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Behavior of reinforced concrete and steel fiber reinforced concrete shield TBM tunnel linings exposed to high temperatures

Zhi-guo Yan [a,b], He-hua Zhu [a,b,*], J. Woody Ju [c]

[a] Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
[b] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, 1239 Siping Road, Shanghai 200092, China
[c] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

HIGHLIGHTS

- ▶ RC and SFRC shield TBM tunnel linings were tested under a HC fire load.
- ▶ Initial loads greatly affect the behavior of the lining segments.
- ▶ Coupled thermal–mechanical effects cause notable internal force redistribution in lining rings.
- ▶ Lining joints play a critical role in the performance of shield TBM tunnel linings.

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ABSTRACT

This paper presents comprehensive experimental test results on the behavior of the reinforced concrete (RC) and the steel fiber reinforced concrete (SFRC) shield TBM (Tunnel Boring Machine) tunnel lining segments and the lining rings exposed to a HC (Hydrocarbon) curve. The experimental results indicate that the nonlinear nonuniform temperature distribution within the concrete linings causes significant nonuniform thermal expansion and material property degradation. The initial loads exert significant effects on the behavior of the lining segments, whose performance was remarkably deteriorated in the fire. The coupled thermal–mechanical effects, induced by the nonuniform thermal expansion, the deterioration of material properties and the interaction between adjacent member segments, lead to considerable deformations of the lining rings, dynamic internal force redistribution and reduction of load bearing capacity. The lining joints play a critical role upon the behavior and the failure pattern of the lining rings. Based on our test results, the RC linings perform better than the SFRC linings under intensive tunnel fire. Other notable, new observations and behavior are also presented in this work.

1. Introduction

With characteristics of high peak temperature, rapid heating rate, long duration and nonuniform temperature distribution inside tunnels, a number of tunnel fire accidents (e.g., the Great Belt Tunnel, the Channel Tunnel and the Mont-Blanc Tunnel) indicated that fires can result in extensive and severe damages to concrete tunnel linings [1]. These damages in mechanical property deterioration of concrete, thickness reduction of linings due to concrete spalling and nonuniform thermal stress severely reduce the concrete lining safety, threaten future safe operation and even cause the tunnel lining collapse. Specifically for the concrete shield TBM (Tunnel Boring Machine) tunnel lining in soft ground with high water pressure, fire damages may also lead to seal failure of the lining joints, resulting in tunnel leakage or gushing water. In addition, considering that the shield TBM tunnel lining is a hyperstatic structure assembled by several member segments that are connected to one another by lining joints, its behavior and failure mechanism under high temperature are complicated. As a weak link of the tunnel lining due to its low stiffness and high risk of water leakage, the lining joint may significantly affect the behavior of the shield TBM tunnel lining exposed to high temperature.

Considerable prior studies had been conducted on fire damages to lining concrete [2–7], effective methods to prevent concrete thermal spalling [4–9] and numerical simulations on the behavior of the concrete linings under fire load [10–15]. In these studies, Caner and Böncü [6] performed hydrocarbon fire tests on an isolated K segment of a shield TBM tunnel in an unloaded state to investigate fire damage to the segment concrete. Yan et al. [7] carried out full-scale experiments to investigate fire damage to the actual rein-

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
E-mail address: zhuhehua@tongji.edu.cn (H.-h. Zhu).

