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Sealant behavior of gasketed segmental joints in shield tunnels: An experimental and numerical study

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ABSTRACT

Segmental joints are vulnerable parts of the lining structure in precast shield tunnels, both from the structural (lower stiffness compared to main segments) and non-structural (potential water leakage points) perspectives. Previous works have focused on the structural behavior of segmental joints rather than the sealant behavior. This paper presents a combined experimental and computational study to investigate the sealant and mechanical behavior of the gasketed joints used for a tunnel prototype, i.e., Nanjing Weisan Road Tunnel, which was recently built using a tunnel-boring machine below the Yangtze River, whose 72-m water table head is the highest in China. A total of 7 gasket profiles were tested using a testing apparatus developed in-house. The objective of the joint waterproof tests was to quantify the water leakage pressure (or joint waterproof capacity) versus the joint opening relationships under various joint offset scenarios. The objective of the gasket-in-groove mechanical tests was to quantify the force versus deformation relationships. Finite element models of the gaskets were developed and verified against the test results. A supplementary parametric study was conducted to investigate the effect of joint opening, joint offset and gasket hardness on the detailed distribution of contact stress of the gasket interface. Combining the experimentally recorded and the numerically computed data presented in this paper, a simplified design formula that quantifies the relationship between the contact stress of the gasket and the water pressure was proposed, and its rationality was validated against the available test data in the literature.

1. Introduction

The tunnel-boring machine has been extensively adopted to construct underground shield tunnels due to its various advantages (e.g., high flexibility, low labor-resource consumption, high cost effectiveness, and minimal environmental disturbance). The lining structure of a shield tunnel comprises a large number of segmental rings in the longitudinal direction. In China, the adjacent rings are permanently connected by longitudinal bolts that form the ring joint. In the transverse direction, each ring comprises a few precast segments, which are permanently connected by the circumferential bolts to complete a ring. The discontinuous interface between adjacent segments is the segmental joint.

The overall behavior of the tunnel lining is primarily governed by the joints. Substantial research has led to in-depth knowledge on the structural behavior of segmental joints. An earlier effort to consider the effect of segmental joints on the lining performance was to reduce the bending stiffness of the tunnel lining in an analytical manner (Wood, 1975; Einstein and Schwartz, 1979; ITA, 2000; Lee and Ge, 2001; Koyama, 2003). However, this method fails to account for the joint distribution and stiffness. Modern analysis, however, utilizes numerical methods to explicitly model tunnel segments and joints. That is, segments are modeled as a beam (Koizumi, 1992; Do et al., 2013) or shell (Ding et al., 2004; Teachavorasinskun and Chub-uppakarn, 2010; Wang and Koizumi, 2010; Wang et al., 2015) element, while joints are simulated by a set of linear or non-linear springs. The value of the joint spring stiffness can be obtained through full-scale joint tests (Ding et al., 2013; Li et al., 2015a; Li et al., 2015b; Gong et al., 2017). However, spring models are not capable of capturing the detailed behavior of joints, such as opening, offset and rotation. More recent efforts include the three-dimensional (3D) finite element modeling of segments considering joint details (i.e., joint geometry, segment contact and bolt) (Arnau and Molins, 2011, 2012; Li et al., 2014, 2015a, 2015b).

Underground tunnels are usually designed with requirements for the load carrying capacity and functional utility. The waterproofness of the entire tunnel is a key aspect in the field of functional requirements. For

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Nomenclature

A_c	closed-hole area of the gasket
A_{gasket}	gross area of the gasket
A_{groove}	gasket groove area
A_h	hole area of the gasket
A_n	net area of the gasket
A_o	open-hole area of the gasket
C_{01}	first coefficient of Mooney-Rivlin model
C_{10}	second coefficient of Mooney-Rivlin model
d_c	concrete compressive damage variable
d_t	concrete tensile damage variable
E_c	Young's modulus of the concrete
E_g	Young's modulus of the gasket
e_f	flow potential eccentricity
$F_{g,max}$	ultimate compression force of the gasket
F_{jack}	assembly capacity of the TBM jack
f_{b0}	initial equibiaxial compressive yield stress
f_{c0}	initial uniaxial compressive yield stress
G_g	initial shear modulus of the gasket
H_A	gasket hardness
$H_{w,max}$	maximum water height
h_g	gasket height
I_1	first strain invariant of Mooney-Rivlin model
I_2	second strain invariant of Mooney-Rivlin model
K_C	ratio of the second stress invariant on the tensile meridian to that on the compressive meridian
P_c	contact stress of the gasket-to-gasket interface
$P_{c,ave}$	average contact stress of the gasket-to-gasket interface
P_w	water pressure
P_{wd}	theoretical water pressure
P_{wl}	water leakage pressure
R_j	waterproof capacity of the joint
S	joint offset
S_d	design joint offset
W	strain energy function of Mooney-Rivlin model
ν_c	Poisson's ratio of the concrete
α	safety factor
γ_0	partial load coefficient
Δ_g	joint opening
$\Delta_{g,d}$	design joint opening
ε	degradation coefficient of EPDM materials
$\tilde{\varepsilon}_c^{in}$	inelastic strain of the concrete
$\tilde{\varepsilon}_t^{ck}$	cracking strain of the concrete
μ_c	viscosity parameter of the concrete
ξ_a	aperture ratio of the gasket
ξ_c	closed-hole ratio of the gasket
ξ_g	gasket-in-groove ratio of the gasket
σ_c	compressive stress of the concrete
σ_t	tensile stress of the concrete
ψ	dilation angle of the concrete

