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Behaviour of bolted cast iron joints

Aikaterini Tsiampousi[a], Jessica Yu[a,b,*], Jamie Standing[a], Robert Vollum[a], David Potts[a]

[a] Faculty of Engineering, Department of Civil and Environmental Engineering, Imperial College, London SW7 2AZ, UK
[b] BuroHappold, 17 Newman Street, London W1T 1PD, UK

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ABSTRACT

The structural testing and finite element (FE) analysis described in this paper were part of a major research project undertaken at Imperial College London to investigate the deformation of bolted segmental grey cast iron (GCI) tunnel linings. A key aim was to quantify how joints influence the behaviour of the lining, through a three-path approach comprising physical experiments, finite element modelling, and field instrumentation. The laboratory results have been used to assess the validity of the tunnel assessment methods used by industry.

This study examined joint articulation under the serviceability limit state in the absence of hoop force focussing on factors such as applied bolt preload, the loading direction and the freedom of the circumferential flange to deflect. Two half-scale GCI lining segments were bolted together at the longitudinal flanges to form a bolted arch in a similar fashion to the tests performed by Thomas (1977). Modern instrumentation was implemented to gain detailed measurements quantifying changes in global displacements of the two segments, bolt forces and joint opening under applied loading. For the first time, the physical experiments were conducted contemporaneously with the development of a three-dimensional FE model of the joint. The experimental data and the results from the FE analysis indicate a reduction in joint stiffness as the joint articulates under applied load. It is shown that the *presence* of a joint has far greater influence on the behaviour of the 'arch' than the *level of preload* applied to the bolts in the joint. The FE analysis allowed the deformation behaviour of the joint under positive and negative bending to be investigated: its response under the two modes differs significantly.

1. Introduction

This paper describes a programme of laboratory and finite element investigations carried out on a bolted GCI tunnel lining joint under zero hoop force, investigating the influence of factors including the applied bolt preload, the presence of grommets, the loading direction and the freedom of the circumferential flange to deflect on the joint articulation.

The details and geometries of the joint and segments were at half the scale of a typical London Underground (LU) running tunnel lining. The design of the laboratory experiments was based on the work carried out in the 1970s by Thomas (1977) who measured the increase in bolt load and the angle of joint opening as load was applied. He showed qualitatively, but not quantitatively, that the joint opened more at the edge compared to the middle. The global movements of the bolted arch, and in particular, the response at the supports, were not monitored by Thomas (1977).

Since Thomas' seminal research, several other studies have been undertaken to investigate lining response and, given the key role that the joints play in lining response, particular attention is often focussed on the behaviour and influence of the connections between the segments. The tests performed in these studies all involved structural testing, where the test elements were loaded directly rather than via applied soil pressures. Most of these studies involved concrete segments with steel reinforcement, tested either in a full-ring configuration or in pairs bolted together (Mashimo et al., 2001, 2002; Blom, 2003; Bilotta et al., 2006; Okano, 2007; Cao et al., 2008). More recently segments manufactured from fibre-reinforced concrete have been tested to assess their performance (Ahn, 2011; Blazejowski, 2012). Little information is given in these studies concerning the detailed response of the joints because of the difficulties involved, as described later, and generally detailed numerical analyses have not been performed in conjunction with the mechanical experiments in the same way as undertaken in this study. Li et al. (2014) validated a numerical model of a GCI segmental joint using the data presented by Thomas (1977), but as mentioned above the data from Thomas' tests provided more of a qualitative sense of response rather than detailed quantitative information, of the form presented in this paper where modern instrumentation was utilised in the experiments.

The two-segment test setup at Imperial College included instrumen-

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[*] Corresponding author at: BuroHappold, 17 Newman Street, London W1T 1PD, UK.
E-mail address: jessicabyyu@gmail.com (J. Yu).

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tation to monitor the local joint opening at three locations along the joint intrados and instrumentation for monitoring global movements. Significantly, the two-segment tests at Imperial College were conducted in conjunction with the development of a three-dimensional FE model. Care was taken to limit the applied loading so that the response of the GCI material could be considered elastic and a series of parametric experiments could be conducted on the same two segments without having to account for the non-linear, hysteretic, elastoplastic stress–-strain behaviour of GCI. The laboratory test results were used to calibrate and validate the FE model. Ultimately the FE model was used to project the behaviour of the two-segment test outside the range tested in the laboratory.

The knowledge gained from this investigation was used to guide the planning and analysis of the full-ring experiments carried out as part of a major research project at Imperial College studying the effects of constructing new tunnels close to the Victorian age bolted segmental GCI tunnels of the LU network (Standing et al., 2015). The research was prompted by the Crossrail tunnelling project, which has an alignment that criss-crosses numerous LU tunnels with bolted segmental GCI linings. Currently there is a lack of understanding of the behaviour of bolted segmental GCI linings under both serviceability and ultimate limit states, largely because of the lack of experimental investigations on the bolted GCI joints. The two-segment experiments described in this paper and the full ring experiments described by Yu et al. (2017) focused on the application of load under serviceability limit state. The full ring experiments were subsequently taken to large deformations and failure as detailed by Afshan et al. (2017).

