Combined experimental-computational approach to multiscale structural analysis of segmented tunnel linings

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Abstract

This contribution deals with the behavior of segmented tunnel linings used in mechanized tunneling. Part I refers to the hybrid analysis of a real-scale test on a segmented tunnel ring. The structural analysis is *hybrid* in the sense that both (i) the prescribed external forces *and* (ii) the measured displacement/rotation discontinuities of the joints are used as inputs. This provides valuable insight into the structural behavior, without the need to describe the nontrivial behavior of the joints. As for future design calculations, however, the moment-rotation relations of the joints must be modeled. This is the motivation for part II which refers to the combined experimental-computational analysis of the bearing capacity of concrete hinges subjected to eccentric compression. Nonlinear Finite Element simulations are combined with a multiscale model for concrete. This allows for conveying state-of-the-art knowledge regarding microstructural processes associated with concrete cracking up to the macrostructural scales of concrete hinges.

Keywords: mechanized tunneling, multiscale modeling of concrete, concrete hinges, Finite Element simulation

1. Introduction

The conventional structural analysis of segmented tunnel linings is challenging due to the non-trivial behavior of the joints. This calls for combined experimental-computational research. To this end, a real-scale test of a segmented tunnel ring was carried out at Tongji University [1]. The tested ring, with a diameter of 6.2 m, consisted of six reinforced concrete segments, see Fig. 1. The tunnel ring was subjected to anisotopic loading by means of 24 hydraulic jacks. Displacement monitoring concerned (i) the convergences in both the vertical and the horizontal direction and (ii) the displacement/rotation discontinuities at the joints. The latter, together with the jacks forces, serve as input for "hybrid analysis", see Section 2.

Figure 1: Real-scale test on a segmented tunnel ring [1].

Such a hybrid analysis increases the insight into the structural behavior of the *displacement-monitored* segmented tunnel lining. However, when it comes to structural simulations regarding the *design* of a segmented tunnel linings, the discontinuities at the joints are unknown. The relative rotation angles resulting from combined compression/bending of joints are of prime interest for designers who typically rely on formulae by Gladwell [3] or Janßen [4]. However, these formulae refer to serviceability conditions, i.e. they do not provide information on the bearing capacity of concrete hinges. This is the motivation for combined experimental-computational research on segment-to-segment joints, see Section 3.

2. Hybrid analysis of a displacement-monitored segmented tunnel ring

Hybrid analyses in mechanized tunneling are based on transfer relations which represent analytical solutions of the first-order circular arch theory [2]. Step-by-step integrations of the governing differential equations provided solutions for the following load cases: (i) unloaded part of an arch, (ii) point loads, and (iii) interfacial discontinuities of kinematic variables at segment-to-segment interfaces. The obtained solutions provide access to the state variables, i.e. to the radial displacement, the tangential displacement, the cross-sectional rotation, the bending moment, the normal force, and the shear force. Solutions for all load cases are superimposed and then arranged in matrix-vector form, resulting in the so-called transfer relations [2].

The *prescribed* point loads imposed by hydraulic jacks and the *measured* displacement/rotation discontinuities at the joints serve as input for the "hybrid analysis" [2]. The only unknowns of the transfer relations are the six integration constants, referring to the six state variables at the initial cross-section. The static variables are determined from the deformation compatibility conditions of the close ring, i.e. the radial and the tangential displacement as well as the cross-sectional rotation at the initial

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cross-section are equal to those at the final cross-section. The kinematic state variables at the initial cross-section refer to rigid body motions. Therefore, they may be set equal to zero or to arbitrary non-zero values. After the determination of the integration constants, the transfer relations allow for computation of the state variables at any position of the segmented tunnel ring, see Fig. 2. The usefulness of the presented hybrid analysis is underlined by the satisfactory agreement between model-predicted and measured convergences [2].

