A Method of Monitoring the Cross-Section Deformation of Tunnels Using the Strain Data from the Fully Distributed Optical Fibre Sensors

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Abstract. Fully distributed optical fiber sensing technology allows the high-density strain to measure the overall curvature and cross-section deformation of tunnels. However, there are few studies on the use of longitudinal strain along the tunnel to measure the cross-section convergence deformation, and the method of obtaining the strain along the tunnel loop is costly. To address this issue, a method of monitoring the cross-section deformation of tunnels using the strain data is proposed. First, a model of the relationship between strain and deformation in tunnels is constructed to obtain the overall settlement using the longitudinal strain. Second, based on the finite element method (FEM), the deformation law about the strain measured points and non-measured points on the cross-section of the tunnel is proposed, and on this basis, the correlation coefficient is presented. Using the product of overall settlement and correlation coefficient, the cross-section deformation at non-measured points is obtained. The results of numerical examples shown that the proposed method can effectively expand the monitoring scale and realize high-density cross-section deformation measurement of tunnels.

1. Introduction
During the whole life span of shield tunnel operation, tunnel defects increase over time due to geological condition, ground settlement, construction activities, tunnel structural differences, upper loads, vibration loads, material corrosion, and member fatigue, which have a significant impact on operational safety [1]. Monitoring the cross-section deformation of tunnels over time and space spans has become a widespread concern for researchers.

Traditional methods for monitoring the cross-section deformation of tunnels include the hydrostatic leveling [2], total station observation technology [3], direct point measurement technique [4], digital close-range photogrammetry [5], and terrestrial laser scanning technology (LiDAR). However, the above methods exist problems, such as few measured points, short measured distance, measurement accuracy affected by the environment, and costly. Strain data have been proven to be good evaluation indicators for structural health monitoring (SHM) [6-7]. The fully distributed optical fiber sensing technology, based on Brillouin scattering [8-9], can acquire strain and temperature data along the entire length of the optical cable. Shen et al. [10] used the conjugated beam method to efficiently obtain the cross-section convergence deformation through distributed strain data along the tunnel loop. However,
this strain acquisition method is costly. In this article, we investigate a method of monitoring the cross-section deformation of tunnels using the longitudinal strain data. A strain-deformation mechanical model is proposed. Combined with the deep learning method, the overall settlement and the deformation distribution in the cross-section of tunnel can be obtained.

This article is organized as follows. First, a strain-deformation mechanical model is derived, and the overall settlement is calculated using the strain data. Second, based on a subway tunnel finite element model, a deep learning method is employed to obtain the deformation relationship between the measured points and non-measured points of the cross-section. Finally, the effectiveness of the proposed method is verified using numerical examples.

2. A method of monitoring the cross-section deformation based on the strain data
In this section, the principle and characteristics of the fully distributed optical fiber sensing technology are introduced. Then, the strain-deformation mechanical model is discussed. On this basis, the locations of tunnel optical cable deployment are determined. Finally, based on a deep learning method, the cross-section deformation distribution law of the tunnel is proposed.

2.1. Principle and characteristics of the fully distributed optical fiber sensing technology
The fully distributed optical fiber sensing technology based on Brillouin scattering is used for strain and temperature sensing. When the optical fiber is subjected to an external force or temperature, it causes a change in the speed of sound and the refractive index of the optical fiber, resulting in Brillouin frequency shift. In 1989, T. Horigunchi et al. verified the linear relationship between Brillouin frequency shift and strain and temperature. This characteristic can be used to obtain the strain data along the optical fiber direction. The basic principle is shown in Figure 1. In recent years, many researchers [11-15] have studied and extended the fully distributed optical fiber sensing technology. Nowadays, its features such as distributed measured points, high resolution, and high accuracy are very suitable for bridge and tunnel structural health monitoring (SHM), ensuring the integrity and global nature of monitoring information.

