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AN EVALUATION OF PRIMARY LINING DEFORMATION USING MEASUREMENTS WITH FBG SENSORS DURING A TUNNEL EXCAVATION

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Abstract. The paper presents an evaluation of data gathered with the FBG (Fiber Bragg Gratings) instrument for primary lining deformation measurement, which was installed into primary lining of adit during construction. The evaluation is related to the initial shape of primary lining, and its deflection curve is computed. Definition of appropriate boundary conditions can be verified with the use of geodetic convergence monitoring results. The developed evaluation procedure can be used also for determination of Bragg wavelengths during the design of primary lining monitoring.

Keywords: Geotechnical monitoring, underground structures, primary lining, fibre optics Fiber Bragg Gratings.

1. Introduction

The evaluation method of data acquired with the newly developed FBG (Fiber Bragg Gratings) instrument for primary lining deformation measurement is described in the article. A series of sensors is installed into reinforcement frames before the application of primary lining shotcrete layers of tunnels or adits. The FBG measurement principle as well as the instrumentation of the selected cross-section of the exploratory adit for construction of Metro, Line D in Prague was presented in detail in [1].

Axial elongation and temperature change of the optical fiber can be directly measured with the Bragg grating. Monitoring of deformation development in the primary lining is based on measurements of strain change along the inner and outer perimeter of the "Bretex" reinforcement rib. The FBG strain sensors are always deployed in pairs above each other, as in Figure 1. The change of the primary lining centre line shape can be determined from the pairs of strains of top and bottom fibres. FBG temperature sensors are added to the strain sensors in order enable the temperature compensation of the strain measurement. Therefore, a record of temperature development due to shotcrete hydration heat is obtained. Geodetic convergence measurement is also a part of the monitoring, and seven geodetic prisms were installed in the instrumented adit profile, as in Figure 1.

The measurements were performed from January 2021 to July 2022 during the progress with the ex-

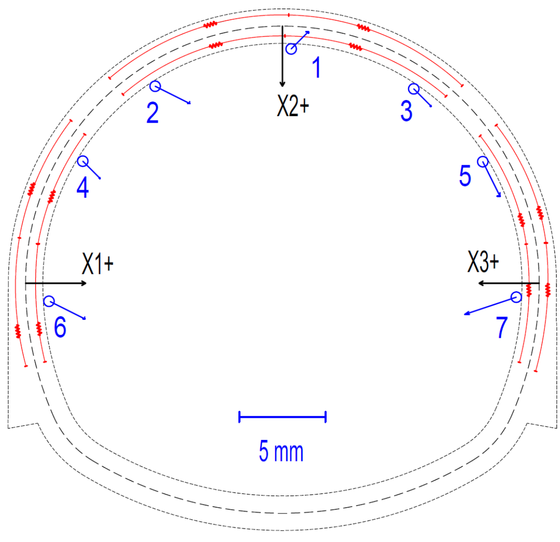

Figure 1. Scheme of primary lining with FBG deformation sensors; black dotted line – theoretical shape of primary lining; black dashed line – centre line of the primary lining; red – deformation sensors in the primary lining, FBG sensors are displayed schematically, temperature sensors are not displayed; blue numbered points – geodetical observed points for convergence measurements; blue vectors – cumulative displacement of observed points; black arrows – indication of sign convention for points X1 to X3; reference measurement 27th January 2021; deformation sensors were not deployed in the invert.

ploratory adit VO-OL which was built for additional geological exploration of section I.D1 and for the line D of Metro in Prague [1]. Raw measured data represent the strain development of the FBG sensors over time after performing the temperature compensation.

2. Evaluation of measurements with the FBG sensors

2.1. Computation of primary lining deflection curve

The theoretical centre line of the primary lining from the workshop (execution) drawings is considered as the initial shape. It consists of three adjacent circular arcs, as in Figure 2. Deformations of the primary lining are evaluated (related) with respect to the initial shape after the shotcrete layers are completed.