2. Purpose of the study

One of the objectives of the overall project was to study the behaviour of grey cast iron (GCI) tunnel linings. To this end, experimental tests were performed on a model tunnel lining (Yu et al., 2017; Afshan et al., 2017) which consisted of six segments bolted together to form a full ring with dimensions scaled to be 50% of those of the running tunnel linings of the Central Line in the LU network (Fig. 1). This was the smallest size that could be manufactured with GCI while maintaining true proportionality of all dimensions, particularly the skin of the segment.

It was anticipated that understanding the behaviour of the bolted joints would be essential in order to understand the behaviour of the ring. For this reason, before performing the tests on the model lining, the behaviour of a bolted joint was investigated under zero hoop forces. This was achieved by adopting the experimental setup illustrated in Fig. 2 (explained in detail in the subsequent section), where two segments were bolted together along their longitudinal flanges to form an arch, pinned at one end and simply supported (on a roller) at the other. A downward line load was applied to the extrados of each segment producing a positive bending moment about the joint. The segments were heavily instrumented and the behaviour of the joint under the applied load was studied in detail.

The simplified geometry of the experimental setup enabled thorough investigation of the joint behaviour under well-controlled conditions. Nonetheless, the loading conditions imposed (i.e. zero hoop force and moment only applied in one direction) were not entirely representative of the loading conditions expected at the joints of a tunnel lining. For this reason, finite element (FE) analysis was employed to investigate the behaviour of the joint under boundary conditions which were not easy to implement in the laboratory.

The FE model adopted had first to be calibrated using the experimental data obtained from the two-segment test, before being used in a predictive, parametric study. Various difficulties were involved with this task. The first relates to the interface between the two segments. In the FE model this interface was modelled by means of zero thickness joint elements which can accommodate relative movement between the two longitudinal flanges. Nonetheless, the stiffness of the interface under the loading conditions imposed is not measurable in the laboratory. In practice it is influenced by a number of factors such as: tightness of the bolts (potentially causing warping of the faces if not bolted in stages sequentially); degree of flatness and parallelism between the faces (potentially affected by casting and grinding processes and alignment of the two segments when setting up the test); roughness of the interface between the longitudinal flange surfaces (i.e. presence of asperities which may or may not be flattened after bolt tightening); and the presence of any coating on these surfaces (rust and other oxidation). As such, the stiffness of the joint elements used in the FE analysis had to be back-calculated.

Another difficulty in calibrating the FE model relates to the stiffness of the system of nuts and bolts, their threads and washers (bolting system). This stiffness, as with the interface between the longitudinal flanges, can also be influenced by factors such as: tightness of the bolts; roughness of the washers and underside of bolt heads and nuts where they meet (see Fig. 1d); the flatness of the washers and the surface of the segment flange on which they bear; the degree of parallelism between the mating surfaces; any deformation of washers that takes place as the nuts are tightened; screw thread pitch; and whether grommets were used. It was anticipated that the overall stiffness of the bolting system is lower than the stiffness of the independent components comprising it, due to the discrete interfaces between the different components. Nonetheless, to avoid generating an overly complicated FE mesh, as well as to avoid the problem of having to back-calculate their stiffness, joint elements were not used between the different components of the bolting system. This simplification had to be compensated for by adjusting the stiffness of the solid elements representing the bolting system. However, there is no straightforward method of calculating the appropriate shear and bulk moduli to be adopted in the FE analysis. For this reason, the stiffness of the bolting system was back-calculated by matching the numerical prediction to the experimental results.

The purpose of the FE analysis was not to merely reproduce the two-segment test but to provide insight into the behaviour of the joint under different boundary conditions. The ultimate aim of the FE analysis was to help establish the experimental setup for the model tunnel lining (Yu et al., 2017; Afshan et al., 2017). Therefore, the FE mesh employed in the analyses presented here forms part of the FE mesh adopted in the analysis of the full ring, consisting of six bolted GCI segments, as explained later.

3. The two-segment test

3.1. Experimental setup

As the behaviour of the joint in the two-segment test was being investigated in order to provide insight into the behaviour of joints in the model tunnel ring, it was imperative that the segments in the two-segment and model tunnel lining tests had the same geometries. The dimensions of the half-scale segments forming a ring are given in Fig. 1.

Segments of the same dimensions were employed in the two-segment test. A schematic drawing showing the setup is given in Fig. 2. The two half-scale GCI segments were bolted together to form an ‘arch’ with a joint at the axis of symmetry as shown. A line load was applied to the extrados of each segment through two brass rods as shown in Fig. 3 (labelled “a”), each positioned 110 mm from the axis of symmetry. Loading was applied using one of the 14.5″ diameter stainless steel air-bellow actuators procured for the full ring tests, as described by Yu et al. (2017) and Standing et al. (2015). Five load cells were positioned as shown in Fig. 2. One load cell measured the total load applied to the segments, and the other four were used to check that the loading was applied evenly on the specimen. Minor adjustments could be made to the small ‘foot’ that extended below each load cell so that the loads were more evenly spread (labelled “b” in Fig. 3).

The horizontal displacement at the roller support was measured