2.2. Simplified strain-deformation mechanical model
In the tunnel structure, the foundation is assumed to be a homogeneous, continuous, and elastic semi-infinite ground. The simplified strain-deformation mechanical model is shown in Figure 2.

Figure 1. Basic principle of fully distributed optical fiber sensing technology

Figure 2. Simplified strain-deformation mechanical model of the tunnel
As shown in figure 2, for an infinitesimal segment $dx$ of the cross-section, $Q_1Q_2$ represents the neutral axis, and $z$ represents the distance from the neutral axis to the bottom of the beam, and $\rho$ represents the radius of curvature. When bending deformation occurs, the length of the neutral axis will not change, so that the strain-curvature relationship can be obtained first as Eq. (1).

$$\varepsilon = \frac{zd\theta}{\rho d\theta} = \frac{z}{\rho}$$

(1)

The differential relationship between curvature and deformation can be derived from Eq. (2). The curvature of the cross-section is approximately equal to the second derivative of the deformation. Therefore, from the above approximate relationship, it can be considered that under the premise of plane section assumption, the bending deformation of the tunnel can be calculated by Eq. (3).

$$K(x) = \frac{1}{\rho(x)} \frac{\varepsilon(x)}{z(x)} = \frac{w(x)^n}{\left\{1 + [w(x)]^2\right\}^{1/2}} \approx w(x)^n$$

(2)

$$w(x) = \int \left(\frac{\varepsilon(x)}{z(x)} dx\right) dx + Bx + C$$

(3)

Where $x$ denotes the tunnel length. $K(x)$ is the cross-sectional curvature, and $w(x)$ is the deformation of the tunnel. Parameters $B$ and $C$ are determined by the deformation boundary conditions measured by point displacement sensors. However, the cross-section of shield tunnel is difficult to satisfy plane section assumption after convergence deformation occurs, and Eq. (3) cannot be used directly for the tunnel cross-section. Therefore, we lay the optical cables along the longitudinal direction of the tunnel at the top and bottom of the cross-section, as well as the midpoint of the left and right sidewalls. The locations of the optical cable deployment are shown in figure 3. The thickness of the tunnel lining is used as the beam height and the longitudinal length is used as the beam length. Thus, the calculated deformation at $T_N, B_N, L_N$ and $R_N$ as shown in figure 3 are directly obtained using Eq. (3).

![Locations of Cross-Sectional Optical Cable Deployment](image1)

![Locations of Longitudinal Optical Cable Deployment](image2)

**Figure 3.** Descriptions of the locations of optical cable deployment

2.3. *The cross-section deformation distribution law of the tunnel*

Shield tunnels are considered to be slender structures that are prone to longitudinal deformation [16-18]. As the longitudinal deformation increases, the transverse compressive deformation in the tunnel cross-section will become significant. For shield tunnels, the cross-section deformation pattern will be like a ‘horizontal duck-egg’. Due to the complexity of deformation on different cross-sections of the tunnel,
cannot be described using a simple model. To solve this problem, this paper proposed a long short-term memory (LSTM) network to model the deformation relationship between the sequence of measured points and the sequence of non-measured points. A ‘sequence input layer’, an ‘LSTM layer’, a ‘fully connected layer’ and a ‘regression layer’ are used to build the network to realize the regression from ‘measured points deformation’ to ‘non-measured points deformation’.

3. Numerical analysis of a subway tunnel

3.1. Brief introduction of a subway tunnel finite element model

To simulate the operational tunnel deformation, large commercial finite element software (ANSYS) was used. It is assumed that a subway shield tunnel has an inner diameter of 5.4m, an outer diameter of 6m, and a burial depth of 12m. In order to minimize the interference of boundary conditions on the calculation results of the finite element model, the calculation range of this model is about 5 times of the tunnel diameter. The model is 60 meters wide, 40 meters high, and the longitudinal length is 100m. The classical Drucker-Prager (DP) constitutive model for the surrounding rock and soil materials was selected. The simulated ground material properties and tunnel parameters are shown in Table 1.

