rigidity. The failure process of segmental joint was different between under positive and negative bending moment, the compressive capacity of concrete in compression zone near the intrados played a vital role in the process of improving the bending capacity of segmental joint. The numerical results of joint opening and bending stiffness were in good agreement with tests during small deformation stage, while after visible cracking the results differ relatively. It is reasonable to simulate joint bending performance before visible concrete cracking, and estimated joint failure mode and its approximate range by using the proposed numerical model.

1. Introduction

Shield tunnels, which are playing a crucial role in public transportation systems around the world, are usually constructed under unfavorable ground conditions (e.g. soft ground, riverbed, and seabed). Over the past decade, a considerably number of underwater shield tunnels have been constructed as river-cross channels in China. Compared with other tunnels (e.g. subway tunnels, road tunnels, water conveyance tunnels and power or gas tunnels, etc.), the underwater shield tunnel has larger cross-section (from $\Phi 10$ m to $\Phi 15$ m), deeper buried depth (from 48 m to 66 m depth), and bears higher water pressure (from 0.6 MPa to 1.4 MPa).

Precast concrete segments and segmental joints are main components in the shield tunnel. The joints are used to connect adjacent segments to form segmental rings as shown in Fig. 1, which are the weakest and most complex components in tunnel lining structures. Due to the presence of the joints, a segmental lining structure is usually considered as a multi-hinged structure, which shows very complex structural behavior (Koyama, 2003). Past research (Murakami and Koizumi, 1978; Teachavorasinskun et al., 2010; Ye et al., 2014) has shown that the bending stiffness of the segmental joint is a key factor in the structural design and analysis of segmental lining rings. It is also found that the bending performance and the opening value of each joint have significant influence on the mechanical behavior of the whole tunnel structure, especially in the complex underwater environment.

The segmental joints of recent built and designed large-scale river-cross shield tunnel in China are presented in Table 1. With the aim of bearing high water and earth pressure, the joints shown in Table 1 are different with the joints used in normal shield tunnels, which have the following features: (1) the segments are thicker and wider to form a larger compression section; (2) oblique bolts are more preferable in the construction of segmental rings; (3) mortises are applied on the contact surfaces in the joints to enhance assembly precision; (4) rubber packers are rarely set to increase the friction between the concrete contact surface under high compression; (5) dual-channeled waterproof materials are applied in the joints to fulfill water proof requirements of the tunnels structures. Fig. 2 shows some typical segments and the arrangement of joints employed in Shiziyang underwater shield tunnel to

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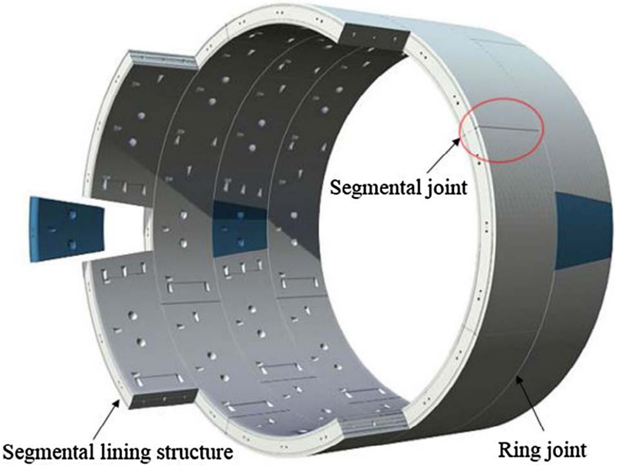

Fig. 1. Sketch of segmental joints and ring joints of a shield tunnel.

provide a clear understanding of the above mentioned features. Due to the complex geometric and material features, the segmental joint in the underwater shield tunnel usually shows complicated structural behaviour under high compression-bending forces (caused by the high water and earth pressure), especially in transferring forces and constraints between adjacent segments, and allocating rigidity of the whole segmental lining structure. As a result, the contact behavior of the segmental joint in the underwater shield tunnel is usually controlled by the axial force, causing significant differences in load transfer effect, deformation and failure pattern compared with the joints in normal shied tunnels.