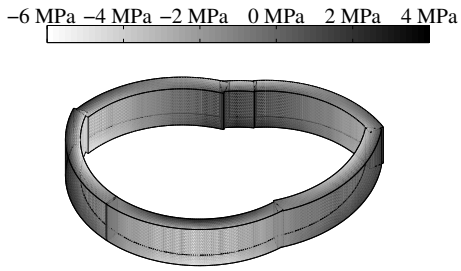

Figure 2: Deformed configuration of the ring and the distribution of the normal stresses of concrete at 4th loading step; the magnification factors of the cross-sectional dimensions and the displacements are 1 and 50, respectively [2]

3. Combined experimental-computational research on segment-to-segment joints (= concrete hinges)

The structural behavior of concrete hinges under eccentric compression was recently studied by Schlappal et al. [5]. During testing, three nominally identical steel-reinforced concrete hinges were subjected, one after another, to eccentric line loads with eccentricity $e = 25\,\text{mm}$. This resulted in combined compression and bending. The measured relation between the increasing eccentric normal force and the resulting rotation angle of the concrete hinges is shown in Fig. 3. Once the normal force exceeded 200 kN, the rotation angles increased superlinearly with increasing loading. When the rotation angles exceeded 15 mrad, the loading could no longer be increased significantly. The bearing capacity of all three tested concrete hinges, in terms of the eccentric line load, was equal to approximately 700 kN.

Existing guidelines do not consider the nonlinear behavior of concrete hinges under eccentric compression, see the linear functions in Fig. 3. Therefore, the experimental observations were analyzed by means of FE simulations by Kalliauer et al. [6]. 2-D plane strain FE simulations allowed for quantifying the characteristic principal compressive stress ratios in the neck region as $1.00 : 0.45 : 0.30$. The corresponding confinement results in a significant strengthening of concrete relative to its uniaxial compressive strength. 3-D FE simulations based on *default* input values do not deliver quantitatively reliable results. In particular, the initial structural stiffness and the bearing capacity are overestimated. This indicates pre-existing damage of the concrete hinges. Model updating consists of identifying suitable values for the Young's modulus, the tensile strength, the fracture energy, and the triaxial strength. A multiscale model for tensile softening of concrete is used to establish quantitative links between the increasing crack density on the one hand, and the corresponding reductions of the elastic stiffness, the tensile strength, and the fracture energy of concrete on the other hand [6]. This results in micromechanics-assisted FE simulations of concrete hinges. As for reducing the triaxial compressive strength of concrete, the value of the input parameter λ_t is increased. This results in Menétrey-Willam failure surfaces exhibiting decreasing slopes in the ξ - ρ diagram. It is found that $\lambda_t = 8.5$ allows for reproducing the experimentally obtained bearing capacity of the tested concrete hinges in a qualitatively and quantitatively satisfactory fashion, see Fig 3. Notably, $\lambda_t = 8.5$ refers to a triaxial-to-uniaxial compressive strength ratio amounting to 2, which is consistent with Eurocode regulations for *partially loaded areas* [6].

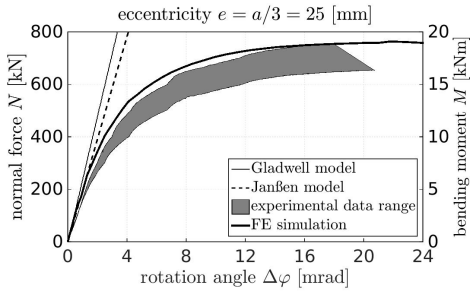

Figure 3: Comparison of (i) measurements from eccentric compression tests with $e = 25\,\text{mm}$ [5], with (ii) numerical results from three-dimensional FE simulations [6], and with (iii) relationships by Gladwell [3] and Janßen [4].

4. Conclusions

"Hybrid analysis" provides valuable insight into the structural behavior of *displacement-monitored* segmented tunnel linings. As for future design calculations, in turn, the complex behavior of segment-to-segment interfaces needs to be modeled. In this context, the presented experimental-computational research on concrete hinges will support the development of a predictive model. Nonlinear FE simulations allowed for reproducing the structural behavior of concrete hinges right up to the bearing capacity. In the future, both research directions will be combined in order to facilitate the design of segmented tunnel linings.

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