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A hybrid analysis method for displacement-monitored segmented circular tunnel rings

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ABSTRACT

Segmented tunnel rings exhibit load-induced interfacial dislocations. In order to facilitate structural analysis, a hybrid method is developed and applied to a real-scale test of a segmented tunnel ring. Point loads, imposed on the tested ring, and measured interfacial discontinuities serve as input for the analysis. Moreover, the method accounts for the structural behavior of the individual segments by means of newly derived transfer relations. They represent analytical solutions of the first-order theory of slender circular arches, exhibiting constant cross-sectional properties. The tool for the development of this basically well-known theory is the principle of virtual power. Its involvement is motivated by the possibility of a mechanically consistent derivation of relations, some of which have been used for a long time without analyzing their scientific background. The validity and the usefulness of the transfer relations follow from a comparison of newly derived solutions with (i) alternative analytical solutions, (ii) Finite Element solutions, and (iii) experimental data. The computational efficiency and the usefulness of the developed hybrid method are demonstrated by structural analysis of a segmented tunnel ring. It provides valuable insight into the load-carrying behavior of the tested structure without the need to describe the nontrivial behavior of segment-to-segment interfaces.

1. Introduction

The motivation for the present paper is structural analysis of a real-scale experiment of a segmented tunnel ring, tested at Tongji University [1], see Fig. 1. 24 hydraulic jacks imposed concentrated loads on the structure, simulating non-uniform ground pressure. During the stepwise loading process, monitoring instrumentation was used to measure convergences as well as discontinuities at segment-to-segment interfaces, i.e. relative rotation angles and displacement jumps in the radial and tangential direction. Both, point loads and interfacial dislocations result in discontinuities of static and kinematic state variables. They render structural simulations a challenging task.

The complex contact behavior of segment-to-segment interfaces depends on many factors including their geometric layout, the potential use of prestressed connecting bolts, the stresses acting in the contact zone, as well as potential dislocations and relative rotation angles. This was the motivation for several testing series, in which interfaces were subjected to normal forces and bending moments [2,3] or to normal and shear forces [4]. Corresponding models for the nonlinear interfacial behavior include analytical approaches [5–8] and numerical approaches, where the interfacial regions are modeled in great detail [9,10].

The structural behavior of segmented tunnel rings strongly depends on the complex interface behavior. This was the motivation for many structural experiments [11–14,1]. As for the corresponding structural analyses, several approaches exist. Interfaces were simulated as perfect hinges [15]. Closed ring models with reduced moments of inertia at the locations of interfaces were developed [16–19]. Interfaces were modeled explicitly based on rotational springs [20–23] and on systems of springs, allowing for both dislocations and relative rotation angles [24,25]. If realistic *nonlinear* interfacial behavior is taken into account, an incremental-iterative solution scheme is required even if the reinforced concrete segments exhibit linear elastic material behavior. This provides the motivation for the present study.

The aim of the present work is to establish a hybrid method for displacement-monitored segmented tunnel rings. This is inspired by existing hybrid methods, developed for structural analysis of displacement-monitored shotcrete shells, used as linings in the New Austrian Tunneling Method, see, e.g. [26–29]. Herein, the

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Fig. 1. Setup of the real-scale experiment of a segmented tunnel ring at Tongji University [1].

word “hybrid” refers to the combination of *measurements* and analytical or numerical *computations* in structural mechanics. In the present context, *measured* interfacial discontinuities will be used (together with prescribed point loads) as input for the *computational* structural analysis. This eliminates the interfacial nonlinearities, and thus simplifies the structural analysis significantly. In addition, the structural behavior of the individual segments will be accounted for by means of analytical solutions of the small strain (“first-order”) theory for slender circular arches with constant cross-sectional properties. Such transfer relations are appealing because they are capable of considering discontinuities of static and kinematic state variables, for example, the ones resulting from point loads and interfacial dislocations, in a straightforward manner.