| Material            | Thickness (m) | Deformation modulus (MPa) | Poisson’s ratio | Density (kg/m³) | Cohesion (kPa) | Friction angle (°) |
|---------------------|---------------|---------------------------|-----------------|-----------------|----------------|--------------------|
| Miscellaneous Fill  | 8             | 3.94                      | 0.35            | 1828            | 15             | 30                 |
| clay                | 18            | 20.6                      | 0.3             | 2062            | 160            | 25                 |
| Weathered marl      | 15            | 500                       | 0.33            | 2160            | 310            | 27                 |
| Lining              | 0.3           | 32500                     | 0.2             | 2500            | /              | /                  |
| Grouting layer      | 0.2           | 1000                      | 0.2             | 2100            | /              | /                  |

The surrounding rock and soil, lining, and grouting layer were simulated using solid45 unit, and the mesh of the plane was divided using mesh200 unit. The tunnel lining segment was simulated with equal stiffness homogeneous circular method for joints. As for the boundary conditions of the model, the Y-direction of the surrounding rock at the lower boundary was constrained. The X-direction of the rock at the left and right boundaries was constrained, and the Z-direction of the surrounding rock along the longitudinal boundary of the tunnel was constrained. The model is shown in figure 4.

3.2. Analysis of the proposed method

The self-weight vertical displacement nephogram is shown in figure 5. The locations of the optical cable are as shown in figure 3, and each optical cable consists of 100 strain measured points. In order to simulate the overall settlement and convergence deformation of the tunnel, uniform loads of different
degrees are applied to some nodes of the upper soil. The uniform loads are located at Region P in the longitudinal direction of the tunnel from 40 to 60 meters and at Region L in the longitudinal direction from 60 to 80 meters. Besides the loads are applied symmetrically in the transverse direction. The description of different load cases is shown in Table 2.

Table 2. Description of uniform load cases considered in the simulations.

| Number | Loads degree | Loads position | Symmetry  |
|--------|--------------|----------------|-----------|
| Case 1 | 1t/m         | Region P       | Y-axis    |
| Case 2 | 5t/m         | Region P       | Y-axis    |
| Case 3 | 10t/m        | Region P       | Y-axis    |
| Case 4 | 15t/m        | Region L       | Y-axis    |

Figure 6. Deformation based on strain data (Case 1)

Figure 7. Deformation based on strain data (Case 2)

Figure 8. Deformation based on strain data (Case 3)
Deformation based on strain data (Points $T_N$)

Deformation based on strain data (Points $B_N$)

Deformation based on strain data (Points $L_N, R_N$)

**Figure 9.** Deformation based on strain data (Case 4)

Figure 6 to figure 9 shows the calculated deformation using the strain data at $T_N$, $B_N$, $L_N$ and $R_N$, and the actual deformation under the action of the four cases, respectively. It should be noted that the displacement sensors should be set at both ends of the tunnel portal as well as the mid-point and quarter-point of the tunnel body. Using the measured displacement at the critical cross-section of the tunnel, the strain-deformation mechanical relationship is corrected and the deformation boundary conditions are determined. During the operation monitoring period, inspections should be carried out, and the cross-sections at the abnormal deformation should be maintained on time.

As shown in the figures, the calculated results of the vertical deformation at $T_N$ and $B_N$ have quite small relative errors with the actual results under different cases. The maximum relative error of horizontal deformation at $L_N$ and $R_N$ is close to 7%. This may be due to the fact that the strain data generated by horizontal bending is considered to be the major component of the longitudinal strain in the left and right sidewalls when calculating the horizontal deformation. However, it includes a portion of the strain generated by vertical bending. In order to reduce the impact of this problem, the overall deformation trend can be corrected using critical cross-sectional deformation and inspections.

