Tunnelling and Underground Space Technology 71 (2018) 180–192

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

On the behavior of radial joints in segmental tunnel linings

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ARTICLE INFO

Keywords:
Segmental tunnel linings
Radial joints
Experimental tests
Analytical procedure

ABSTRACT

Radial joints are defined as the contact part between precast segments in each ring of mechanical excavated tunnel lining. The behavior of flat radial joints without connectors is investigated in this paper through full-scale experimental tests on fiber reinforced concrete elements without any traditional reinforcement. The tests were performed by imposing a joint opening, as typical can occur when higher level of ovalization in the lining are required. The results showed the effect of concrete crushing as well as the bursting phenomena. Finally, an analytical interpretation of the behavior is presented, providing useful information that can support the design of this type of joints.

1. Introduction

The behavior of radial joints in concrete precast tunnel lining is become of interest in the last years. Radial (or longitudinal) joints are the connection part between the segments in the lining ring as well as the circumferential joints link the different rings (Fig. 1). Among the several typologies of radial joints, the most used are the flat and convex ones, even if most of the tunnels are nowadays considering the flat joint solution only. Furthermore, connecting systems can be adopted in radial joints, typically using bolts. These connectors can be temporary placed for helping the installation of the segment or can be permanent. A solution with flat radial joint with no connecting system is anyway widely used in tunnels. This last solution is investigated herein.

The knowledge of the behavior of the radial joints is important at different steps of tunnel design. The stiffness of the joints is important for evaluating the geotechnical actions on the lining as well as the evaluation of the bearing capacity of the joint is necessary for the structural lining design.

The effects of the radial joints on the local and global behavior of tunnel segments is of topical interest, mainly in these last years, as witnessed by the studies available in literature, based on theoretical and experimental evaluations. The classical models account for the radial joints behavior through rotational springs, and are mainly devoted to the evaluation of the related stiffness (Janssen, 1983; ITA, 2000; Lee and Ge, 2001; Lee et al., 2001; Blom, 2002; Koyama, 2003; Ding et al., 2004; El Naggar and Hinchberger, 2008; Teachavorasinskun and Chub-uppakarn, 2010).

Experimental test methodologies and results are presented in different papers. Li et al. (2015) carried out full-scale tests with the aim of investigating the longitudinal joint opening at the Ultimate Limit State (ULS). The system, composed of two segments with a bolted joint, was subjected to both sagging and hogging bending moment, under different axial stress levels.

The mechanical behavior of the segment joint in a water conveyance tunnel was studied by Ding et al. (2013), through experimental bending test set-up able to simulate both the external loads and the internal water pressure during the tunnel's service life. More recently the same problem was faced by Jin et al. (2017) with bending tests on segmental joints, accounting for the influence of the axial force on the rotational behavior of joints. A comparison between the experimental structural response of Reinforced Concrete and Fiber Reinforced Concrete joints was recently presented in Gong et al. (2017).

A full-scale test facility for the study of the whole ring, with particular reference to the joints behavior, was designed and developed at the TNO Delft University (Blom, 2002; Luttikholt, 2007). Three vertical oriented rings with varying positions of the radial joints were loaded in radial and axial direction. A similar test set-up was adopted by Liu et al. (2017), for the evaluation of the structural bearing capacity of stagger joint assembled shield tunnels. Finally, Arnau and Molins (2011a) performed in-situ full scale tests on whole ring of the Barcelona Metro Line.

Numerical models are proposed in (Arnau and Molins, 2011b; Do et al., 2013; Li et al., 2014). Recent studies also focus the sealant or waterproof behavior of the joint (Shalabi et al., 2012; Ding et al., 2017).

Joint opening could be a consequence of loading effect, and also could be caused by imperfections and/or construction errors. This latter

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http://dx.doi.org/10.1016/j.tust.2017.08.022
Received 3 February 2017; Received in revised form 16 August 2017; Accepted 17 August 2017
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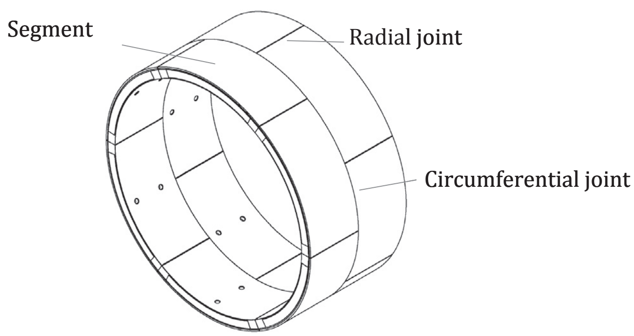

Fig. 1. Radial and circumferential joints.

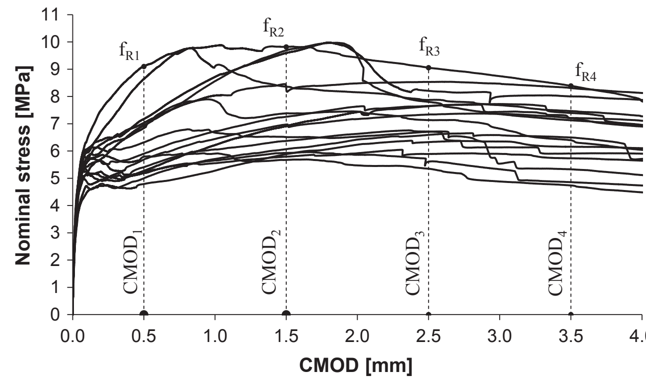

Fig. 3. Flexural tests for the FRC characterization in tension: Stress-CMOD curves.