The primary lining centre line displaces transversally in the direction perpendicular to the centre line, whereas the influence of deformations along the centre line is ignored. Further, the deformations perpendicular to the instrumented cross-section of the adit (along the adit longitudinal axis) are ignored as well. The pair of FBG strain sensors are placed normally to the known initial centre line at the top (outer) and bottom edge (perimeter) of the primary lining measures strains ε_h and ε_d induced by the change of primary lining deflection line shape. The measured values ε_h and ε_d are used for computation of strain of the fibres at the top (outer) edge of the primary lining, which corresponds to the rotation of the section according to the relationship

$$e_o(s_i) := \frac{\varepsilon_h(s_i) - \varepsilon_d(s_i)}{2}$$

and for computation of primary lining centre line strain

$$e_l(s_i) := \frac{\varepsilon_h(s_i) + \varepsilon_d(s_i)}{2},$$

where s_i stands for the distance from the left end of the primary lining (where s=0) to the FBG sensor (measured along the centre line), see Figure 2. The radial deflection ξ_l caused by the centre line strain is defined by a simplified equation

$$e_l(s_i) := \frac{-\xi_l(s_i)}{R(s_i)}$$

because the displacements along the arc length of the centre line are ignored.

Next, we deal with the radial deflection shape ξ_o due to centre line bending. The values of $e_o(s_i)$ are used to determine the radius of curvature, $r(s_i)$, at each measurement point (s_i). Based on the small-deflection theory, the strain e_o and the radius of curvature r (or the curvature κ, respectively) obey the following equation

$$\kappa(s_i) = \frac{1}{r(s_i)} = \frac{e_o(s_i)}{h/2},$$

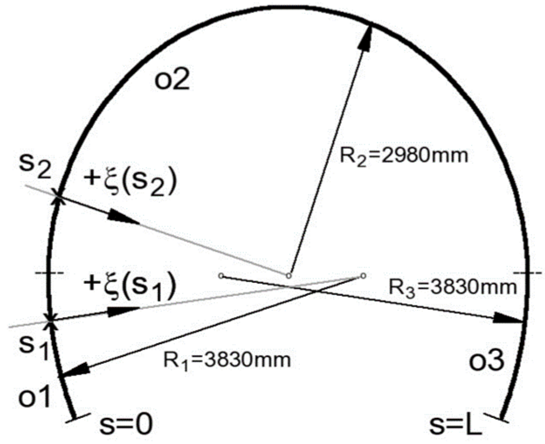

Figure 2. Scheme of the primary lining centre line geometry.

where h represents the distance between the top (outer) and bottom edge (perimeter) of the primary lining. The intermediate values of $e_o(s)$ can be determined by interpolation theory to get e_o as a function of s, the position on the centre line measured along its length. Then, the radial deflection ξ_o (the positive sign means the direction to the centre of the arc) that results from *bending* is given as the solution of the differential equation of the bending curve in the form (under the assumption of small deformations) [2]

$$\frac{d^2\xi_o(s)}{ds^2} + \frac{1}{R^2(s)}\xi_o(s) = \frac{e_o(s)}{h/2}, \quad s \in (0, L),$$

where L stands for the length of the centre line.

2.2. Boundary conditions of the computation

To deal with the well-posed problem, the differential equation of the bending curve must be completed by the appropriate additional geometrical restrictions. One possible way is to prescribe the boundary conditions at the end points of the centre line (as an example). Robin type boundary conditions of the form

$$\frac{-d\xi_o(0)}{ds} = K_L(\xi_o(0) - \xi_L)$$

and

$$\frac{-d\xi_o(L)}{ds} = K_P(\xi_o(L) - \xi_P)$$

are considered at the points s=0 and $s = L$, respectively. Here, K_L and K_P are compliance coefficients and the given radial deflections at the end points are denoted by ξ_L a ξ_P , respectively.

By setting $K_L = K_P = 0$, the well-known homogeneous Neumann boundary conditions are obtained:

