Investigating the impact of viscoelastic material models for accurate stress estimation in precast concrete tunnel segments

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ABSTRACT: The segmental tunnel lining of Koralmtunnel in Austria is equipped with state-of-the-art structural health monitoring methods. Vibrating wire strain gauges measure histories of normal strains at specific locations along the steel reinforcement of precast concrete tubbings. To translate these strains into normal stresses, viscoelastic behavior of concrete needs to be considered, and a Boltzmann-type convolution integral needs to be solved. In order to quantify the needed relaxation function of concrete, its creep function is represented in a format that distinguishes between short-term and long-term portions, linked to a power law and logarithmic law, respectively. This function is converted into the corresponding relaxation function. It allows for translating measured strain histories into stress evolutions. It is shown that accounting for relaxation of concrete is crucial for long-term stress quantification in segmental tunnel linings. Linear elastically quantified stresses overestimate linear visco-elastically quantified stresses by 75% already three years after tunnel ring installation.

Keywords: precast concrete, viscoelastic material model, creep function, strain measurements, strain gauges.

1. INTRODUCTION

The Koralmtunnel (KAT) is a railway tunnel in Austria. It strengthens the transportation corridor between the Baltic and Adriatic regions. The monitoring program of the tunnel involves the use of vibrating wire strain gauges in selected sections to record normal strains at various locations on steel reinforcements embedded in precast concrete tubbings (Moritz et al. 2023). The data obtained from these strain gauges provide valuable insights into the mechanical behavior of the tunnel structure. It is the central aim of the present contribution to emphasize that translating measured strains into mechanical stresses experienced by concrete requires consideration of the viscoelastic behavior of the material, while a purely elastic simulation leads to significantly overestimated stress levels.

As regards shotcrete tunnel shells used in the New Austrian Tunneling Method (NATM), it is well known that quantification of realistic stress states requires consideration of creep of concrete, because shotcrete is loaded already at very early ages at which concrete is highly creep active

(Ausweger et al. 2019). However, segmental tunnel linings consist of precast reinforced concrete segments which are already several months old at the time when they are installed in the tunnel. Thus, concrete is already very mature when exposed to loading, and mature concrete is significantly less creep active than at early ages.

In the present study, the stress evolution in the concrete segments of the KAT is investigated, highlighting the significance of employing a viscoelastic material model for precise stress calculations. Accounting for the viscoelastic behavior of concrete can enhance our comprehension of the tunnel's long-term behavior and aid in making informed decisions to ensure its safe and dependable operation.

2. STATEMENT OF THE PROBLEM

Translating measured strains into mechanical stresses, under consideration of the viscoelastic behavior of concrete, requires the use of a Boltzmann-type convolution integral with a suitable relaxation function. However, obtaining creep functions in standard viscoelastic material tests requires strains resulting from constant mechanical stress, which is not the case for the strains obtained from the strain gauges in the tunnel segments. Therefore, the aim of this study is to develop a method for calculating the stress evolution in the concrete segments of the KAT based on the measured strains, using a viscoelastic material model.

In this study, we analyze strains measured at specific positions of the steel reinforcements embedded in the tubbings of selected segmental lining rings of the KAT. The tunnel lining has an inner diameter of 8.80 m. Every ring consists of seven segments. Six segments have an opening angle of 55.385 degrees; the one of the keystone amounts to 27.69 degrees, see Figure 1. The radial thickness and axial length of each segment amount to 0.35 m and 1.90 m, respectively. The concrete used for the production of the segments has the following specification C50/60(56)-F38-GK16-XC4-XA1L. Its cube compressive strength, reached 28 days after production, amounts to 69.2 MPa. Multiplying this value with 0.86 yields the cylinder compressive strength (= genuine uniaxial compressive strength) of concrete. It amounts to 59.5 MPa. This value allows for quantification of the elastic modulus $E = 38.96$ GPa and the creep modulus $E_C = 170.4$ GPa of concrete, following the developments of Ausweger et al. (2019).

The annular gap between the segmental tunnel ring and the ground-mass was filled with a cementitious grout, see the dark gray area in Figure 1. Vibrating wire strain sensors were attached to circumferential reinforcement bars (Figure 2) in order to measure the evolution of circumferential normal strains (Radončić et al. 2015).

