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Numerical investigation of the mechanical behavior of deformed segmental tunnel linings, strengthened by epoxy-bonded filament wound profiles

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ABSTRACT

Large deformations of shield tunnels may be the consequence of a long period of operation or of nearby pit construction. To reduce them, a novel strengthening method was recently proposed. It makes use of epoxy-bonded filament wound profiles (FWP). Full-scale tests were performed to prove the effectiveness of this method. The present paper contains a report on a comprehensive parametric study of the influence of several design parameters, such as, for example, the mechanical properties of the bond between the FWP and a segment of the tunnel and Young's modulus of the FWP, on the increase of the load-carrying capacity of the structure. Several tests were conducted to obtain these parameters. The influence of the lateral earth pressure coefficient of the surrounding soil and of the geometry of segmental tunnel linings on the strengthening benefits was also investigated. The parametric study was based on a numerical model, established in the course of this research. It was validated by comparing the numerical results with the experimental results and by demonstrating the model's capacity to describe the experimentally observed failure mechanism of the strengthened structure. Based on this analysis, an optimum combination of design parameters for the proposed strengthening method is suggested to ensure its safety, reliability, and effectiveness.

1. Introduction

Shield tunnels have been extensively used in urban metro railway systems. Large deformations of such tunnels may be caused by pit construction in the vicinity of the tunnels. Under certain ground conditions they may also occur with increasing years of operation. This may lead to problems, such as spalling of concrete, leakage, and cracks (Yuan et al., 2013) , which can endanger the safety of the operation of an urban metro railway. In order to reduce the large deformations of shield tunnels, strengthening of these structures by epoxy-bonded steel plates is widely used in Japan (Kiriyama et al., 2005), England (Moss, 2014), and China (Chang et al., 2001). Because of the relatively great self-weight of the steel plates, a hoisting machine is needed during construction, which render this mode of strengthening inefficient.

A new strengthening method, making use of epoxy-bonded filament wound profiles (FWP), was recently proposed (Liu et al., 2016). Four rectangular steel tubes are welded together to form one profile, which is then cladded with carbon fiber cloth to form a FWP. Thereafter, the FWP is deployed on the inner surface of the deformed segmental lining, and several plug bolts are employed for temporary fixation. Epoxy is used to establish the bond between the FWP and the concrete. Finally, high-strength mortar is grouted into the cavity of the FWP when the epoxy has developed its strength. This strengthening method overcomes the weaknesses of the one with steel plates, as regards weight and efficiency of construction. Full-scale tests were conducted to investigate the ultimate capacity of deformed segmental tunnel linings, strengthened by FWP. Knowledge of the failure process facilitated the investigation of the failure mechanism. However, the overall mechanical behavior and the failure modes of such composite structures, consisting of FWP and reinforced concrete, and the parameters that have a significant influence on the strengthening effect due to FWP are still unclear. Hence, further research is needed to provide guidance to the design and the optimization of strengthening of tunnel linings by epoxy-bonded FWP. Full-scale tests are inefficient, because they are time-consuming and expensive. However, numerical simulation is an efficient alternative to identify the parameters with a significant influence on the strengthening effect due to FWP.

Models of structural analysis of segmental tunnel linings have been discussed extensively. Wong et al. (2013) presented an analytical solution of the strengthening effect of steel sets, embedded in the primary

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lining of a tunnel. The steel sets are treated as plane rings in the cylindrical shell. Finite element models, based on continuum mechanics, were developed to study the structural behavior of segmented tunnels (Blom, 2002). These linings were modeled in detail, and advanced material models were used to capture the mechanical behavior of the joints and of its influence on the overall structural response. An approach, based on a macroscopic model, has proved to be effective and reliable to analyze the complex behavior of frame walls structures (Bao et al., 2014; Bao and Kunnath, 2010). Zhao et al. (2015) proposed a highly efficient computational component-based macroscopic model, which is both simple and general. It can be employed to analyze segmental tunnel linings, strengthened by FWP. However, it is not clear, how to simulate FWP and to determine the relevant mechanical parameters, because FWP consists of profiles, carbon fiber cloth, and high-strength mortar. Besides, the quality of the bond between the FWP and the concrete is not known.

This paper contains a description of a simple nonlinear analysis model of a circular ring, consisting of six segments, i.e. five regular segments and one key segment. The segmental tunnel ring is discretized by straight elements. Two types of elements are used in the analysis. One of them are so-called fiber-beam elements, used for the segments. The other one is applied to modeling of the joint and of the bond between the FWP and the concrete segment. In the course of modeling, it has turned out that the original way of considering FWP could be simplified. This has resulted in the proposal of a simplification of the original manner of modeling FWP. A parameter study was conducted to investigate the sensitivity of the tensile and the shear strength of the bond, Young's modulus of the FWP, the geometry of the FWP, the type of the inserted joint between FWP sections, the lateral earth pressure coefficient, and the geometry of the segmental tunnel linings on the strengthening benefits.