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forced concrete (RC) metro shield TBM tunnel linings that are exposed to a standard ISO834 curve, and to develop a feasible method to improve the fire safety of existing metro shield TBM tunnel linings. Yasuda et al. [8] conducted a full-scale fire test to determine appropriate fire protection measures for shield TBM tunnel composite segments under a RABT (Richtlinien fuer Ausstattung und Betrieb von Strassentunneln) fire curve. Savov et al. [10] performed a numerical analysis on the stability of a shallow NATM (New Austrian Tunneling Method) tunnel lining under fire load based on an expanded multilayer beam model. Pichler et al. [11] numerically investigated the structural safety of the polypropylene fiber reinforced concrete tunnel lining of the Lainzer Tunnel subjected to fire load, employing thermo-chemo-mechanical material models. Zeiml et al. [12] conducted a coupled thermo-hygro-chemical analysis, simulating the heat and mass transport in concrete under fire load, and studied the fire safety of the Lainzer Tunnel. Caner et al. [13] developed an analytical method that combined a heat transfer analysis and a nonlinear structural analysis to evaluate the performance of a concrete or a shotcrete tunnel lining in fire. Moreover, Caner and Böncü [6] analyzed the fire safety of a circular concrete railroad tunnel lining under HC (Hydrocarbon) and RWS (Rijkswaterstaat) loads. Park et al. [14] conducted a 2D finite element analysis on the damage and safety of the box structure of the Daegu subway after a fire accident. Feist et al. [15] developed a numerical model to evaluate the load-carrying behavior of a fire exposed reinforced concrete structure and applied the technique to evaluate the fire response of a cut-and-cover tunnel structure. Furthermore, several guidelines, directives and specifications were issued, which provided recommendations and requirements on the fire safety of the tunnel linings [16–18]. However, little research was documented on the mechanical behavior of the shield TBM tunnel lining in a fire, especially for the complete shield TBM tunnel lining ring with lining joints; most previous works involved numerical analysis and laboratory experimental test results remain inadequate. On the other hand, the steel fiber reinforced concrete (SFRC) has been increasingly applied to the tunnel linings [19], as its use improves tensile strength and ductility, reduces cracking and crack propagation and lowers permeability of the concrete at ambient temperature. Nevertheless, little investigation has been documented on the behavior and the feasibility of the use of SFRC shield TBM tunnel lining under high temperature. Therefore, it is essential and beneficial to experimentally investigate the behavior of the RC and the SFRC shield TBM tunnel linings under different thermal–mechanical conditions.

In this paper, we present comprehensive experimental test results on the behavior of the RC and the SFRC lining segments and the lining rings under the standard HC curve. The present study contributes to an improved understanding of the complex behavior of the shield TBM tunnel linings under high temperatures, and to an improved analytical/numerical model of the coupled thermal-hygro-mechanical performance of the underlining problems and engineering applications.

2. Experimental test program

2.1. Design and fabrication of test specimens

Given that the behavior of an isolated segment may not fully reflect the behavior and the performance of the complete tunnel lining in a fire [20], the laboratory experimental tests are conducted at both the isolated segment level and the complete lining ring level. It is notable that there will be the longitudinal restraint to the thermal expansion and displacement of the tunnel lining in the lateral direction in reality. In this paper, since we focus on clearly investigating the lateral response of the isolated lining segment and the single lining ring under high temperature, these longitudinal restraint induced by adjacent lining rings is not considered.

Small scale specimens are employed in our tests here based on the following considerations: (a) although small scale specimens may not be quantitatively representative of the real large scale tunnel linings due to possible size effects, the key characteristics and response of the tunnel linings exposed to high temperature such as thermal expansion, variation and redistribution of internal forces and fire damages can be reasonably investigated when the key structural features and thermal–mechanical conditions of the shield TBM tunnel lining are carefully considered in the tests, and (b) it is overly time-consuming and cost-prohibitive to carry out a comprehensive series of coupled thermal–mechanical fire tests on the full-scale tunnel linings adopted in construction projects. The lining segments here are 300 mm in width and 120 mm in thickness; their average radius is 990 mm, cf. Fig. 1. According to the realistic metro shield TBM tunnel lining, the hand hole, the longitudinal and the circumferential tongue and groove of the lining segment are designed and fabricated. Each of the lining rings is assembled by four lining segments, which are connected by two curving steel bolts (10 mm in diameter) at each of the four joints (cf. Fig. 2). The diameter of the lining rings is 2100 mm.