$$\frac{-d\xi_o(0)}{ds} = 0 \text{ and } \frac{-d\xi_o(L)}{ds} = 0.$$

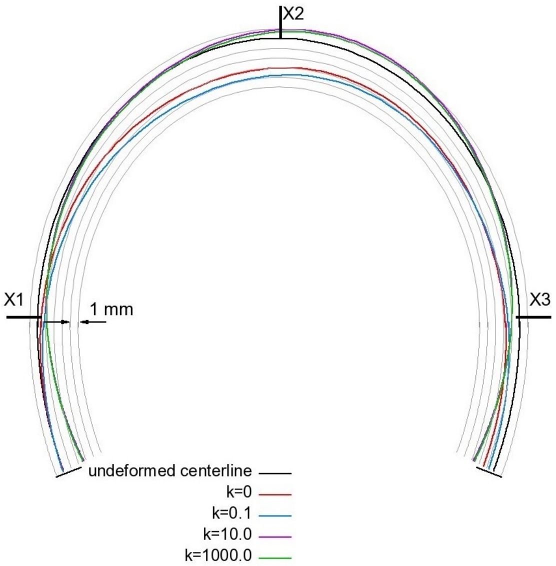

FIGURE 3. Scheme of computed deflection curves from the measurement on 28th March 2021 for different values of k; $k = K_L = K_P$; reference measurement on 27th January 2021.

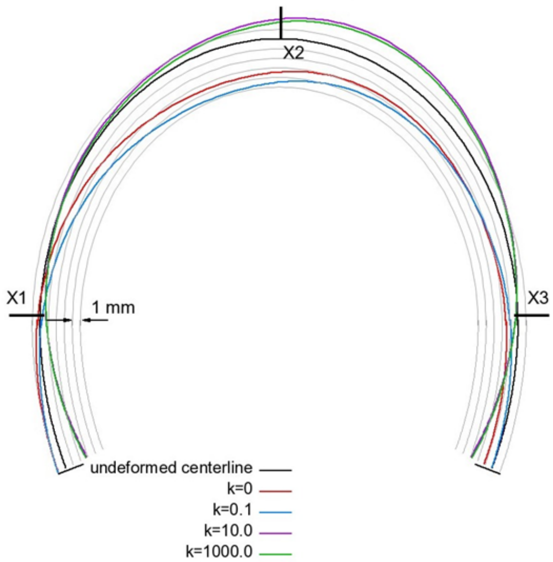

FIGURE 4. Scheme of computed deflection curves from the measurement on 28th March 2021 for different values of k; $k = K_L = K_P$; reference measurement on 27th January 2021.

Consequently, the slope of the centre line is zero at both points $s = 0$ and $s = L$.

On the other hand, letting K_L and $K_P \to +\infty$ gives the Dirichlet boundary conditions. In addition, assumption of zero radial deflections at the end points of the centre line leads to

$$\xi_o(0) = 0 \text{ and } \xi_o(L) = 0.$$

In order to obtain an approximate numerical solution of the corresponding boundary value problem, the space discretization is carried out by means of the one-dimensional finite element method (FEM). In particular, linear elements with the element size of 0.01 m are considered. A combination of the radial deflection ξ_l caused by the centre line strain and FEM-approximation of the radial deflection shape ξ_o due to centre line bending gives the numerical approximation of the resulting (total) radial deflection. A computational algorithm has been included in an in-house PYTHON code, which is employed to determine the distribution of primary lining deformations. As an example of the numerical procedure and implementation of different types of boundary conditions, numerical results are presented in Figures 3 and 4. These results are computed from FBG-measurements on 28th March and 10th June 2021 with respect to the reference measurement on 27th January 2021.

2.3. BOUNDARY CONDITIONS OF THE SHOTCRETE PRIMARY LINING

The computation of deformations is proposed for the primary lining after finishing of shotcrete layers, which means, that the Bretex reinforcement ribs with surrounding reinforcement rebar and meshes are fully covered with shotcrete. The supports of the frame at the boundary between bench and invert cannot be covered with sprayed concrete in order to enable the connection with the reinforcement of invert in the future construction stage(s). Therefore, the primary lining is temporarily supported by the reinforcement frame standing on its base plates at its toes, see Figure 5. Until the invert is finished, the primary lining horse-shoe has supports with lower stiffness, where rotation and/or displacements may occur.

The question is then how the primary lining arch behaves with such supports in the particular conditions of the rock massif excavation at its location. Two approaches can be used to set suitable boundary conditions for the computation of the primary lining deflection curve:

- search for the best fit of computed primary lining deflection curve with the geodetic convergence measurements by setting appropriate boundary conditions in the computation
- perform measurements – observation of rotations and relative horizontal displacements at the bottom part of the reinforcement frame with suitable sensors and set the boundary conditions according to measured deformations and rotations.

