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Comparison of the structural behavior of reinforced concrete and steel fiber reinforced concrete tunnel segmental joints

Chenjie Gong[a,b,c], Wenqi Ding[a,b,*], Khalid M. Mosalam[c], Selim Günay[c], Kenichi Soga[c]

[a] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China
[b] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China
[c] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA

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ABSTRACT

Segmental joints act as a weak link in the tunnel lining both in terms of structural responses (due to the lower stiffness and strength compared to the main segments) and the serviceability considerations (high risk of water/gas leakage). Despite the wide applications of steel fiber as an alternative material due to the corrosion resistance and the labor reduction in shield tunnel engineering, very limited studies focus on the structural performance of segmental joints with steel fiber reinforced concrete (SFRC). In this paper, full-scale tests were conducted to study the ultimate bearing capacity of the conventional reinforced concrete (RC) and the SFRC joints under different loading conditions with a special attention on the corresponding cracking process. The experimental results demonstrated that the peak load bearing capacity of the SFRC joints was slightly higher than that of the RC joints. Furthermore, SFRC joints provided higher initial cracking load, sufficient ductility in the compressive-flexural actions, equivalent energy absorption capacity at initial cracking, and significant reduction in crack width compared to that of the RC joints. The performance-based engineering (PBE) concept was introduced to assess the robustness of the tested joints. According to these results, it is suggested that the SFRC can substitute the traditional reinforcement in terms of maintained bearing capacity and improved cracking control. Finally, it was verified that the classical joint design method was able to capture the flexural capacity of the tested RC and SFRC joints.

1. Introduction

The mechanized tunnelling technology has been commonly used in tunnel construction both in the soft and hard ground conditions, due to various advantages (e.g., safety, high efficiency, slight environmental disturbance and reduced labor). The tunnel linings are constructed in a circular or other shape (e.g., double circular, mixed, rectangle) using the tunnel boring machine (TBM). The tunnel linings consist of several precast segments connected by bolts. The segment is usually reinforced with conventional steel bars to withstand both the outer and inner loadings. According to a technical report published by the International Tunnelling and Underground Space Association (ITA, 1991), conventional precast concrete segments reinforced with steel bars are typically vulnerable to corrosion, which may lead to concrete spalling and associated loss of structural capacity. Moreover, tunnel segments are subjected to tension during the transitional stages (i.e., demoulding, storage, transport, and fabrication), which may contribute to the occurrence of cracking and reduction in the reliability of maintenance. These issues can be mitigated with steel fiber reinforced concrete (SFRC) since the fiber reinforcement can increase the toughness, enhance the cracking-control capacity and the consequent enhancement of corrosion resistance. On the other hand, the strength can be maintained (or even enhanced) with acceptable ductility. Hence, partial or even complete replacement of the conventional steel bars by the steel fibers demonstrates the applicability and popularity in engineering practices from an economical and technical viewpoint. Table 1 lists the representative shield/TBM tunnel applications using precast SFRC segments worldwide.

The research concerning SFRC originated from the 1960s. Since then, extensive studies have been conducted to provide a better understanding of its material properties and mechanical performance. Several standards and codes are available to guide the design of the fiber reinforced concrete (e.g., CNR-DT204, 2006; JGJ/T, 2010; Model Code, 2012; ITA, 2015; ACI, 2016). Among them, the ITAtech report (2015) provides a comprehensive guidance on the use of fiber reinforcement for its application in the shield/TBM tunnel engineering. The academia also conduct systematical studies on the SFRC applications. Table 2 summarizes a classification of previous research on this

* Corresponding author at: Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China.
E-mail address: dingwq@tongji.edu.cn (W. Ding).