The plain concrete composition is shown in Table 1. The steel fiber utilizes the HAREX® cold-drawing steel wire fiber with hooked-end; its length–diameter aspect ratio is 55 and the fiber volume fraction is 0.8%. The measured standard cube strengths of the plain concrete and the steel fiber reinforced concrete at the ambient temperature are 53.5 MPa and 57.1 MPa, respectively, at 28 days. Furthermore, for the RC lining segments and the RC lining rings, the reinforcements (hot-rolled rebars) are installed with 15 mm concrete cover thickness (cf. Fig. 1).

To ensure the production quality, concrete mix design and production, specimens casting and curing, all concrete works have been conducted by a professional concrete plant. The concrete age of the specimens at the time of the experimental tests is listed in Table 2.

2.2. Test procedure and set-up

An international standard HC curve is employed in the experimental tests to simulate the heating phase [16]; see following equation:

$$T(t) = 20 + 1080\,(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) \quad (1)$$

where t is time (in min) and $T(t)$ is the gas temperature inside the furnace (in °C).

The peak temperature inside the furnace is 1100 °C, and the heating duration is 60 min. Subsequently, taking into account the cooling phase of a actual fire [20], the furnace is turned off, and the specimens are gradually cooled to the ambient temperature. The comparison between the measured temperature curve and the HC curve is displayed in Fig. 3. We observe that the measured temperature is slightly lower than the HC curve within a short duration. Since the maximum error is small and the time duration is short, this difference may exert an insignificant influence upon the documented test results.

To simulate the thermal boundary condition of the actual tunnel lining, the heating surfaces of the lining segments are uniformly exposed to the fire, and the unexposed surfaces are covered by 20 cm thick soils to reflect the heat transfer between the tunnel lining and the surrounding ground (cf. Fig. 1). The soils used in the tests are typical soft saturated clay of a shield TBM tunnel construction site in East China. For each of the lining rings (cf. Fig. 2), the upper zone is defined as the uniform heating zone (UHZ), where the heating surface of the lining ring is uniformly exposed to the fire; and the under zone is termed the ambient temperature zone (ATZ) maintaining ambient temperature in the tests. The unexposed surfaces of the lining rings are covered by soils as well.

As exhibited in Fig. 1, both ends of the lining segments are fixed with the exception of rotation. Based on the load equivalent principle and the mechanical characteristics of the tunnel lining, the point loading strategy is employed in the tests to facilitate the loading control and to highlight the thermal–mechanical effects on the tunnel linings under high temperatures. It is notable that the soil pressure loaded to the tunnel lining is continuous in reality, thus the point loading is not completely representative of the soil structure interaction. For the lining segments, the vertical load (P_v^s) is applied by a hydraulic jack at the two points. For the lining rings, the vertical loads (P_v^r) and the horizontal loads (P_u^r) are applied by hydraulic jacks at the center of each of the member segments to simulate the ground pressure (cf. Fig. 2). To investigate the effect of the joint position on the behavior, the loading positions of the vertical loads and the horizontal loads of the lining ring, RC R-3, are adjusted to the lining joints by rotating the lining ring, RC R-3, 45° clockwise around its center.

Two types of loading cases are employed in the experimental tests as follows (cf. Table 2):

(a) The loading case LC_s-A or LC_r-A: The lining segments or the lining rings are heated without the initial loads (P_{v0}^s, P_{v0}^r and P_{u0}^r).> After approximately 60-min duration of heating, the specimens are loaded to investigate the ultimate loads during high temperature. The lining segments are loaded by increasing the vertical load. Furthermore, the lining rings are loaded by simultaneously increasing the vertical and the horizontal loads; the ratio of the horizontal load to the vertical load is kept at 0.7 to reflect a common ratio of horizontal ground pressure to vertical ground pressure in soft soils.
(b) The loading case LC_s-B or LC_r-B: The lining segments or the lining rings are heated with the initial loads; the initial loads are kept constant in both the heating and cooling phases. After complete cooling, the specimens are