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Simplified nonlinear simulation of shield tunnel lining reinforced by epoxy bonded steel plates

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ABSTRACT

A high-efficiency simplified modeling approach based on fiber-beam elements and discrete elements is proposed for investigating the nonlinear response of shield tunnel reinforced concrete linings. The proposed approach focus on following main features: modeling simplicity and computational efficiency, the considerations of critical material and geometric nonlinearity associated with the entire loading process, including the stage of reinforcing the deformed concrete lining by steel plates. Comparison between the analysis results of the proposed numerical model and the experimental results from the full-scale structural test are presented to validate the developed model. The results show that the proposed model can capture the essential characteristics of the nonlinear load–deformation response of segmental tunnel lining. The modeling approach presents a balance between simplicity and accuracy, and serves as a viable alternative to detailed finite elements analysis.

1. Introduction

Shield tunnel has been in extensive engineering application for more than 50 years. As years of operation, some reinforced concrete shield tunnel structures have gradually arisen some structure aging problems such as concrete crack and spalling, and leakage (Yuan et al., 2013). The excessive transversal oval deformation of the tunnel lining is one of the primary reasons potentially initiating these local structural damages. The solution of bonding steel plates to the already deformed tunnel lining under operation is proposed to enhance the resistance to the developing and progressive deformation (Kiriyama and Takeuchi, 2005). The utmost knowledge and the predictions of tunnel mechanical behaviors are necessarily required to guide the optimization of the steel plate reinforcement to the segmental tunnel linings already with deformations caused by high ground and water pressures. However, there is a general lack of information on the mechanical behaviors and failure modes of such composite shield tunnel linings subjected to the complicated loads from underground soil.

The deformed tunnel lining reinforced by inner bonding steel plates essentially becomes a distinctive secondary lining structure. According to the guideline document issued by International Tunneling Association (2000), a tunnel lining combined by a segmental lining and a secondary lining should be treated a double-shell structure, in which only axial force must be transmitted through the border of both linings.

As for the reinforced tunnel lining in this study, the approaches used for the secondary lining do not account for the considerable deformation already appeared in segmental lining. Also, the combining and composite effects of the inner steel plate ring and the segmental lining are significantly different from the concrete cohesion of double linings.

The structural analysis models of segmental tunnel linings have been discussed extensively in literatures. Wong et al. (2013) studied the analytical solution of the reinforcement effect of the steel sets embedded in the primary lining of a tunnel, in which the steel sets are represented by plane rings in the cylindrical shell. Continuum mechanics-based finite element models were developed to study the structural behavior of segmental tunnel linings (Blom, 2002; Klappers et al., 2006; Arnau and Molins, 2011). In their models, segmental tunnel linings were modeled in detail and advanced material models were used to capture the joint behavior and its influence on the overall response. Other researchers have used spring elements or interface elements to simulate the joint behavior. Ding et al. (2004) employed rotational springs to model their particular joint configuration between segments. In Van Empel

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and Kaalberg's analysis (2002) the joint behavior was considered by a combination of three springs. Plizzari and Tiberti (2006) used interface elements to consider the mechanical characteristics of segmental joints.

Macromodel-based approach has been approved to be an efficient and reliable modeling approach to analyze the complex behavior of structures (Bao et al., 2014; Bao and Kunnath, 2010). This study is concerned with development of a macroscopic model to simulate essential and critical responses of the segmental lining reinforced by steel plates after large deformation. The development of the simulation model is guided by the force transfer mechanism between the segments and the steel plates. One of the critical effects is the bond-slip constitutive model between two borders. The proposed model is then validated by comparing the analysis results with experiment results obtained from a full-scale test of a segmental lining. Lastly, parametric analysis of the steel plate reinforcement in terms of reinforcing time, cohesive strength, and steel plate size is conducted based on the proposed model.

2. Modeling for segmental tunnel lining

The model is proposed to represent critical characteristics of the inelastic response of the segmental tunnel lining reinforced by steel plates, with emphasis on high computational efficiency, simplicity and generality. The proposed model is a component-based macroscopic model, which can be applied to analyze the most typical segmental lining structures. These abilities of the proposed model make it particularly attractive compared to high fidelity continuum mechanics-based finite element models.