Each tubbing (except for the keystone) is equipped with six strain sensors. Three sensors each are attached to the outer and the inner circumferential reinforcements, such that three pairs of sensors are located at angular positions referred to φ_1, φ_2, and φ_3, see Figure 3. This arrangement of sensors provides representative insight into the deformation of the tubbings.

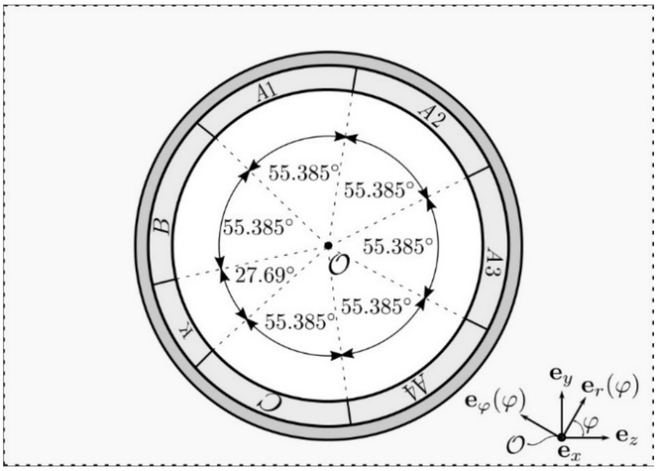

Figure 1. Arrangement of seven tubbings constituting one segmental lining ring of the Koralmtunnel (KAT).

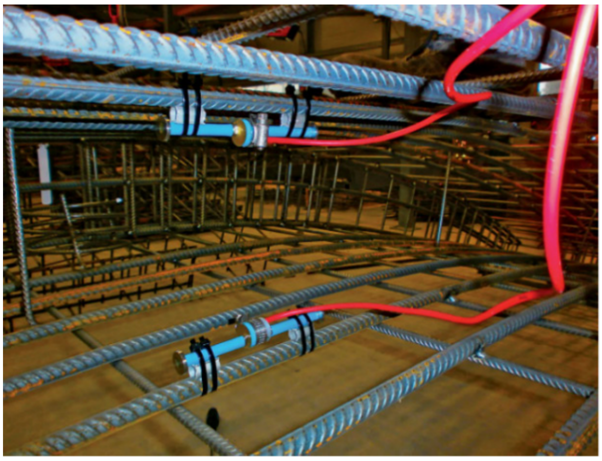

Figure 2. Vibrating wire strain sensors attached to circumferential reinforcement bars, before the placement of concrete (Radončić et al. 2015, copyright Ernst & Sohn GmbH. Reproduced with permission).

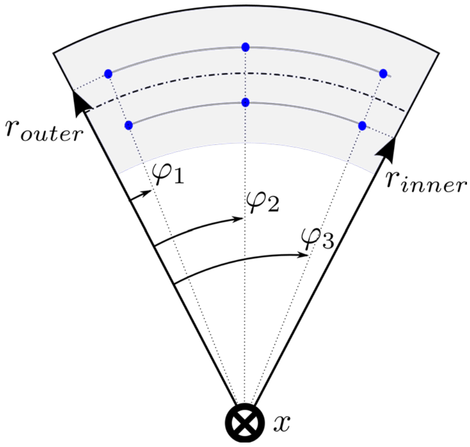

Figure 3. Positions of six vibrating wire strain gauges (see the blue dots) embedded in the segments A1, A2, A3, A4, B, and C, see Figure 1.

3. METHODOLOGY

Assuming firm bond between concrete and steel, the measured strains refer to both steel and concrete. The Boltzmann superposition principle is utilized to translate the strains obtained from the vibrating wire strain gauges to stresses of concrete.

The Boltzmann superposition principle provides a way to predict the response of a linear viscoelastic system by summing up the deformation (or "creep") effects of each individual loading step, so as to arrive at the deformation response to the combined loading history. In the present case, where the deformation states are known and the loading or stress states need to be determined, the response of a viscoelastic system results from summing up the stress (or "relaxation") response of the material to each individual prescribed deformation step. In case the latter steps arise from a continuous deformation history, this reads mathematically as:

$$\sigma_{\varphi\varphi}(t) = \int_{-\infty}^{t} R_{\varphi\varphi\varphi\varphi}(t-\tau)\,\dot{\varepsilon}_{\varphi\varphi}(\tau)\,\mathrm{d}\tau\,, \tag{1}$$

where t is the time instant where the stress response is sought, τ refers to (past) time instants associated with deformation prescription, $R_{\varphi\varphi\varphi\varphi}$ the non-aging relaxation function of concrete, and $\dot{\varepsilon}_{\varphi\varphi}$ the rate (= the time-derivative) of the strain history.