The calculated results of the finite element model under the four cases mentioned above were used to build a sample database. The long short-term memory (LSTM) network, a deep learning method, was used to predict the deformation of other non-measured points on the cross-section. An LSTM model was built using a ‘sequence layer’, an ‘LSTM layer’, a ‘fully connected layer’ and a ‘regression layer’, and the command ‘trainNetwork’ was applied to train the generated network. The first 70% of the data from the sample database was employed to train the relationship between measured and non-measured deformation, and the remaining 30% of the database was employed to verify the efficiency of the training model. Taking the deformation of a point sequence $Q_{1/4}$ at the 1/4 vault as an example, figure 10 compares the training results with the actual results. As shown in figure 10, it can be seen that when the measured points deformation is small, the maximum relative error between the predicted results of the non-measured points deformation and the actual results is close to 2%. As the deformation of measured points increases, the prediction becomes better and better, which proves the training results of this network are satisfactory.

**Figure 10.** Actual deformation and predicted deformation at $Q_{1/4}$
Due to the long-distance and complex stratigraphic environment of the subway shield tunnel, problems such as groundwater crossing and stratigraphic cavity are often encountered. It is impossible to grasp the changes in the stratigraphy after the shield tunnel construction is completed. At inhomogeneous strata, the tunnel lining segment will undergo drastic convergence deformation and uneven settlement, so researchers should focus on such abnormal deformation. Based on the above finite element model, a stratigraphic cavity was simulated above the lining of the operating tunnel. A 3m×3m×3m soil unit above the lining was “killed” at 77-80m in the longitudinal direction of the tunnel to simulate a stratigraphic cavity. Figure 11 represents the tunnel settlement obtained from the distributed strain data using the proposed method. Figure 12 shows the predicted deformation at $Q_{1/4}$ and the actual deformation under the action of Case 1.

![Figure 11](image1.png)

**Figure 11.** Deformation based on strain data

![Figure 12](image2.png)

**Figure 12.** Predicted deformation and actual deformation at $Q_{1/4}$ (Case 1)

As can be seen from figure 11 and figure 12, the deformation measured by the fully distributed strain data is not significantly different from the actual deformation. The proposed method can be used to effectively measure the severe longitudinal settlement and cross-sectional convergence deformation in the tunnel due to stratigraphic changes.

4. Conclusions
In this paper, a method is proposed for monitoring the cross-section deformation of tunnels using the strain data from the fully distributed optical fiber sensors. The following conclusions can be drawn.

(1) The strain-deformation mechanical model was used to convert the high-density strain data from the fully distributed optical fiber sensors into deformation at critical locations in the tunnel. The results from the finite element model of a subway shield tunnel show that the maximum relative error between the calculated deformation and actual deformation is only 7%.

(2) A long short-term memory (LSTM) network was employed to predict the sequence of measured deformation and the sequence of non-measured deformation at the tunnel cross-section by regression. The maximum relative error between the predicted deformation and actual deformation is only 2%. Therefore, the cross-section deformation can be predicted by using deep learning method very
well. In this paper, the symmetric cross-sectional uneven settlement and convergence deformation were simulated. In future work, the symmetry of deformation can be judged using the relationship between the magnitude of strain data of the left and right sidewalls ($L_N$ and $R_N$), and the asymmetric cross-section deformation can be predicted using more sophisticated and comprehensive deep learning methods.

(3) Under the simulated stratigraphic cavity damage case, the calculated results show that the proposed method can effectively measure the tunnel settlement and cross-section deformation. This method can improve the problem of few measured points caused by traditional sensing technology while reducing the difficulty and cost of sensor installation and realizing high-density cross-section deformation measurement of tunnels.