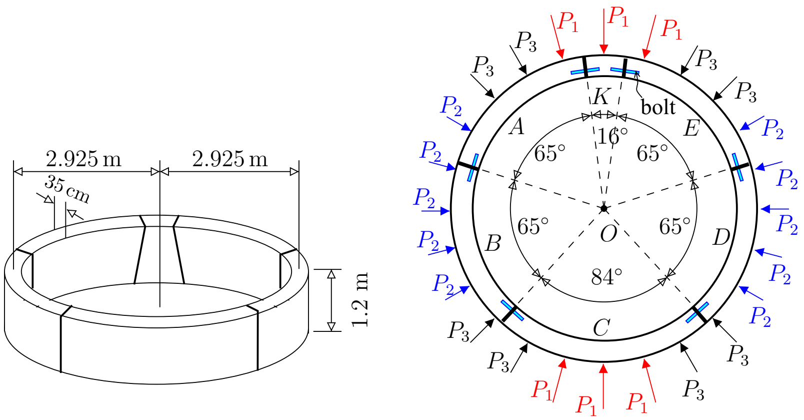
The present paper is organized as follows. In Section 2, the analyzed experiment on a segmented tunnel ring is described. Section 3 is devoted to the derivation and an exemplary validation of transfer relations, representing analytical solutions of the first-order theory for slender circular arches with constant cross-sectional properties. As for the validation, the transfer relations are applied to a two-hinged arch, subjected to a point load and to a three-hinged arch, subjected to dead load. Results obtained with the help of the derived transfer relations are compared with alternative analytical solutions obtained by the unit force method, results from Finite Element simulations, and experimental data. Section 4 is devoted to the application of the transfer relations to the aforementioned hybrid analysis of a displacement-monitored experiment on a segmented tunnel ring. In the discussion in Section 5, (i) the reason for the unsymmetric structural response under symmetric external loading is explained, (ii) the question whether the tested segmented tunnel ring may be treated as a slender arch is answered, and (iii) the benefits from the presented hybrid approach are highlighted. Section 6 contains conclusions drawn from the presented study. Appendix A is devoted to the first-order theory of slender circular arches. The tool for the development of this basically well-known theory is the principle of virtual power. Its involvement is motivated by the possibility of a mechanically consistent derivation of relations, some of which have been used for a long time without analyzing their scientific background. Appendix B contains an analytical solution of an arch problem based on the unit force method. Appendix C contains a list of symbols.

2. Data from a real-scale test on a segmented tunnel ring

In this section, data from a full-scale experiment of a segmented tunnel ring, tested at Tongji University [1], are presented (Fig. 1). The radius R of the ring was 2.925 m, see Fig. 2(a). It consisted of six reinforced concrete segments, named K, A, B, C, D, E. Their thickness, H, and axial length, B, were 35 cm and 1.2 m, respectively. Young’s modulus of concrete, E_c, amounted to 43,478 MPa [30,31], the extensional stiffness EA amounted to 18,260 MN, and the bending stiffness EI amounted to 186 MNm^2. Compressive loading was imposed by 3 groups of altogether 24 hydraulic jacks, see Fig. 2(b). They simulated the action of non-uniform earth pressure. The available measurements included jack forces and the interfacial displacement/rotation discontinuities (Fig. 3), as well as the vertical and horizontal convergences, see Fig. 4. The present re-analysis of the test focuses on the first 4 load steps, during which the segments remained uncracked [1]. Thus, the mechanical behavior of the segments can be modeled by linear elasticity theory.

3. Transfer relations for circular arches

Consider a slender arch with constant radius R, extensional stiffness EA, and bending stiffness EI, subjected to radial and tangential distributed loads, q_r and q_φ (Fig. 5). The first-order theory for such an arch consists of the following basic equations; for their derivation see Appendix A. The displacement vector, $\mathbf{u}$, and the cross-sectional rotation, θ, are given as



(a) (b)

Fig. 2. (a) Geometric dimensions of the analyzed segmented tunnel ring, (b) composition of the ring and layout of the hydraulic jacks.