The non-aging relaxation function of concrete is derived from the non-aging creep function of concrete. This creep function describes the progressive increase of normal strain which is obtained if a unit normal stress is imposed instantaneously and kept constant thereafter, i.e. from a test in which concrete is exposed to a stress history representing the Heaviside step function. The creep function of concrete comprises a power law for the short-term portion and a logarithmic law for the long-term portion, linked at a typical transition time (Irfan-ul Hassan et al., 2016). The properties of the power law are quantified according to (Ausweger et al., 2019), with the uniaxial compressive strength of concrete as input. The transition time is set equal to 35 days (Irfan-ul Hassan et al., 2016). The logarithmic law is adjusted such that the creep function is continuous and differentiable at the transition time instant. The relaxation function is obtained by (i) transforming the creep function to the Laplace-Carson space, (ii) inversion in the Laplace Carson space, and (iii) numerical back-transformation to the time domain, see (Scharf et al., 2022) and Figure 4.

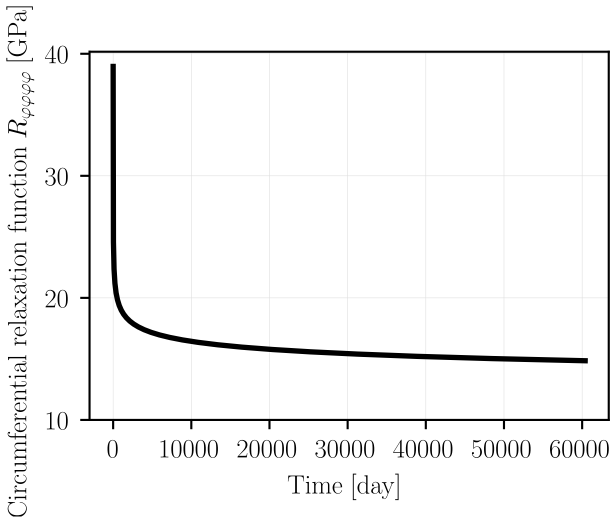

Figure 4. Relaxation function of concrete, see $R_{\varphi\varphi\varphi\varphi}$ in Eq. (1),
derived from a combined power-law and logarithmic-law creep function.

In order to obtain circumferential normal stress histories $\sigma_{\varphi\varphi}(t)$ at the measurement points, the circumferential normal strain readings of the vibrating wire strain gauges are represented in a semi-logarithmic diagram, see the blue dots in Figure 5. Accordingly, the strains are shown in natural scale along the ordinate, while the time after installation of the tunnel ring is represented in logarithmic scale along the abscissa. Such measured strain evolutions can be approximated by means of polygons, i.e. in a piece-wise linear fashion, see e.g. the red graph in Figure 5. The piece-wise constant slopes are optimized, by means of a machine learning algorithm (Pedregosa et al., 2011), in order to minimize the root mean squared error between measured and approximated strain evolutions. In this way, the tri-linear representation of the strain history shown in Figure 5 allows for computing the strain rates required for evaluation of Eq. (1). Insertion of the relaxation function of concrete according to Figure 4 and the strain history according to Figure 5 into the Volterra-type convolution integral of Eq. (1), allows for determination of normal stress evolutions at the position of the vibrating wire strain gauges.

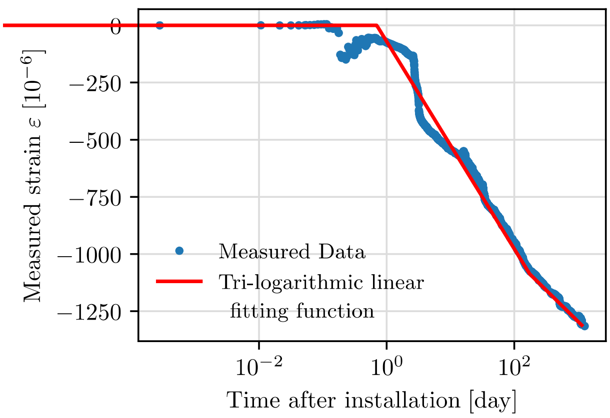

Figure 5. Semi-logarithmic representation of the strain evolution measured by a vibrating wire strain gauge, see the blue dots, and a piece-wise linear approximation, see the red graph.

