Tunnelling and Underground Space Technology 64 (2017) 74–84

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Ultimate capacity of a segmental grey cast iron tunnel lining ring subjected to large deformations

S. Afshan [a], J.B.Y. Yu [b], J.R. Standing [c,*], R.L. Vollum [c], D.M. Potts [c]

[a] Brunel University London, UK[1]
[b] BuroHappold Engineering, UK[2]
[c] Imperial College London, UK

ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 4 November 2016
Accepted 14 January 2017
Available online xxxx

Keywords:
Bending moment
Experiment
Grey cast iron
Tunnel lining
Ultimate capacity

ABSTRACT

Understanding the behaviour of existing tunnels subjected to in-service deformations, as a result of the construction of underground works (e.g. new tunnels) in their proximity, is of importance in order to safeguard infrastructure within the urban environment. The associated deformations that take place during tunnelling have to be carefully assessed and their impact on the existing tunnels needs to be considered. A half-scale segmental grey cast iron (GCI) tunnel lining ring was tested as part of an extensive research project investigating the impact of new tunnel excavations on existing tunnels conducted at Imperial College London. A sophisticated experimental arrangement was developed to deform the ring in a variety of modes under combined displacement and load control. This paper reports on experiments carried out to assess its structural response when subjected to large deformations. The tests reported are the first to be conducted on a realistic scale model under carefully controlled conditions, and provide valuable insight into the behaviour of a GCI segmental ring during distortions commonly observed in reality. Details of the experiments, including the adopted test set-up and the instrumentation employed, are presented. The measured bending moments around the ring, as a result of the applied deformations, are determined and compared with those predicted using the well-known equations given by Morgan (1961) and Muir Wood (1975), often used in industry, as well as those obtained assuming an elastic continuous ring.

1. Introduction

With increasing exploitation of underground space within the urban environment, particularly for transportation infrastructure, there is frequently a need to excavate close to existing tunnels. In London, and other major cities, many of the existing tunnels were constructed more than a century ago, are lined with grey cast iron segmental linings and form part of dense underground transport systems. The trains that run within them often have a tight kinematic envelope and so minimising deformations from nearby excavations is crucial. It is equally important to understand the stress and bending moment regimes within the tunnels to assess how close they are to yielding or, in the extreme, failure. A comprehensive study by Imperial College London has investigated this complex boundary value problem through three main activities: (i) field monitoring of the ground and existing tunnels during nearby construction of the new Crossrail tunnels; (ii) performing sophisticated structural tests on a half-scale segmental lining and (iii) analysing the ground and structural elements using the Imperial College Finite Element Program (ICFEP). Further details of the research project and a summary of the main findings are given by Standing et al. (2015). This paper describes and presents results from the final stages of the second activity.

2. Experimental investigation

2.1. Overview

Achieving a detailed understanding of the development of stresses, bending moments and bolt forces as a tunnel lining deforms can only be assessed realistically using large-scale models. The philosophy with the test set-up used in the study described here was to use half-scale segments (the smallest size that could be cast such that true proportionality of all dimensions was possible) bolted together to form a ring which was deformed using a combi-

* Corresponding author.
E-mail address: j.standing@imperial.ac.uk (J.R. Standing).
[1] Formerly Imperial College London, UK.
[2] Formerly Crossrail Ltd and Imperial College London, UK.

http://dx.doi.org/10.1016/j.tust.2017.01.007
0886-7798/

nation of load and displacement control by means of actuators rather than soil. Prior to embarking on the half-scale set-up, the methodology was checked using a simplified small-scale model (Standing and Lau, 2017).

In the past, other researchers have used large- or full-scale segments to investigate lining response, usually with particular attention focussed on the behaviour and influence of the joints. In all cases, loads were applied directly (e.g. by pressure membranes, load actuators or tensioned tie rods) rather than via a soil medium. Leung (1967) and Thomas (1977) tested cast iron segments while more recently there have been investigations into concrete segments with traditional steel reinforcement (Mashimo et al., 2001, 2002; Blom, 2003; Bilotta et al., 2006; Okano, 2007; Cao et al., 2008). Full rings were tested in a number of these studies, the largest being the ring of 15 m outer diameter and 2 m width used to analyse the linings for the Shanghai Yangtze River tunnel (Cao et al., 2008). Such tests have also been performed to assess new materials such as fibre-reinforced concrete (Ahn, 2011; Blazejowski, 2012).