FBG and geodetical measurements began after spraying of the first shotcrete layer. The computation is made of deformations from the FBG measurements as well as the determination of boundary conditions after finishing of all primary lining shotcrete layers. The FBG measurements can be used to obtain information on initial strain development of the reinforcement frame before all layers of shotcrete are finished.

Figure 5. Spraying of first shotcrete layer in the new advance, while reinforcement with no concrete can be seen in the bench area of the previous advance.

2.4. Selected results

Detailed evaluation of geodetic and fibre-optic measurements shows that the range of deformations computed from FBG measurements corresponds with subsequent geodetic measurements. Determination of appropriate boundary conditions is essential for the interpretation of FBG measurements of primary lining deformations. The primary lining supports at the boundary between bench and invert can be considered as semi-rigid joints, where rotation and horizontal displacement are enabled. The boundary conditions were determined with the use of geodetic convergence measurements and a parametric study, where the stiffness of the semi-rigid joints at the primary lining supports was varied, see Figure 6. Further, allowed horizontal displacement was considered. The best setting of Dirichlet and Neuman boundary conditions was determined. Geodetic convergence measurement showed displacements between 2 and 3 mm into the excavation at bench. The deformations measured by FBG sensors reached 2.5 mm in the same direction. The deformations observed geodetically in the top heading were 1 to 2 mm towards the "right bench". The FBG measurements showed deformations up to 2 mm in the top heading.

3. Geotechnical and numerical model of the observed adit profile

A geotechnical model of the observed adit cross-section was created. One of the objectives was to verify the feasibility of the numerical model in such a level of detail as to describe the deformation development at the inner and outer perimeter of the primary lining, where FBG deformation sensors were installed. Two independent finite element (FEM) numerical models were created: one with the use of GeoStudio software at SG Geotechnika a.s. Comp., and another with the use of Geo5 FEM at the Department of Geotechnics at the Faculty of Civil Engineering, Czech Technical University in Prague.

The geometry was defined in the design of the exploratory adit, and the geotechnical profile was adjusted according to the geological documentation of adit face at the instrumented cross-section, and also previous adit faces were considered. The Mohr-Coulomb constitutive model and steady ground water level (hydrostatic stress) were used in both numerical models. A detail of FEM mesh from the top heading area of the primary lining (a model in GeoStudio) is presented in Figure 7. The approx. 0.3 m thick primary lining was divided into 4 layers in order to enable readout of deformations computed by the FE model at the positions of FBG deformation sensors. The properties of rocks were taken from the detailed geotechnical exploration. The computation phases were similar with the construction sequence.

Although an unusually detailed mesh of elongated quadrangle-shaped finite elements was chosen for solution in the primary lining, no problems with the model convergence were noticed. The calibration of the FE model was based on available results of common geotechnical and geodetic monitoring. The be-

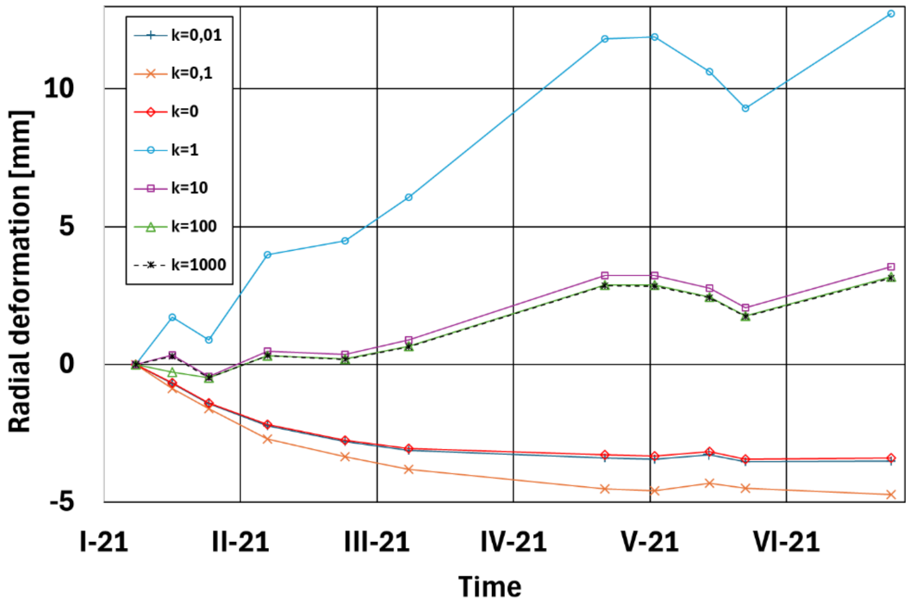

FIGURE 6. Example of a parametric study output for point X1: k – auxiliary unit of support stiffnesse.

