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Experimental study of tunnel segmental joints subjected to elevated temperature

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Segmental joints present a weak link in the tunnel lining both structurally (due to its low stiffness) and non-structurally (high risk of water leakage); therefore the behaviour of the lining joints has a significant effect on the performance of the shield TBM tunnel lining. Segmental joints are thus a particular concern when the tunnel lining is exposed to high temperature in the case of a tunnel fire. This paper presents an experimental study on the behaviour of TBM tunnel joints in fire under different mechanical loading and boundary conditions, and with both the normal reinforced concrete (RC) segments and hybrid fibre reinforced concrete (HFRC) segments. Totally thirteen jointed specimens were constructed at a scale of 1:3 and tested. Eleven specimens were exposed to a HC (Hydrocarbon) curve and mechanically loaded to failure either under-fire or post-fire, while two specimens were tested in ambient temperature to provide benchmark data. The results demonstrate that the initial loading conditions have a significant effect on the jointed segments during and after fire, and this is closely related to different rate of degradation of concrete in different stress state under high temperature. In general, the resistance capacity of both RC and HFRC joints increased with axial force. The use of HFRC material provided good spalling resistance.

1. Introduction

In 2005, a small fire broke out in a shield TBM (Tunnel Boring Machine) tunnel construction site of Shanghai Metro Line 8. The upper part of about 430-m long tunnel lining segments was affected by elevated temperature. More seriously, concrete spalling damage occurred in a region of 16.8 m long, and the maximum damage thickness of the lining concrete was 25 mm (Yan et al., 2012). The incident reminds the engineering community that tunnel fire is a real risk not only to the safety of tunnel users but also to the structural integrity of the tunnel itself. As a matter of fact, several major tunnel fires occurred in the past and they involved severe damage to the tunnel structure in addition to human casualties. Table 1 gives a list of over a dozen of major tunnel fire accidents throughout the world in the last few decades.

The shield TBM tunnel lining is a special steel–concrete composite structure assembled by individual member segments through lining joints. As a weak link of the tunnel lining due to its low stiffness, and a major source of water leakage, the behaviour of the lining joints significantly affects the performance of the shield TBM tunnel, and it is even more so in the event of high temperature. For instance, in the case of metro shield TBM tunnel linings in soft ground with high water pressure, fire can trigger the failure of the joint seal, causing tunnel lining leakage and even water gushing into the tunnel.

Most previous studies on the TBM tunnel joints have been concerned with the mechanical behaviour of the joints under ambient temperature. Jointed lining has a smaller maximum bending moment capacity than non-jointed lining (Teachavorasinskun and Chub-Uppakarn, 2010). With a certain level of the bending moment a loss of contact can develop on one side of the joint, and this results in nonlinear behaviour which is closely dependent on the axial stress (Arnau and Molins, 2011; Blom, 2002; Molins and Arnau, 2011). The development of the opening angle of the joint affects the rotational stiffness of the joint (Do et al., 2013). The load eccentricity is also a key parameter affecting the capacity of the joint. In cases where failure is governed by the maximum compressive stress of the concrete in the compressive zone of the joint, ultimate loads decrease as the load eccentricity increases (Zhang and Koizumi, 2007).

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Table 1
Major tunnel fire accidents.[a]

Year	Tunnel	Country	Fatalities and injured	Structure damage	Accident type
1968	Moorfleet	Germany	–	Serious damage on vault and side wall	Car accident
1994	Hugouenot	South Africa	59	Serious damage on tunnel lining	Bus accident
1994	Great Belt	Denmark	–	Widespread damage on tunnel region	Construction turnover
1996	Channel Tunnel	Britain–France	–	Widespread damage on tunnel region	Cargo fire
1999	Mont Blanc	France–Italy	38	Serious damage on tunnel lining	Cargo fire
1999	Tauren	Austria	12	Serious spalling on tunnel lining	Multi-car collision
2001	Gothard	Switzerland	21	Part of tunnel vault collapsed	Two trucks collision
2002	A86 Road Tunnel	France	–	Serious spalling on tunnel lining	Construction turnover
2004	Takayama	Japan	5	Surface concrete damage	Collision
2005	Fréjus	France–Italy	23	Serious damage on tunnel lining	Car accident
2011	Xinqingdaoliang	China	5	Widespread damage on tunnel region	Shunt
2014	Yanhou	China	31	Serious damage on tunnel lining	Collision

[a] This list is based on data from the following sources: Cafaro and Bertola (2010), Haack (2002, 2004), ITA (2005), Khoury (2000), Kim et al. (2010), Leitner (2001), Park et al. (2006), Schrefler et al. (2002), and Vianello et al. (2012).

