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Practical nonlinear analysis of unreinforced concrete tunnel linings

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ABSTRACT

A comprehensive methodology for modelling, analyzing and assessing the structural response of unreinforced concrete tunnel linings is presented. Various modelling techniques are described, considering the plane finite element representation of the lining geometry, material constitutive laws, and boundary and interface conditions. Furthermore, all relevant external loading cases are studied, including gravity, environmental, fire, blast, and seismic loading. Potential pitfalls in the modelling and analysis procedures are identified and properly dealt with. The suggested methodology is finally applied to actual tunnel linings and the interpretation of the analysis results leads to important conclusions regarding the applicability of different analysis methods and the performance of unreinforced concrete linings.

1. Introduction

Although the lining of modern roadway tunnels is typically constructed in reinforced concrete, cost considerations sometimes lead to the use of unreinforced (plain) concrete when the right conditions are met, mainly when the tunnel is constructed in solid rock and when dynamic loads are not critical for the design of the lining. Notwithstanding cost considerations, the use of plain concrete has the advantage that it relieves construction from the problems associated with the use of reinforcement bars, i.e. compaction of concrete in congested regions and possible damage inflicted to waterproofing membranes by the steel bars.

Unreinforced concrete linings are expected to crack and the extent of cracking is the most critical design criterion in such linings. It is notable that modern design specifications for tunnels, like the German ZTV-ING (BASt, 2007), or the American Technical Manual for Design and Construction of Road Tunnels (FHWA, 2009) do not contain any specific requirements for this case; in fact, allowable crack criteria for unreinforced linings are the subject of current research (see http://www.bast.de/nn_74576/EN/E-Forschungsprojekte/e-laufende/e-fp-laufend-b3.html). Other documents like the French Recommendations for plain concrete in tunnels (AFTES, 2000) adopt indirect criteria for crack control, i.e. they place limits on the residual compression zone, by requiring that the eccentricity of the axial load $e = M/N$ (where M is the bending moment and N the axial load) should not exceed 30% of the lining thickness.

Noticeable differences exist among current codes with respect to the assumptions made for the verification of unreinforced linings against bending moment and axial load, in particular with respect to the way the tensile strength of concrete is taken into account. The European code for concrete, Eurocode 2 (CEN, 2004a), includes rather detailed provisions for plain concrete (meant for static loading only) and specifies that tensile strength of concrete can be taken into account; however, the pertinent design equation adopted by Eurocode 2 ignores this strength and only involves the compression strength and the eccentricity (e). The FHWA (2009) Manual requires a check of the tensile stresses (and also the compressive stresses) under the design M and N. Other documents like the AFTES (2000) recommendations ignore the tensile strength of concrete and the basic design verification is a limitation of the eccentricity (see above); a similar procedure is adopted in the German Recommendations for Unreinforced Linings (DAUB, 2007). Further discrepancies exist in shear verifications, which are mandatory in some codes (FHWA, Eurocode 2) but are not required in others (DAUB).

The above remarks make it clear that there is still substantial room for improving/refining the existing procedures for the design of unreinforced concrete linings. Moreover, the paramount role of parameters like the crack width, which are difficult to estimate reliably using elastic methods, point to the need of using sophisticated methods of analysis, namely nonlinear finite element analysis, as part of the design process of plain concrete linings and/or for calibrating simpler methods for practical design.

The present study is a contribution in this direction, using existing regulations as a starting point for introducing appropriate analysis methods that allow proper checking of the pertinent

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performance criteria, focussing on deformation quantities. It has to be pointed out here that use of advanced analysis tools (nonlinear finite elements or finite differences) is already part of actual design practice (e.g. Corigliano et al., 2011), at least in important tunnels, and are specifically recognised by pertinent documents like the American FHWA (2009). The present study originated in a very practical context, i.e. the assessment of the capacity of the unreinforced concrete linings proposed by the Constructor's team for parts of three major tunnels (up to 6 km long) currently being built in Greece, and nonlinear finite element analysis was used both by the consultants of the Constructor and by the authors who acted as reviewers of the design of the tunnel linings. The paper attempts to provide proper guidance for the reliable and efficient use of the aforementioned advanced analysis tools by designers with adequate experience in the field. Furthermore, it addresses for the first time the detailed analysis of plain concrete linings subjected to seismic loading, an issue that is typically ignored in previous studies.

2. Modelling procedures

In this section, various techniques for finite element modelling of unreinforced tunnel linings are described, considering geometry, material constitutive laws, and boundary and interface conditions. Furthermore, the relevant load cases will be presented, including gravity, environmental, fire, blast, and seismic loading. Specific numerical values together with corresponding analysis results in an actual application will be presented in the next section. The discussion focuses on two typical cross-section types used in roadway tunnels, nevertheless the modelling approach used can be applied to other cross-sections as well.