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References
[1] Y. Ning, “Application of safety monitoring and prediction in road tunnel construction,” Modern Tunnelling Technology, vol. 40(5), pp. 59-66, 2003.
[2] Z. X. Sun, S. F. Zhang, “Application and analysis of hydrostatic level gauges in deformation monitoring of subway tunnels during operation,” Modern Tunnelling Technology, vol. 52(1), pp. 203-208, 2015.
[3] H. Hu, J. X. Gao, Y. F. Yao, “Land deformation monitoring in mining area with PPP-AR,” International Journal of Mining Science and Technology, vol. 24 (2), pp. 207-212. 2014.
[4] R. Van Gosliga, R. Lindenbergh, N. Pfeifer, “Deformation analysis of a bored tunnel by means of terrestrial laser scanning,” 2006 ISPRS Commission V Symposium on Image Engineering and Vision Metrology, pp. 167-172, 2006.
[5] M.J. Lato, M.S. Diederichs, “Mapping shotcrete thickness using LiDAR and photogrammetry data: correcting for over-calculation due to rock mass convergence,” Tunnelling and Underground Space Technology, vol. 41(1), pp. 234-240, 2012.
[6] S. Y. Zhang, Y. Liu, “Damage detection of bridges monitored within one cluster based on the residual between the cumulative distribution functions of strain monitoring data,” Structural Health Monitoring, vol. 19(6), pp. 1764-1789, 2020.
[7] J. X. Cao, Y. Liu, “Damage cross detection between bridges monitored within one cluster using the difference ratio of projected strain monitoring data,” Structural Health Monitoring 2021; Published online.
[8] Z. Chen, Q. Li, F. Ansari, A. Mendez, “Serial multiplexing of optical fibres for sensing of structural strains,” Journal of Structural Control, vol. 7, pp. 103-117, 2000.
[9] X. Bao, M. DeMerchant, A. Brown, T. Bremner, “Tensile and compressive strain measurement in the lab and field with the distributed Brillouin scattering sensor,” Journal of Lightwave Technology, vol. 19(11), pp.1698-1704, 2001.
[10] S. Shen, Z. S. Wu, “Convergence deformation monitoring of shield tunnels based on distributed optical fiber strain sensing technique,” China Civil Engineering Journal, vol. 46(9), pp. 104-116, 2013.
[11] L. Zou, X. Bao, et al., “Dependence of the Brillouin Frequency Shift on Strain and Temperature in a Photonic Crystal Fiber,” Optics Letters, vol. 29, pp. 1485-1487, 2004.
[12] B. Shi, et al., “A feasibility study on the application of fibre-optic distributed sensors for strain measurement in the Taiwan Strait Tunnel project,” Marine Geotechnology, vol.21, pp. 333-343, 2003.
[13] X. Bao, “Optical fibre sensors based on Brillouin scattering,” Optics and Photonic News, vol. 20(9), pp. 40-46, 2009.
[14] Y. Dong, et al., “Long-range and high-spatial-resolution distributed birefringence measurement
of a polarization-maintaining fibre based on Brillouin dynamic grating, ” *Journal of Lightwave Technology*, vol. 31, pp. 2981-2986, 2013.

[15] Y. Liu, H. Li, Y. L. Wang, “Damage detection of tunnel based on the high-density cross-sectional curvature obtained using strain data from BOTDA sensors,” *Mechanical Systems and Signal Processing*, vol. 158(3), pp. 107728, 2021.

[16] H. Hongwei, Z. Xiaolong, “Research and analysis on longitudinal deformation characteristics of shield tunnel, ” *Underground Space*, vol. 22(3), pp. 244-251, 2002.

[17] C. Molins, O. Arnau, “Experimental and analytical study of the structural response of segmental tunnel linings based on an in situ loading test. Part 1. test configuration and execution,” *Tunnelling and Underground Space Technology*, vol. 26(6), pp. 764, 2011.

[18] C. Molins, O. Arnau, “Experimental and analytical study of the structural response of segmental tunnel linings based on an in situ loading test. Part 2. Numerical simulation,” *Tunnelling and Underground Space Technology*, vol. 26(6), pp. 778, 2011.