2. Modeling of strengthened segmental tunnel linings

2.1. Modeling of unreinforced segmental tunnel linings

A component-based macroscopic model is employed to simulate an unreinforced segmental lining. It is characterized by high computational efficiency, simplicity, and generality (Zhao et al., 2015). The reinforced concrete segments are simulated by fiber-discretized beam elements. The cross-section is divided into eight layers, i.e., two steel layers and six concrete layers.

The radial joint, connecting two adjacent segments of a ring by two bolts, is modeled by a collection of fictitious nonlinear springs and rigid beam elements. The contact between two adjacent segments is considered by a series of fictitious springs, which only have compressive strength and stiffness. The bolt is simulated by a fictitious spring with both compressive and tensile strength and stiffness. The bending moment and the axial force of the radial joint are transferred by these springs.

2.2. Modeling of FWP

2.2.1. FWP

FWP are combinations of profiles, carbon fiber cloth, and high strength mortar by means of a special technology. For the sake of simplicity, the material is considered as homogeneous, with macroscopic mechanical properties. FWP are simulated by using fiber-beam elements that are divided into four layers, with altogether 16 integration points, as shown in Fig. 1I. Since the deformation of the ring is plane, a subdivision in the longitudinal direction of the cross-section is actually not necessary. However, because the employed commercial computing program allows for consideration of skew bending, this subdivision was made to avoid an intervention in the commercial computer code. As shown in Fig. 1(b), a FWP is 160 mm wide. However, in engineering applications, different numbers of FWP are deployed along the width of the concrete segment, namely, four or six. Hence, in Fig. 1(c), the width of the elements is 640 mm and 960 mm, respectively. The properties of FWP, i.e. Young's modulus, E_f, and the yield strength, σ_{fy}, are obtained from tests, as described in Section 3.2.

2.2.2. Inserted joint between filament wound profiles

When strengthening segmental tunnel linings by FWP, there are two kinds of strengthening areas: one is from -50° to 50° (Area 1), whereas the other is from 50° to 145° and from -50° to -145° (Area 2). Hence, the strengthening material is divided into three parts. In the full-scale test, the number of the FWP in Area 1 is six, while that in Area 2 is four. The respective combination of the FWP is denoted as 6 + 4. Two adjacent parts are connected by an inserted joint.

Part 1 has grooves, see Fig. 2(a), and part 2 has embossments, see Fig. 2(b). The size of the embossments is smaller than that of the grooves. As shown in Fig. 2(c), the embossments in part 2 (right part) are inserted into the grooves in part 1 (left part), resulting in an inserted joint, which is finally sealed by structural adhesive. In the numerical model, an inserted joint is simulated by a discrete spring element with strength and stiffness both in compression and shear, as shown in Fig. 2(d). The rotational stiffness is not considered.

2.2.3. Modeling of the bond between the FWP and the concrete segment

In engineering practice, epoxy is employed to establish the bond between the FWP and the concrete segment. A set of fictitious springs, which are capable of carrying tension, compression, and shear slip, are used to represent the bond. These spring elements allow movements in the radial and the tangential direction. The strength and stiffness of the springs are obtained from tests (see Section 3.3).

The full numerical model is presented in Fig. 3.

3. Determination of modeling parameters

3.1. Unreinforced segmental lining

3.1.1. Reinforced concrete segment

The material parameters and the spring stiffness of the unreinforced segmental lining correspond to those used in a previous study (Zhao et al., 2015). The stress-strain diagram of concrete is shown in Fig. 4(a). It is similar to the one of the concrete model proposed by Park and Paulay (1975). The stress-strain diagram of steel is illustrated in Fig. 4(b). The material properties of concrete and of the steel fibers are listed in Table 1. σ_c, σ_{cu}, and σ_t denote the compressive strength, the ultimate strength, and the tensile strength of concrete, respectively. ε_c and ε_{cu} are the strains, corresponding to σ_c and σ_{cu}. σ_y is the yield stress and σ_{ult} is the ultimate strength of steel. ε_{sh} and ε_{ult} are the strains corresponding to σ_y and σ_{ult}.

3.1.2. Radial joint

Each radial joint contains two bolts. Their diameters are 30 mm. The yield stress σ_{boy} and the ultimate stress σ_{bou} are 400 MPa and 500 MPa, respectively. Young's modulus of elasticity, E_{bo}, is $2 \times 10^5 \text{N/mm}^2$. The length of the bolts, L_{bo}, is 400 mm. Fig. 5(a) shows the force-elongation diagram of the bolts.

As mentioned in Section 2.1, the contact between neighboring concrete segments is established by a set of compressive springs. Because of two gaps of 20 mm each at the two ends of the radial joint, the force-compression diagrams of the concrete spring elements in different zones of the joint are different, as shown in Fig. 5(b).

3.2. Axial properties of the FWP

FWP is a composite material, consisting of steel profiles, carbon fiber cloth and high strength mortar. Steel is a homogeneous material with the same properties in tension and compression. Carbon fiber cloth has advantages concerning tensile strength. When it is used to clade the