Two typical lining cross-section 'prototypes' are considered (Fig. 1), the first of the horseshoe type with strip footings, and the second of the closed type with an invert (typically required in weak rock conditions); the vault geometry is identical in both sections. The outer radius of the vault of the actual sections depicted in Fig. 1, from the centre of the traffic lane, is 7.85 m and the lining thickness is 0.45 m. For modelling and analysis, the finite element package ATENA (Červenka et al., 2012), specifically developed for plain and reinforced concrete structures, is employed throughout the present study.

2.1. Modelling of the lining section

Following the usual assumption of infinite tunnel length (in reality the length of a tunnel segment is about 14 m), a two-dimensional (2D) finite element formulation under plane strain conditions ($\varepsilon_z = 0$, $\sigma_z \neq 0$) is adopted. Four-node quadrilateral finite elements with typical size of 7.5 cm and thickness of 1.0 m are utilized, leading to a dense mesh of a total of 2538 and 4050 elements (6 elements across lining thickness) for the horseshoe and invert geometries, respectively (Fig. 2). The mesh density is selected with a view to striking a balance between (a) adequate resolution in analysis results and (b) heavy computational requirements, considering the use of advanced nonlinear material models and boundary conditions.

For the unreinforced concrete vault, a nonlinear fracture–plastic material model (Červenka et al., 1998; Červenka and Papanikolaou, 2008) is assigned to the vault elements, capable of capturing important aspects of concrete behaviour such as cracking, crushing, and crack closure. On the contrary, the reinforced concrete footings and invert are modelled using an elastic isotropic material (concrete elastic properties), since cracking in these regions is generally not expected due to the presence of reinforcement. An alternative approach would have been to model the above regions either with explicit or smeared reinforcement, however this would have led to increased computational demands without considerable benefit.

Boundary conditions between the tunnel lining and the surrounding rock-mass are modelled following the familiar Winkler spring approach (Dutta and Roy, 2002). Specifically, unilateral compression-only, linearly distributed springs are applied along the vault and the foundation (footings/invert) outer boundary (Fig. 3). The spring compression stiffness (K_V) is calculated considering plane strain conditions, as follows:

$$K_V = \frac{E_s}{1 - \nu_s^2} \ (\text{kN/m}^2 = \text{kN per meter of spring contraction per meter of line length}) \quad (1)$$

where (E_s) and (ν_s) are the subgrade reaction modulus and Poisson's ratio of the rock mass, respectively. Furthermore, the horizontal friction between footings and underlying rock mass is modelled with elastic bilateral springs of stiffness K_H, typically equal to 30–50% of K_V (Fig. 3, left).

Another important modelling aspect is the consideration of the construction joints between the vault and the foundation. These joints are modelled using interface elements, connecting the adjacent vault and foundation line boundaries. The interface elements are configured as unilateral contacts, incorporating a concrete-to-concrete friction coefficient (μ), which depends on

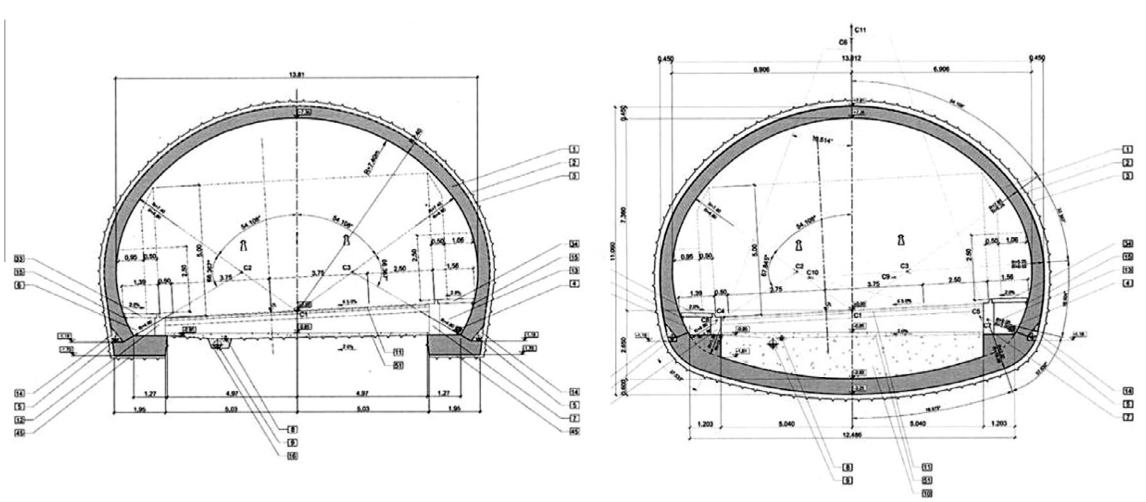

Fig. 1. Typical lining sections: horseshoe (left) and closed section with invert (right). Courtesy of EOAE SA.