Over the past few decades, a large number of research has been carried out to understand the bending behaviour of the segmental joint. Theoretical models (Murakami and Koizumi, 1980; Iftimie, 1992; Huang, 2003) were established to describe the bilinear/non-linear behavior of the bending stiffness of segmental joints with different types. Numerical investigations on the influences of joint size, bolt type or other factors were carried out (Zhang et al., 2002; Zeng et al., 2004; Zhong et al, 2006; Shi et al., 2015), where the bending stiffness and deformation properties were also provided. Laboratory and in-situ tests were carried out to investigate the bending performance of the segmental joint with different configuration and dimensions for different functions such as gas pipelines (Hayashi, 1997), metro tunnel (Wang and Li, 2005; Li et al., 2015), water conveyance tunnel (Zhang et al., 2002; Yan et al., 2011) and river-cross highway tunnel (Chen et al., 2010; Teng and Lu, 2010). In the above research, the general law of the joint bending stiffness under small joint deformation was obtained. However, most of the abovementioned theoretical models were established based on the plane section assumption under small deformation condition, which are not able to provide accurate description of the contact behavior of the segmental joints under high axial compression and large deformation condition. Besides, most of the theoretical models and numerical analyses have taken in to account the influence of sealing gasket and rubber waterstop, while the stiffness of the sealing gasket and rubber waterstop is too small compared with the joints. Therefore, the influence of the sealing gasket and waterstop on the bending capacity of segmental joints needs to be investigated. Moreover, most of the experimental research focused on the joint bending behavior in the linear-elastic stage, without investigating the bending performance, bending capacity and failure characteristics under large deformation condition and in the failure state. As concrete segments are required to bear very high water and earth pressure in existing underwater shield tunnels, concrete cracks may easily occur at the contact surfaces of adjacent segments under high axial compression. Thus, the structural performance of segmental joints under compression-bending loads after crack happening is essential to the structural design and maintenance of tunnel lining structures.

In this paper, a series of full-scale tests are carried out to investigate the bending performance and bending capacity of segmental joints in underwater shield tunnels. The opening behavior and bending stiffness of segmental joints, strain condition of concrete segments, and stress condition of joint bolts under different axial compression-bending loads are carefully examined. In particular, the influence of sealing gasket and rubber waterstop on the bending performance segmental joints are discussed. Then, the failure behavior and failure pattern of segmental joints under high compression-bending loads are investigated. A numerical study based on the finite element (FE) method is carried out to provide an experimental-numerical comparison and to provide a better understanding of the joint bending behavior from small deformation stage to failure stage.

2. Full-scale test program

2.1. Project overview

The full-scale tests are carried out based on the construction project of the Shiziyang tunnel, which is the first and longest underwater shield tunnel in China. The Shiziyang tunnel is a railway tunnel connecting the Dongchong Station and Humen Station, and crossing several rivers (e.g. Shiziyang River), with a total length of 10.8 km (the shield tunnel section is 9.34 km long). As shown in Fig. 3, the Shiziyang tunnel crosses through muddy silty clay (Q), strongly weathered sandstone (W_3, W_4), and weakly weathered sandstone (W_2), with abundant and high underground water (the highest water pressure is about 0.67 MPa).

The Shiziyang tunnel are constructed using reinforced concrete (RC) segments, and the concrete type is C50. Fig. 4 shows the layout of the segmental ring of Shiziyang tunnel. The outer diameter and inner diameter are 10,800 mm and 9800 mm respectively, with a 500 mm thickness. The segmental ring is assembled by eight universal wedge-shaped segments with an average width of 2000 mm, using 24 M36 circumferential bolts and 22 M30 longitudinal bolts in the segmental joints. The central angle of the key segment is 16°21′49.09″, while the angle of other segments is 49°5′27.27″. As shown in Fig. 5, each segmental joint consists of three M36 oblique bolts with the steel grade of 6.8. The tensile strength and the yield strength of the bolt is 600 MPa and 480 MPa, respectively, while the diameter and the length of the bolt is 42 mm and 639 mm, respectively. The bolt is inserted into the hand hole, passing through the bolt hole, and finally it is screwed into the embedded bolt nuts to connect the two adjacent segments. The bolt pretightening loads can be applied to the segmental joint by the pulling force from bolt nuts and steel cushion. Two sides dual-channeled waterproof is employed in the segmental joint, while tenon and mortise are applied in the middle section of the joints allowing the segments to be guided into the appropriate positions during construction.

2.2. Test arrangement and procedure

There were two types of specimens (named A and B) in the tests, and the size and mechanical properties of the specimens are listed in Table 2. In order to obtain the common regularity of the joint deformation and the complete process of the joint failure, four sets of test specimens have been casted before the experiment. Two sets are employed with a range of axial force from 3000 kN to 8000 kN respectively under normal load (positive bending and negative bending), while the other two sets are used for failure load under the effect of the axial force of 6000 kN (positive bending and negative bending). Due to the limit of loading system capacity, the width of specimens was selected as 1/3 segment width (667 mm) of the full-scale segment with one bolt in the middle connecting two specimens to meet the destructive test requirements. The configuration of specimen interface, the thickness and reinforcement ratio were manufactured exactly the same with the