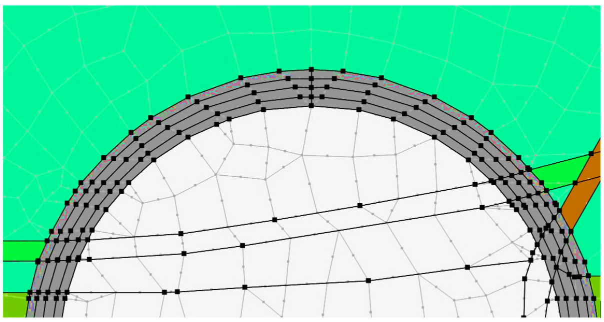

FIGURE 7. Detail of finite element mesh, which was refined in order to determine the deformations at the primary lining perimeters, where the FBG deformation sensors were deployed [3].

haviour of both numerical models was in accordance with expectations.

A numerical model created during the design of the underground structure can be used also for design of primary lining instrumentation with the FBG deformation sensors. The mesh of such a model has to be refined in the area of instrumentation similarly as shown in the example in Figure 6. The estimate of probable maximal deformations at the inner and outer primary lining surface will be an input for determination of a suitable measurement range of the fibre optic deformation sensors as well as for the deployment of the sensors.

4. CONCLUSIONS

The paper describes the mathematical solution of primary lining deflection curve computation with the use of data measured by the newly developed FBG (Fiber Brag Gratings) instrument. Principles of boundary conditions settings are discussed. A detailed finite element model of shotcrete primary lining of the excavation in the rock massif is presented.

Measurements with FBG strain and temperature sensors in one cross-section of the exploratory gallery for the construction of Metro Line D in Prague were evaluated. The results of fibre optic measurements show a very good match with the geodetic convergence monitoring, both methods indicated displacements in a range of first millimetres. In this case geodetic and fibre optic measurements began at the same time due to the course adit construction.

The geodetic convergence measurement cannot capture the whole amount of rock massif deformation, which develops from the actual tunnel face advance, because there is a technological delay between the excavation and installation of the observed points. The geodetic measurement can usually record about 50 % of the total deformation. Multi-level extensometers, which are usually installed, enable monitoring of the overall vertical deformation development and are also used for calibration of the underground structure's numerical model.

The numerical model created in GeoStudio describes deformations from the beginning of excavation or their development between the computation phases, which follow the excavation sequence and primary lining construction.

A detailed numerical model provides an estimate of assumed maximal deformations along the FBG deformation sensors, which are installed in the inner and outer perimeter of primary lining. A numerical model from the design of the underground construction can be used for design of the new FBG instrumentation. Increasing the level of detail in the model leads to an estimate of the required measurement range of the FBG deformation sensors, and the model can be also used to check the designed Bragg wavelengths as well as the deployment along the perimeters of primary lining.

Monitoring of 3D deformations in instrumented boreholes in the proximity of the excavation could contribute to reliable description of rock massif response and to increased accuracy of numerical modelling in very sensitive cases. FBG monitoring instruments provide continuous deformation monitoring with resolution higher then $\pm 2\,\mu\varepsilon$ ($\pm 2\,\mu m\,m^{-1}$) without need of personnel access to the instrumented profiles. Fibre optics measurements do not restrict the excavation advance.

After initial setting of appropriate boundary conditions of mathematical solution of the primary lining deflection curve computation, the output of FBG deformation measurements can be available on-line for the owner, constructor, designer as well as for the public authorities.

In case of significant stress field changes in the neighbourhood of the observed cross-section, i.e. by an influence of asymmetrical jet-grouting or excavation of a further tunnel tube, the boundary conditions have to be adjusted accordingly. Geodetic convergence measurements can be used for this purpose.

The instrumentation of primary lining with FBG sensors is currently more expensive than installation of geodetic observed points and episodic measurements with the use of total station.

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