In order to simulate as closely as possible the actual behavior of reinforced concrete segmental linings, the proposed model takes into account: (a) the nonlinear behavior of the steel and concrete material used in the reinforced concrete segments, (b) the complicate but significant nonlinear behavior of the radial joint between the adjacent segments, and (c) the interaction between the reinforcing steel plates and the deformed reinforced concrete segments.

2.1. Segment modeling based on fiber beam element

The model presented herein is composed of the fiber-discretized beam elements for reinforced concrete segments as shown in Fig. 1. Reinforcing steel layers are used to representing the reinforcements located at the segment section. Area of reinforcing steel layers is defined by the actual tangential reinforcement ratio. Because the segments are modeled as nonlinear fiber beam elements, inelastic responses are represented adequately, and also axial load-moment interaction is considered.

2.1.1. Stress–strain relationships for cross section fibers

The stress–strain relationship for concrete fibers, as shown in Fig. 2(a), is similar to the one described by Park and Paulay (1975). In compression, the stress and strain responses follow a parabolic stress–strain curve up to the compressive strength σ_c, and then the stress decays linearly with strain until the ultimate strength σ_{cu} is reached. Unloading is characterized by the initial stiffness followed by a degraded slope. In tension, a linear stress–strain behavior is assumed until the tensile strength σ_t is reached. Thereafter the stiffness and strength decays with increasing strain. ε_c and ε_{cu} are the strains corresponding to σ_c and σ_{cu}, respectively.

As for steel fibers of the segment cross section, stress–strain relationship is adopted as shown in Fig. 2(b), in which, the stress–strain curve is parabolic between ε_{sh} and ε_{ult}. σ_y is the yield strength, and σ_{ult} is the ultimate stress.

2.2. Radial joint modeling

The radial joint connecting the adjacent segments consists of the socket system and bolts. Under the bending moment, the adjacent segments at one end of the joint would contact each other and a growing gap would develop at the other end. The blots will be in tension eventually if the gap development continues.

The proposed radial joint model is conceptually represented in Fig. 3 and comprises a collection of nonlinear springs and beam elements. A rigid beam element with the length equal to the thickness of the reinforced concrete segments is employed at the end node of nonlinear beam element representing the actual geometry of the segments. A series of springs only with compressive strength and stiffness represents the contact between the segments and a nonlinear spring element represents the bolts connecting the adjacent segments. The axial force and moment between the adjacent segments are transferred through these idealized springs.

The determination of the spring properties will be discussed as follows. Experimental data from a full scale test of a segmental lining is used to explain the approach. In the proposed modeling approach, the force–deformation relationship of the spring element, describing the actual bolts located at the interface between two adjacent segments, is assumed to be a trilinear elastic–plastic curve as shown in Fig. 4. The end force of the linear elastic stage F_{by} is defined by the yield strength of the bolts, and the maximum force F_{bu} is defined by the ultimate strength of the bolts. The corresponding deformations s_{by} and s_{bu} are calculated based on the yield strain and ultimate strain of the bolts respectively. After the deformation reaches the ultimate deformation of 2.4 mm, the force–deformation behavior follows a zero-stiffness branch with constant force.

As shown in Fig. 5, two gaps exist at the outmost and the innermost layers of the radial joint respectively. Contact and squeeze of

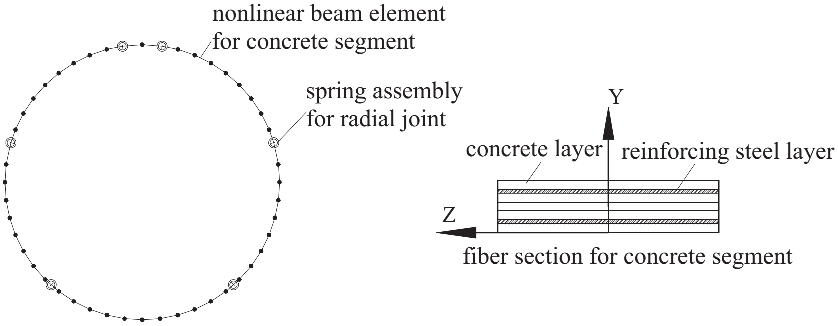

Fig. 1. Assembled macro-model representing a typical segmental lining.