For tunnel joints in a fire condition, only limited research work has been reported in the literature. From a full-scale experiment on actual RC metro shield TBM tunnel linings exposed to a standard ISO834 curve (Yan et al., 2012), it was found that the opening angles and gaps of the tunnel lining joints considerably increased while the flexural stiffness of the tunnel lining joints deteriorated under elevated temperatures. In another experimental study (Yan et al., 2013), models of jointed shield TBM tunnel lining rings were tested under a HC (Hydrocarbon) curve. The results indicated that the behaviour and configuration of the lining joints had a significant effect on the mechanical performance, the dynamic internal force redistribution, and the failure pattern of the lining rings when exposed to high temperature. The tests included RC and steel fibre reinforced concrete (SFRC) segments, but only three specimens were tested for each of these two materials.

Many factors contribute to the deterioration of a tunnel lining structure in fire, and concrete spalling and material degradation are two major factors. In recognition of this, attention has been brought to the use of hybrid fibre reinforced concrete (HFRC) with a mixture of steel and polypropylene (PP) fibres. PP fibres melt at approximately 160–170 °C; although this would result in a certain reduction in the residual strength of the composite material, the melting of the PP fibres within the heated concrete is believed to mitigate the buildup of pore pressure and thus improve the spalling resistance of the concrete material (Chen and Liu, 2004; Kalifa et al., 2001; Pliya et al., 2011; Suhaendi and Horiguchi, 2006). The complementary functions of polypropylene fibres (improving spalling resistance) and steel fibres (ensuring ductility and crack resistance) make HFRC a promising composite material for a desirable fire performance (Yan et al., 2013; Rodrigues et al., 2010).

The work presented in this paper is focused on the experimental behaviour of TBM tunnel joints in fire under different mechanical loading and boundary conditions, and with both RC and HFRC materials. Totally thirteen tunnel joint specimens at a scale of 1:3 were constructed and tested, including six RC specimens and seven HFRC specimens. Eleven of the specimens were exposed to a HC (Hydrocarbon) curve, while two were tested in ambient temperature to provide benchmark data. Among the eleven specimens exposed to fire, six were loaded to failure under fire, and five were loaded post fire. Other parameters investigated include the initial loading condition and the level of the axial force.

2. Experimental program

2.1. Materials and specimens

The standard configuration of the test specimens was an assembly of two lining segments connected to each other by bolts as in a real tunnel lining ring. Reduced scale (1:3) specimens were employed in the experiments. This scale level allows the use of normal RC and HFRC materials with realistic segment details, and at the same time reduces the demands on the test facilities considerably.

The test lining segments were 300 mm in width and 120 mm in thickness. The arc length of each segment was 1.53 m, and the average radius was 990 mm, cf. Fig. 1. To match an actual metro shield TBM tunnel lining segment, details of the hand hole, the longitudinal tongue and groove of the lining segment were retained in the test specimens. The connection between the two segments was made by two curved M-10 Grade-5.8 bolts. Some non-structural details in the real tunnel lining, such as the rubber waterstop and flexible gasket of the lining joints, were omitted.

The mix design of the plain concrete is shown in Table 2. The properties of the polypropylene (PP) and steel fibres as provided by the manufacturer are presented in Tables 3 and 4, respectively. In the HFRC specimens, the volume fraction of steel fibre and PP fibre was 78 kg/m^3 and 2 kg/m^3, respectively. The choice of a relatively high steel fibre volume was made in order to ensure an appropriate level of the flexural strength in the absence of main steel reinforcement. According to some previous research on HFRC (Libre et al., 2011), the volumetric ratio of the steel fibres in the present study is still within a practical limit. The measured standard cube strengths of the plain concrete and the hybrid fibre reinforced concrete, tested at the age of 28 days under ambient temperature, were 69.8 MPa and 61.1 MPa, respectively. Furthermore, for the RC lining segments, the main reinforcing bars (hot-rolled rebar) were 10 mm in diameter and the concrete cover was 15 mm thick (cf. Fig. 1).

To ensure consistent production quality, all test segments were fabricated by a professional concrete plant. The age of the concrete at the time of testing the specimens is listed in Table 5.

2.2. Test procedure

A newly-developed thermo-mechanical test system for tunnel lining segments under elevated temperatures, as shown in Fig. 2, was used for the experiment. This system contains two combustors of industrial grade, and the heating-up procedure can be controlled automatically by a programmable controller. The peak temperature in the furnace can reach 1200 °C and the maximum heating rate is about 250 °C/min. The whole system is capable of simulating different fire scenarios, including high rate heating and high peak temperature, while the test specimens can be subjected to different mechanical loading and boundary conditions.

An international standard HC curve was employed in the experiment to simulate the heating phase of a fire (CEN, 2002), which may be expressed as: