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Assessment of crack patterns along plain concrete tunnel linings using distributed fiber optic sensing

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ABSTRACT: Acquiring the crack patterns along slender unreinforced concrete tunnel final linings, especially behind post installed facings (e.g. fire protection panels), requires extensive manual effort. Even if automated monitoring and inspection systems based on optical measurements are already existing, they are often limited in the spatial resolution, insufficiently reliable and need always an unblocked view to the tunnel lining. One promising alternative is distributed fiber optic sensing, which allows strain measurements with a high precision of about 1µm/m every 10 millimeters and enables therefore the identification of local damages, like cracks in the structure or unexpected changes in the strain pattern. The system can be applied direct to the concrete surface in existing tunnels, even behind fire protection panels. Moreover, the effective crack width can be derived from the measured strain profiles, which however requires the calibration of the sensing system under known conditions. This paper reports about this calibration on three concrete plates, including investigations on various installation types, the fatigue behavior of the sensing fiber and the adhesive as well as the comparison of the derived strain profiles with numerical simulations.

1 INTRODUCTION

The general tunnel design is usually based on two shells, where the outer shell serves to transfer the load from the geotechnical impact. The final inner tunnel lining usually only has to support the cladding itself and can therefore be designed unreinforced. Due to changes in mechanical stresses, unexpected loading may act on this final concrete tunnel lining. Temperature changes (frost effects) or aerodynamic loading can cause also unexpected load situations over time. Cracks serve as indicators of changing mechanical stresses and hence, a comprehensive registration and documentation of cracks of a certain width and changes in the crack pattern is required. Nowadays, the width and depth of existing cracks are usually determined visually by using a crack width ruler during tunnel inspections every 12 years, in special cases more often. Nevertheless, this method is not objective and a reliable and continuous recording is impossible. For automatic monitoring of crack changes, linear displacement transducers or fissurometers can be used. Same as the visual methods, this method provides measurements only at discrete points and a determination of the crack pattern is not possible. In order to map cracks and specify the crack patterns, measurement techniques, which provide continuous measurement data over the completely sensing area, e.g. digital image correlation or laser scanning, are required. These however demand always an unblocked line-of-sight or even direct access to the tunnel lining, which is often not possible due to fire protection panels mounted in front of the unreinforced concrete tunnel lining. Therefore, visual inspection as well as monitoring with the techniques mentioned above can usually not be performed without removing the fire protection panels.

Monitoring systems based on distributed fiber optic sensing (DFOS) offer the advantage to mount a sensing cable on the concrete tunnel lining behind the fire protection panels and can provide an automated crack monitoring without having access to the tunnel lining itself. Reliable crack detection and monitoring of crack movements inside of e.g. reinforced concrete structures (Brault et al, 2019) or tunnel segments (Monsberger et al, 2017) using DFOS were already investigated. Crack monitoring on already existing objects, such as unreinforced concrete tunnel linings, however, requires the subsequent post installed application of the sensing cable on the surface, usually years after the construction of the tunnel. In order to ensure a complete strain transfer from the concrete structure to the optical fiber, a suitable sensing cable and appropriate adhesion method for concrete surfaces have to be found. If mechanical stress acts on the monitoring structure, the measured strain may differ from that on the surface of the structure due to the deformation of the coating of the sensing fiber or the adhesive used for application. Consequently, a calibration of the measurement system under known loading conditions is necessary to calculate the effective crack width from the measured strain profiles, see e.g. Henault et al. (2012).

This paper reports on the calibration of a DFOS measurement system, which was post installed on the surface of concrete structures. It includes the choice of the appropriate components (sensing cable, adhesive and instrument) and investigations on the fatigue of the sensing cable and adhesive as well as on the effect of the measured strain profiles of crossing the crack in certain angles. The measured strain profiles are compared to numerical simulations and an outlook on the practical realization inside a highway tunnel in Austria is given.

2 METHODOLOGY

For application on slender unreinforced concrete tunnel linings, the utilized measurement system must meet special requirements, especially concerning the sensing cable and the adhesive bond. High sensitivity and thus, less protective coatings are needed to ensure a reliable transfer of strain appearing along the surface to the sensitive core of the sensing cable. Tight Buffered (TB) optical sensing fibers fulfill these requirements and have been already used for application on concrete surfaces, see e.g. Broth et al. (2018). Since the investigations discussed in this paper are performed in a laboratory with almost stable temperature conditions over the testing period, a temperature compensation of the measured strain profiles is not necessary. However, during long-term crack monitoring e.g. in a highway tunnel, an additional sensing fiber, which is only sensitive to temperature influences may be installed to compensate the changing temperature conditions.

In addition to suitable optical sensing cables, the bond between the sensing cable and the adhesive as well as the bond between the adhesive and the concrete surface is of major interest. Since applications along tunnel linings may be performed also vertically or even overhead, the adhesive must show high viscosity and has to harden fast. In previous investigations at the IGMS (Institute of Engineering Geodesy and Measurement Systems) laboratory, we evaluated various different adhesives including assembly adhesives, adhesive mortars and spraying glues. We found that adhesive mortars are most suitable for our applications due to their fast curing time as well as their similar material properties to concrete.

Focusing on detecting cracks and measuring changes in the crack width, which requires a high measurement resolution and a high spatial resolution, an optical backscatter reflectometer (OBR) from Luna Innovations Inc. is used for sensing. Based on optical frequency domain reflectometry (OFDR), this unit enables distributed measurements with a resolution of 1 µm/m and a spatial resolution of at least 10 mm (Luna Innovations Inc., 2019). However, the usual sensing range is limited to 70 meters, but can be even extended to 2 km with limitations in the spatial resolution and the measurement precision. Moreover, the instrument is only capable of taking measurements with a temporal resolution of some seconds depending on the prevalent strain. Further information about the measurement principle can be found in Kreger et al. (2006).

Instead of OFDR, Pulse Pre-Pump Brillouin Optical Time Domain Analysis (PPP-BOTDA) or Tunable Wavelength Coherent Optical Time Domain Reflectometry (TW-COTDR) might also be used for crack detection. Using commercially available sensing units based on these techniques, a spatial resolution of 20 mm can be achieved, see e.g. Neubrex Co. Ltd. (2018).

3 SENSOR INSTALLATION AND INVESTIAGTION PROCEDURE

The design and layout for the calibration test is based on the dimension for concrete tunnel inner linings. The concrete quality complies with the national regulation for tunnels (C25/30 XF3/ XC3/ IG GK 16, F1), loading and reinforcement were chosen to typical crack-width up to 2.5 mm in the tunnel. The specimens were loaded in different stages to simulate and calibrate the system on different known cracking situations. Three plates with dimensions of 2.5 m x 0.9 m x 0.2 m were post installed with a TB sensing cable on the intact surface to evaluate situations for new cracks, also cable installation on existing cracks were studied. The cable was glued with the adhesive mortar in a number of ways on each concrete plate, whereby the first plate was instrumented different to the second and the third concrete plate as shown in Figure 1.

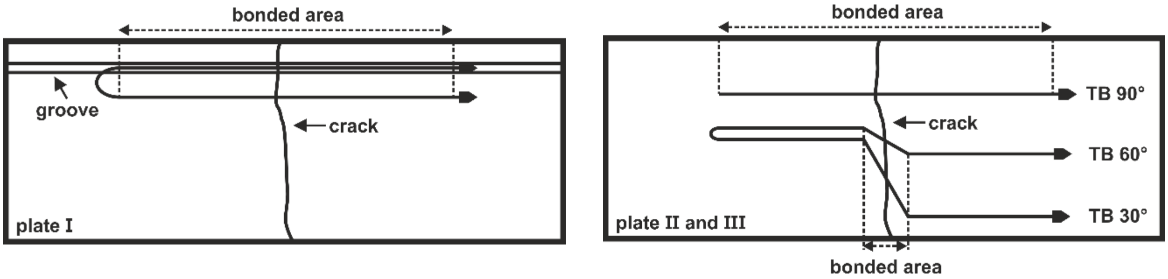

Figure 1. Application scheme of concrete plate I (left) and concrete plate II and III (right).

On concrete plate I, the sensing cable was applied on the surface as well as in a groove to see whether an application on the surface is sufficient or if a groove in the concrete is required to ensure a reliable transfer of the strain to the sensing fiber. The aim of concrete plate II was to investigate the impact of a non-orthogonal angle between sensing cable and crack. Therefore, the cable was applied in angles of 30°, 60° and 90° with respect to the crack direction. Concrete plate III was instrumented in the same way as concrete plate II to verify the results.

In order to be able to compare the measured strain profiles of the individual concrete plates, all three plates were subjected to the same investigation procedure. The load tests were carried out with a hydraulic press, whereby the pressure was exerted from the bottom side of the concrete plate as seen in Figure 2. Since the measurement time of the OBR is in the range of some seconds, the load was applied stepwise and was held at each load stage for a few minutes so that repeated DFOS measurements could be taken. During the whole investigation process, verification measurements using linear displacement transducers a well as manual visual readings were made to determine the true crack width and therefore, to be able to calibrate the measured strain profiles at defined positions.

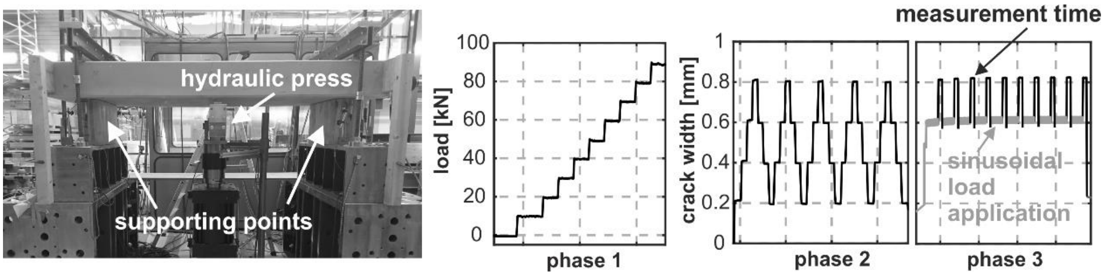

Figure 2. Vertical loading from the bottom side of the concrete plate (left) and profile of the loading during the three phases (right).

As shown in Figure 2, the investigation process consists of three different phases. Within the first phase, the concrete plates were loaded in steps of 10 kN until the first crack appeared. Afterwards, in phase 2, a cyclic loading and unloading was applied to the concrete plate to simulate the crack breathing. Five cycles were performed starting with a crack width of 0.2 mm to 0.8 mm in steps of 0.2 mm. The third phase constitutes an aging simulation to investigate the fatigue of the sensing fiber itself and the fatigue of the bond between sensing fiber, adhesive and the concrete surface. Within this phase a sinusoidal load with an amplitude between 0.4 mm and 0.8 mm and a frequency of about 0.3 Hz was applied to the concrete plates over ten hours. The sinusoidal load was always stopped after three quarters of an hour and remained static at a crack width of 0.8 mm to be able to execute reliable measurements with the OBR. Beside the sensors applied before testing, one additional sensing fiber with an orientation of 90° was mounted to concrete plates after the third test phase, where a crack width of 0.8 mm was prevalent. This should realize the subsequent post installed application of the sensing fiber when a crack at the tunnel lining is already existing. Three further loading cycles were performed after an appropriate curing time of the adhesive mortar to examine the performance of the DFOS approach to monitor already existing cracks.

4 RESULTS

4.1 Comparison of different sensor positions

In order to evaluate the necessity of an application in a groove or if also the application on the surface is sufficient, the sensing fiber was applied in both ways (Figure 1). In Figure 3, the measured strain profiles of the sensing cable glued on the surface (Figure 3, top) and in a groove (Figure 3, bottom) during the first loading scenario are shown. The first crack appeared at a load of 90 kN, where a significant change in strain at the crack positon is visible in both profiles.

Both installations depict a reliable transfer of the crack to the sensitive fiber, although the magnitudes of the strain peaks show numerical differences. These might be, on the one hand, because of the fact that the fiber on the surface is mounted closer to the center compared to the application in the groove and therefore, deviations must appear due to bending of the plate as a result of the vertical loading. On the other hand, the differences might be related to the different positions of the optical fibers along the concrete plate, which might result in slight differences of the crack width. Nevertheless, we can conclude that an application in a groove does not provide significant advantages in comparison to the application on the surface. Since the manufacturing of the groove in the practical realization inside the tunnel is time-consuming and therefore also expensive, following investigations of concrete plate II and III were focused on the surface application only.

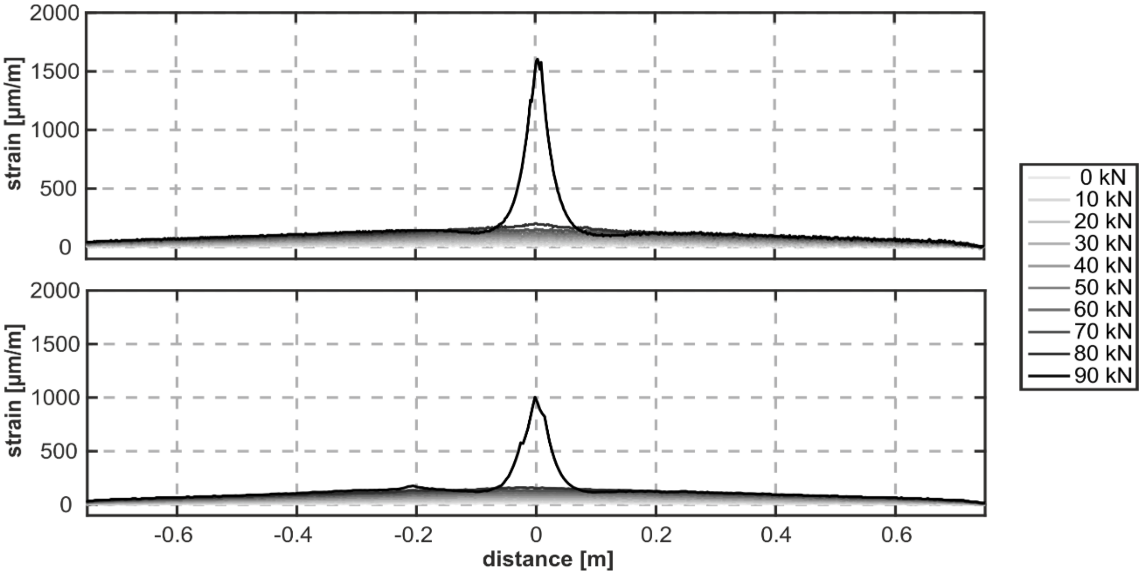

Figure 3. Strain profiles for application on surface (top) and in a groove (bottom) for phase 1

4.2 *Durability of the fiber optic installation*

To verify the durability of the fiber optic installation due to aging and increasing stress, Figure 4 depicts the strain profiles of concrete plate I during the continuous load application over 10 hours (phase 3), where each hour represents approx. 1000 loading cycles and therefore, 10.000 cycles in total. This is equal to 25 years with one temperature course a day. It is important to note that a secondary fatigue crack at the position of about 0.25 m arose during the first cyclic loading, which can also be seen in the fiber optic strain profiles. Even if thousands of load cycles are applied to the fiber optic instrumentation, the measured profiles show a very good repeatability over the entire investigation period. The profiles are almost exactly on top of each other and show only minor numerical differences. Hence, impacts of fatigue of the sensing cable itself, the bond of the adhesive to the concrete surface as well as the bond of the adhesive to the sensing cable, respectively, can be excluded in this case.

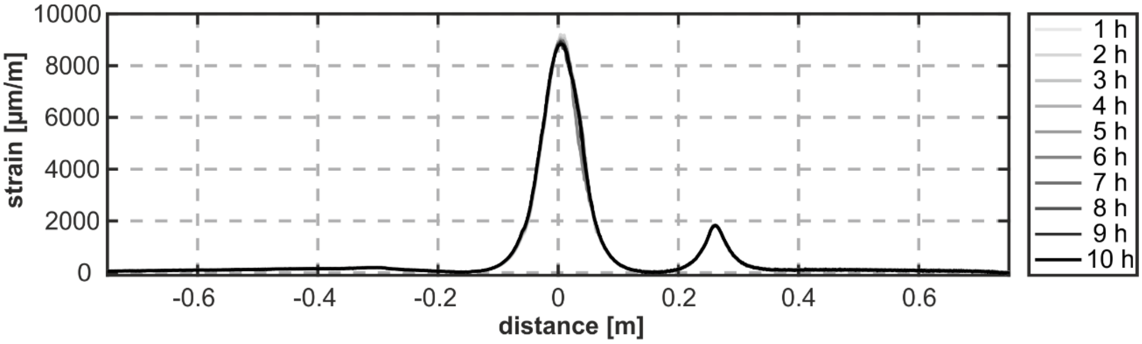

Figure 4. Strain profiles measured at a crack width of approx. 0.8 mm after different times

The loading cycles after the fatigue test show a similar behavior compared to the last cycle of test phase 2. The strain profiles along the post applied fibers depict negative strain maxima due to the crack closing, which can be reproduced in all cycles of the last phase. However, detailed investigations on the relation between the negative crack width and the strain are still ongoing.

4.3 *Comparison to simulated strain profiles*

In order to verify the suitability of the DFOS measurement system, back-calculations using a FEM-based model (Ansys -Mechanical ®) were performed and compared to the fiber optic measurement data. The FEM-based model includes the structural behavior of the concrete plate as well as the sensing fiber and the adhesive mortar. In Figure 5, the results of the loading of the first cycle (top), the unloading of the first cycle (middle) and the loading of the second cycle (bottom) are shown. These results depict a remarkably good agreement between the measured strain profiles (solid line) and the calculated strain profiles (dashed line) for all three load situations.

In addition, the strain profiles of the unloading of the first cycle (Figure 5, middle) show a compression at a crack width of 0.2 mm. As the crack already exists also in the adhesive, the sensing cable cannot return to its original state and thus, is compressed between the breaking edges of the adhesive. Even this compression can be reproduced by the FEM-based model.

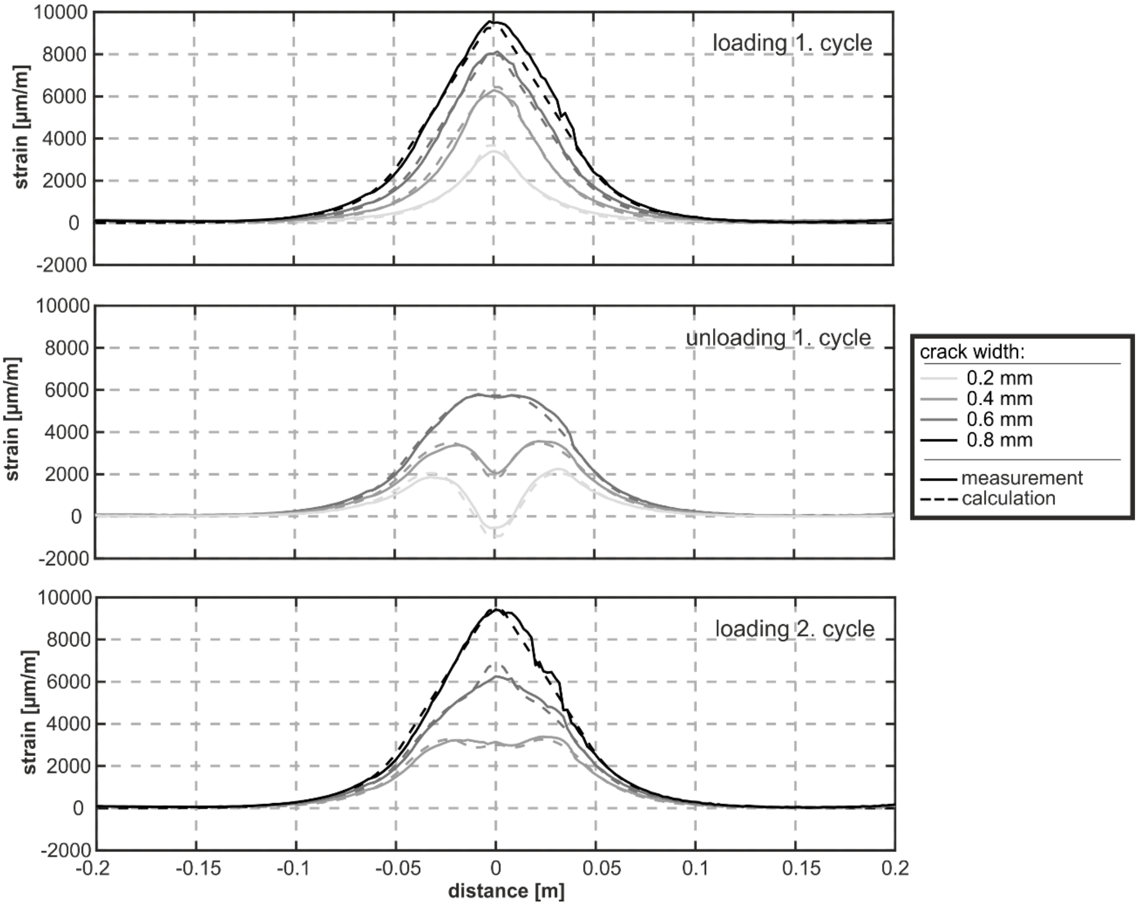

Figure 5. Comparison of measured and calculated strain profiles for loading of the first cycle (top), unloading of the first cycle (middle) and loading of the second cycle (bottom).

4.4 *Impact of different crossing angles of the sensing fiber with respect to the crack*

The primary focus of concrete plate II and III is the evaluation of different angles of the sensing fiber to the arising crack. Figure 6 depicts the strain profiles for concrete plate II for different crack widths during the third cycle of phase 2, where the concrete plate has already been subjected to a loading and unloading. Therefore, the strain profiles of all three measurement directions show a compression at the crack width of 0.2 mm as, as already seen in Figure *5*.

Primarily, the strain profiles depict that the transfer from the strain of the concrete surface to the optical fiber highly depends on the angle under which the sensing cable crosses the crack. In our results, crossing the crack with an angle of 60° has hardly any effect on the peak height of the measured strain profile, whereas crossing with an angle of 30° decreases the measured strain by half. Moreover, the peak width for both the strain profile crossing at 60° and the strain profile crossing at 30° is reduced and disturbances at the tip of the peak occur. These effects can be related to the non-orthogonal alignment of the sensing fibers with respect to the alignment of the crack.

If the effective crack width is calculated from the area under the peak of the strain profile, the calculated crack width might be smaller with decreasing angle under which the sensing cable is crossing the crack. In order to determine the effective crack width from the measured strain profile, the orientation of the sensing cable with respect to the crack must be well known.

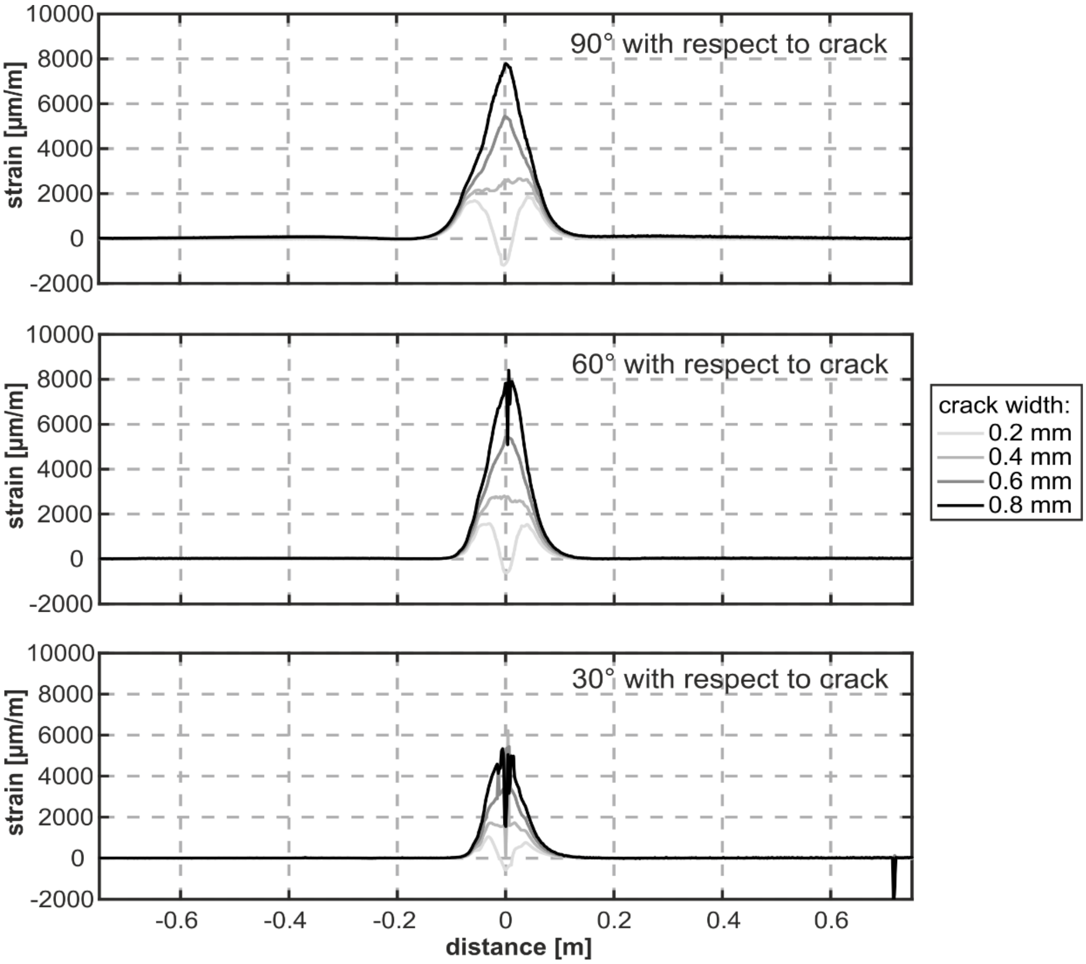

Figure 6. Strain profiles for the application in angles of 90° (top), 60° (middle) and 30° (bottom) with respect to the crack for one cycle of the loading and unloading phase.

5 CONCLUSIONS

This paper presents a post installed DFOS approach to characterize cracks along the surface of concrete structures, e.g. slender plain concrete tunnel linings. We found suitable application methods of a sensing cable for crack monitoring and performed calibration tests of three concrete plates in different setups. The results show that no groove is needed to reliably mount the cable to the structure. However, the orientation of the sensing cable with respect to the crack is highly relevant and shows an impact on the peak width and height of the measured strain profiles. Therefore, the orientation of the sensing fiber must be well known, to ensure a reliable determination of the effective crack width from the measured strain profiles. Indications concerning fatigue of the sensing cable or the bond during the accelerated aging test were not observed. The numerical simulation using a FEM-based model shows a very good agreement. Hence, there is a potential to reliably derive the crack location and crack width with DFOS measurements performed on the surface of concrete linings.

In future investigations, the measurement system will be subjected to a test within real conditions in a highway tunnel in Austria. The main objective of this test is the monitoring of movements of existing cracks e.g. due to the seasonal variations and influence of real environmental conditions (humidity, temperature, etc.). Therefore, an observation period of at least one year is planned, where a larger area along the tunnel lining will be instrumented to enable the detection and characterization of new cracks too. Finally, experiences of the field monitoring in combination with the laboratory tests should lead to an optimization of the developed DFOS system to reliable assess crack patterns along slender plain concrete tunnel linings in future applications. The field installation may also be used for investigations on long time effects on the used materials.

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