4. RESULTS

Herein, circumferential normal stress histories are computed twice. At first, the described linear viscoelastic mode of calculation is used, see the black solid line in Figure 6 for the obtained stress evolution.

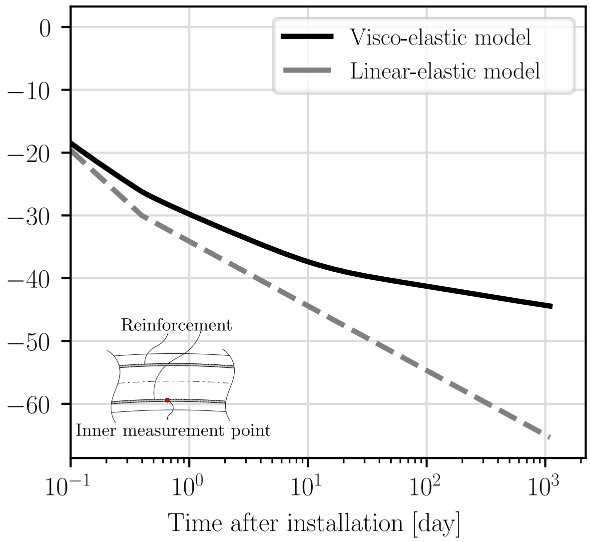

Figure 6. Circumferential normal stress histories $\sigma_{\varphi\varphi}(t)$ obtained from inserting the strain evolution of Figure 5 into Eq. (1): the gray dashed line refers to linear elastic material behavior of concrete, i.e. to $R_{\varphi\varphi\varphi\varphi} = 1/E$, where $E = 38.961$ GPa denotes the modulus of elasticity; the black solid line refers to linear viscoelastic material behavior of concrete with $R_{\varphi\varphi\varphi\varphi}$ following Figure 5.

Then, an alternative linear elastic mode of calculation is performed. To this end, $R_{\varphi\varphi\varphi\varphi}$ in Eq. (1) is set equal to $1/E$, where $E = 38.96$ GPa denotes the modulus of elasticity of concrete, see the gray dashed line in Figure 6 for the corresponding stress evolution. The results underline that the difference between the two approaches increases with increasing time. At the end of the simulation period, i.e. 1000 days after the installation of the analyzed tunnel segment, the linear-elastic model overestimates the stresses quantified by means of the realistic viscoelastic approach by approximately 75%. This suggests that a viscoelastic approach is mandatory to accurately quantify the long-term behavior of segmental tunnel linings, even if they are installed at an already mature age.

5. CONCLUSIONS

Readings from vibrating wire strain gauges, embedded in precast reinforced concrete segments of tubbings of the segmental lining of the Koralmtunnel, were translated into corresponding stress histories. From the presented study, the following conclusions are drawn:

- The theoretically rigorous linear viscoelastic evaluation of measured strain histories is based on Boltzmann's superposition principle and requires the solution of the corresponding Volterra-type convolution integral, see Eq. (1).
- The linear viscoelastic relaxation function of non-aging concrete, which is part of the integrand of the aforementioned integral, is not directly accessible, but it can be determined from the accessible linear viscoelastic creep function by means of a three-step procedure: (i) conversion into the Laplace-Carson space, (ii) inversion, and (iii) numerical back-transformation to the time domain.
- The non-aging creep function of concrete comprises a power law for the short-term portion and a logarithmic law for the long-term portion, linked at a typical transition time (here: 35 days) such that the creep function is continuous and differentiable everywhere. The required creep properties of concrete can be quantified based on knowledge regarding the 28-days cube compressive strength of the material.
- Linear elastically estimated stresses overestimate linear viscoelastically quantified stresses by some 75%, already three years after installation of the lining. This underlines that long-term stress analysis across decades of time must be based on a realistic viscoelastic properties of concrete.

ACKNOWLEDGMENTS

The authors gratefully acknowledge project FFG-COMET #882504 "Rail4Future: Resilient Digital Railway Systems to enhance performance".

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