example, a recent field observation on a segmental tunnel subjected to an unexpected extreme surcharge indicated that the joints had been damaged (i.e., excessive joint opening-rotation and water leakage), even though the lining rings still maintained structural integrity (Huang et al., 2016). According to the findings of Dammyr et al. (2014), the typical leakage points in the entire tunnel linings are located at segmental joints, grouting sockets and cracks in the concrete segment, as illustrated in Fig. 1. In practice, most of the leakage is observed at segmental joints (Wang et al., 2011; Wu et al., 2011; 2014). The state-of-the-art solution against the groundwater ingress is to use gaskets to seal the joint. Therefore, it is of great significance to reveal the leakage behavior of the gasketed joint to ensure the serviceability of the tunnel structure. Although a thorough understanding of all the leakage points is very important, it is a comprehensive research field, and it is beyond the main scope of this paper to go into details on segment cracking and related leakage behavior.

Compared to the large number of publications regarding the structural behavior of the segmental joint, very limited attention has been paid to its sealant behavior. Shalabi et al. (2012) conducted an experimental investigation on the leakage performance of gasketed joints of Los Angeles Metro tunnels subjected to typical design seismic loads. The waterproof capacity of the joint was found to be improved with increased gasket-groove bonding under cyclic loading. Potential leakage channels include the gasket-to-groove interface, cracking zones around the groove and bolt pockets. This pioneering work highlights the necessity of joint waterproofness during the design stage.

In this study, an innovative testing apparatus developed by the authors was used to investigate the sealant performance of gasketed joints in a precast shield tunnel on the basis of 7 gasket profiles. The tested gaskets were manufactured by ethylene-propylene-diene-monomer (EPDM) rubber compounds. Additional details on the testing methodology of the apparatus are available in a companion paper (Ding et al., 2017). The companion paper has published some preliminary experimental observations, but a detailed and further interpretation on the sealant performance of the gasketed joint is still lacking.

Looking at these challenges, this paper presents a combined experimental and computational study on the coupled sealant and mechanical behavior of seven EPDM gasket-based joints for the Nanjing Weisan Road Tunnel in China. The goal of this study is threefold: (1) to determine the design criteria for the waterproofness of gasketed joints; (2) to present a detailed parametric study that examines the effects of controlling variables on the initial sealant state of the gaskets; and (3) to propose a practical design formula that can be used to describe the sealant behavior of gasketed joints under pressurized water on one side.

The remainder of this paper is organized as follows. A brief introduction and the design criteria of the prototype, i.e., Nanjing Weisan Road Tunnel, is presented in Section 2. Next, in Section 3, the experimental program is introduced and includes the test matrix, setup and instrumentation. The experimental results are interpreted in Section 4. The details of the finite element model, its verification, and the findings

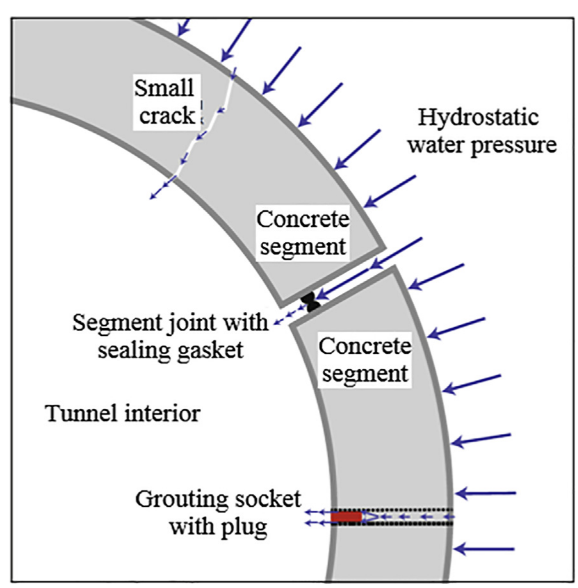

Fig. 1. Illustration of leakage points in the precast tunnel (re-annotated based on Dammyr et al. (2014)).