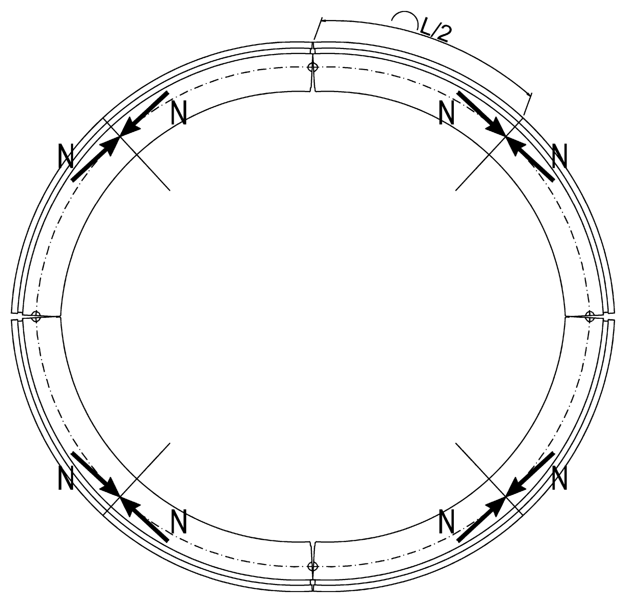

Fig. 2. Segment ovalization.

case is analysed in the paper, since in several tunnel projects, requirements on the lining ovalization are imposed in the design. These requirements can be obtained considering the ovalization due to the elastic deformation of the lining, with the reduced stiffness contribution of the joint that remain anyway in compression, or considering an opening in the joint (partial loss of contact). In this last case, the joint opening exists at first, and the hoop force, applied afterwards, is remarkably deviated in correspondence to the radial joints since it has to pass through the contact area (Fig. 2).

In this paper, the bearing capacity of opened radial joints is evaluated through full-scale tests, developed with the aim to simulate the contact between the precast segments. Tests were performed on fiber reinforced elements without any traditional reinforcement, since this solution is becoming widely adopted in tunnel design (Plizzari and Tiberti, 2008; Caratelli et al., 2011, 2012; De la Fuente et al., 2012; Di Carlo et al., 2016; ACI 544, 2016; ITA, 2016; ITATech, 2016). Furthermore, a formulation for evaluating the joint behavior, validated by test results, is provided, with the aim to support the design procedure. The proposed formulation can be extended to traditionally reinforced segments.

2. Tunnel and radial joint geometry

The loading tests, object of the present paper, aim simulating the behavior of the radial joints in the precast segmental lining of the Doha Red South Metro Line.

The tunnel was made with fiber reinforced concrete (FRC) with 40 kg/m^3 of steel fibers, without any traditional steel reinforcement. The average compressive strength measured on 150 × 150 × × 150 × mm^3 cubic specimens was equal to about 78 MPa. The tensile behavior was characterized through flexural tests on eighteen 150 × 150 × 600 mm^3 beams, in agreement with the MC2010 (2013). The obtained results, expressed in terms of Load-CMOD (Crack Mouth Opening Displacement) are shown in Fig. 3.

The internal and external diameters of the ring are equal to 6.17 m and 6.47 m, respectively (Fig. 3). Hence, the lining thickness is equal to 300 mm. Every ring, having a width of 1.6 m, is made of seven segments, as shown in Fig. 4.

Three joints were tested in the Laboratory of the University of Rome Tor Vergata, with the aim of simulating the radial joints behavior under different load and rotation conditions.

Prism specimens with height equal to 1.0 m (Fig. 5) were cast in fiber reinforced concrete. The geometry of the radial joint surface is illustrated in Fig. 6. Two prisms for every test were used in order to simulate the joint behavior. The height of the prism (1.0 m) is almost half of the segment length (L) in order to simulate the part of the lining (L/2) highlighted in Fig. 2.

3. Radial joint testing procedure

The test set-up, based on the use of a lateral steel frame, was properly designed in order to simulate the joint behavior under axial load combined with an imposed rotation at both the extrados and intrados surfaces (Fig. 7).

The initial rotation was given through two couples of dywidag rebars dywit WR47, with a nominal diameter of 47 mm, (see Figs. 7a, b and 8) pre-tensioned up to 300 kN and placed at the upper part of the upper segment and in the lower part of the bottom specimen. In order to impose this initial rotation, suitable thicknesses, working like supports, were placed between the specimens and the steel frame (A in Fig. 7a and b). Their distance (570 mm) was chosen, after preliminary tests, in order to avoid the concrete confinement and to not influence the formation of bursting cracks.

Once the rotation was given, the load (F) was applied through five 2000 kN jacks, up to the maximum value equal to 10.000 kN (Fig. 8).