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Nomenclature

a_2^*	dimensionless coefficient
b_2^*	dimensionless coefficient
G	segment gravity
H	segment thickness
H_t	tunnel depth
J	joint toughness
J_{cr}	joint toughness at cracking
J_u	joint toughness at ultimate load
K_0	lateral earth pressure coefficient
L	segment length
$L1$	horizontal distance from the joint section to the vertical load
M	joint bending moment
M_A	joint bending moment caused by vertical and horizontal loads
M_B	joint bending moment caused by gravity load
M_{cr}	joint cracking bending moment
M_{gd}	joint bending moment at gasket detaching
M_{open}	joint bending moment at the end of joint full-section closure
M_u	joint ultimate bending moment
N	horizontal load applied by the lateral actuators
P	vertical load applied by the vertical actuators
P_{cr}	cracking load
P_{gd}	load at gasket detaching
P_{open}	load at the end of joint full-section closure
P_u	ultimate load
R	external tunnel radius
w	crack width
w_{cr}	crack width at cracking
w_u	crack width at ultimate load
γ	soil unit weight
δ	joint deflection
δ_{cr}	joint cracking deflection
δ_{gd}	joint deflection at gasket detaching
δ_{open}	joint deflection at the end of joint full-section closure
δ_u	joint ultimate deflection
ε_y^b	bolt yield strain
ε_u^b	bolt ultimate tensile strain
ε_t^c	ultimate tensile strain of the concrete
η	reduction factor for bending stiffness of homogeneous lining rings
θ	joint rotational angle
θ_{cr}	joint cracking rotational angle
θ_{gd}	joint rotational angle at gasket detaching
θ_{open}	joint rotational angle at the end of joint full-section closure
θ_u	joint ultimate rotational angle
μ_δ	joint deflection ductility index
μ_θ	joint rotation ductility index
σ_v	vertical earth stress
φ	angle measured counter clockwise from the right spring line around the tunnel
$\Delta 1$	joint opening change in the extrados face
$\Delta 2$	joint opening change in the intrados face
Δ_{cr}	joint net opening amount at cracking
Δ_{gd}	joint net opening amount at gasket detaching
Δ_{open}	joint net opening amount at the end of joint full-section closure
Δ_u	joint ultimate net opening amount

Glossary of technical abbreviations

2D	two dimensional
3D	three dimensional
CFRC	conventional fiber reinforced concrete
COV	coefficient of variation
DAUB	german tunnelling committee
EPDM	ethylene-propylene-diene-monomer
FRHPC	fiber reinforced high performance concrete
HFRC	hybrid fiber reinforced concrete
HPC	high performance concrete
HS	hybrid simulation
ITA	International Tunnelling and Underground Space Association
PBE	performance-based engineering
PBEE	performance-based earthquake engineering
PC	plain concrete
PEER	Pacific Earthquake Engineering Center
RC	reinforced concrete
SCFRC	self-compacting fiber reinforced concrete
SFRC	steel fiber reinforced concrete
SLS	serviceability limit state
TBM	tunnel boring machine
UHPFRC	ultra high performance fiber reinforced concrete
ULS	ultimate limit state

subject.

As shown in Table 2, experimental, numerical, analytical or a combination of these approaches are used to study the production, design methodology, dosage optimization, structural behavior of SFRC segments in the serviceability limit state (SLS) and the ultimate limit state (ULS), and soil-structure interaction. The fiber dosage ranges from 25 to 120 kg/m^3 and concrete grade ranges from normal concrete C30 to high performance concrete C150. The experiments were conducted using full-scale or reduced-scale segments. Calibrated numerical simulations were ran for the purposes of parametric investigation and design recommendation.

Most of the previous research focused on the tunnel segment and neglected the tunnel joint. The segmental joints are the vulnerable points in the entire tunnel structure, because the joints provide considerably smaller bending capacity than the main segments (ITA, 2000; Ding et al., 2004, 2013; Li et al., 2014). Reduced-scale and full-scale tests (Feng et al., 2013; Li et al., 2014; Liu et al., 2015) have verified that the progressive failure of the tunnel linings is initiated by the joint damage. The joints are also proved to be the potential water-leakage points (ITA, 1991; Shalabi et al., 2012; Ding et al., 2017; Gong et al., 2017).

Yan et al (2016) tested the structural behavior of SFRC segmental joints in fire under different loadings and boundary conditions. This study puts more emphasis on the fire effects on the joint response with the objective of checking the fire resistance. Less attention has been paid to failure modes and mechanisms. Another issue worth mentioning is that 1/3 reduced-scale segments were adopted. Wood (2003) indicates 'The proper use of scaling laws is essential to physical modeling'. The tunnel joint in practice incorporates complex details and configurations (i.e., caulking groove, gasket groove, sealing gasket, hand hole, bolts, utility openings, and guidance rod). Selection of the correct scale factor requires further investigation and verification. Therefore, an in-depth understanding of the realistic structural behavior and failure mode of SFRC joints in shield tunnels is imperative.

The main objective of this paper is to experimentally investigate the structural behavior of SFRC tunnel segmental joints subjected to both positive and negative bending moments under constant axial force states. Special attentions are paid to the cracking process and associated