In this study, grey cast iron (GCI) half-scale lining segments were cast using a similar chemical composition to that of Victorian age GCI segments used in the London Underground (LU) network. The geometric details of the original segments were also carefully replicated. The adopted scale was dictated by the limitation of casting the thinnest part of the segments (the web/skin). Two principal test set-ups were developed and utilised in the structures laboratory at Imperial College London. The first was for performing two-segment tests, similar to those of Thomas (1977), with a primary aim of investigating joint behaviour; full details of the tests and their modelling assumptions using numerical analysis are reported by Yu (2014). The second involved a full ring, made up of six half-scale GCI segments bolted together, where two series of tests were performed to assess the ring's response when subjected to: (1) small elastic deformations; and (2) large plastic deformations, representative of the serviceability and ultimate limit states, respectively.

In these tests, the ring was first loaded radially to simulate ground stresses acting on the lining in situ (loads were applied uniformly in this stage). It was then deformed into elliptical shapes of similar form and magnitude to those observed in existing tunnels. A detailed description of the experimental set-up and the instrumentation employed along with the results of tests at small elastic displacement levels are given by Yu (2014) and Yu et al. (2017). This paper reports on the results of the tests on the full ring when it was taken to high strain levels and ultimate failure. Only a summary of key components of the experimental set-up is provided (details can be sourced in Yu, 2014 and Yu et al., 2017). The planning of the tests, the adopted loading procedure and how the bending moment distribution compares with those from prediction methods available are discussed in detail.

2.2. Test set-up and instrumentation

A total of six GCI segments, each with an arc length of approximately 1 m, were bolted together and placed on the floor in the Structures Laboratory, such that the radial plane of the ring was horizontal. The assembled model segmental lining ring had inner and outer diameters of 1.781 m and 1.905 m respectively and was 0.254 m in width. It rested on bearings to minimise friction and was surrounded by a steel reaction ring. Fig. 1 shows a schematic diagram of the test set-up used, with the various components annotated. Radial loading of the ring was achieved through a total of sixteen actuators, located at 20° intervals around the circumference of the ring. Spreader pads were used to distribute the load from the actuators to the extrados of the test segment. The actuators in Fig. 1 at 250° and 290° were replaced with reaction rods attached to spreader pads in order to prevent rigid body motion of the ring. Each reaction rod was fitted with a load cell. In addition, a tangential tie was fixed to the ring to further increase the overall stability of the ring against rotation.

Electrical resistance strain gauges were used to measure changes in strain on the surface of the GCI segments as a result of the applied loads and deformations. A combination of Tee rosette gauges and uniaxial strain gauges, orientated to measure the circumferential bending strains (the strain component used for determining the bending moments in the segments), were

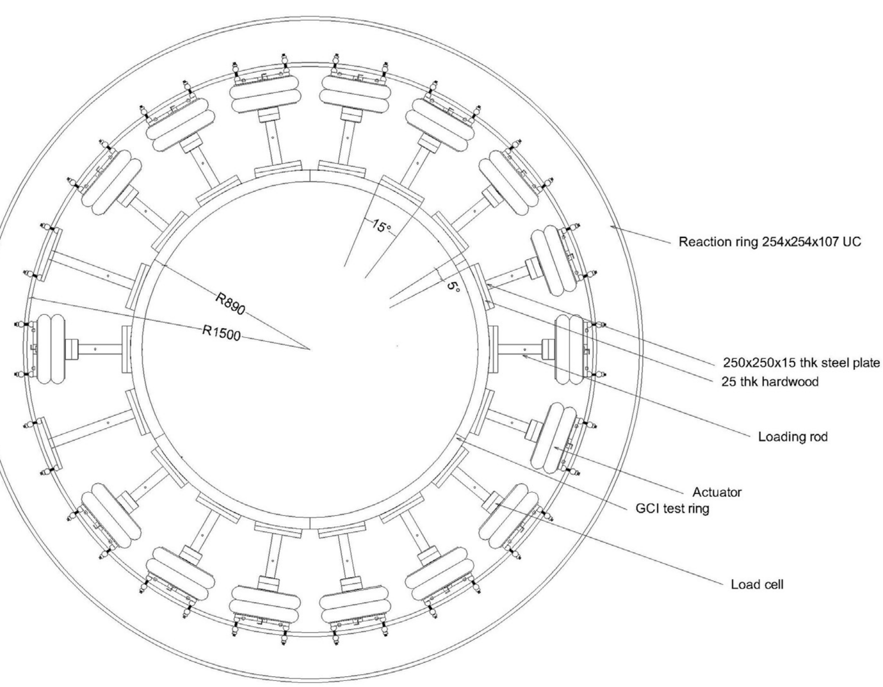

Fig. 1. Schematic drawing of the test set-up.