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Rutting Deformation Monitoring of Asphalt Mixture Based on Distributed Optical Fiber Shape Sensing Technology

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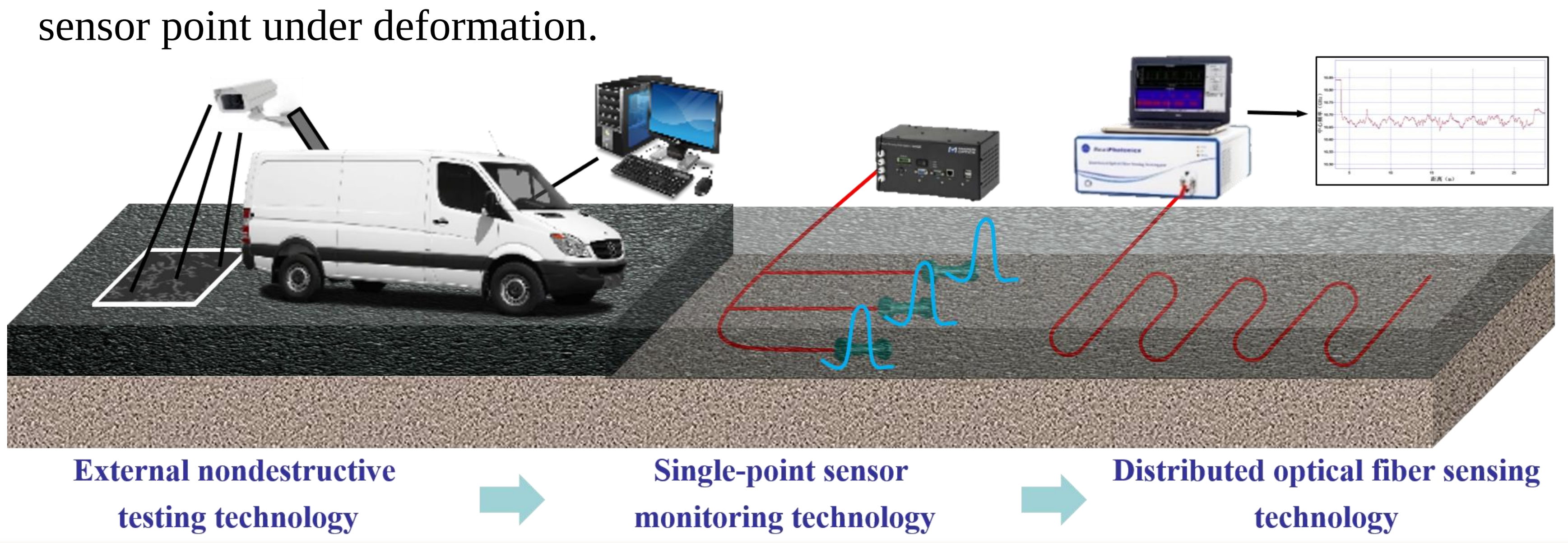
Introduction

- Rutting is a typical disease form of asphalt pavement, which is closely related to the influence of different structural layers.
- It is of great significance to monitor and evaluate the rutting process and cross-section shape of asphalt pavement structure.
- The existing external nondestructive testing technology has the advantages of high efficiency and many measuring points, but it can only detect the rut deformation of asphalt pavement surface, and can not detect the rut inside the structure.
- The distributed optical fiber shape sensor measures the position and shape of the object itself or the object connected with it by using the differential strain response of each sensor point under deformation.



Methodology

Sensors

- The distributed optical fiber shape sensor is composed of package layer, neutral layer and bare fiber.
- The sensor can decouple the strain caused by temperature and axial deformation, thus separating the strain caused only by bending deformation.

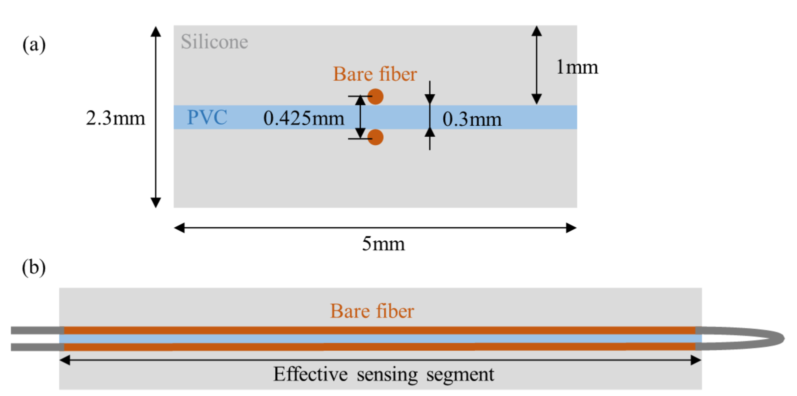
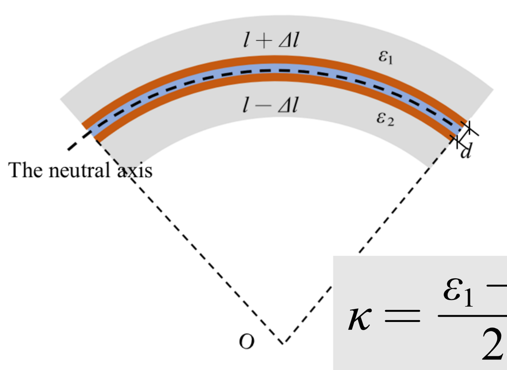


Fig.1 The flexible distributed optical fiber shape sensor.

Strain-curvature relationship

- The distributed optical fiber shape sensor was selected to analyze the force on the micro-segment.
- The theoretical relationship between strain and curvature of shape sensor was presented.
- Based on the calibration experiment in laboratory, the curvature correction coefficient was



$$\kappa = \frac{\varepsilon_1 - \varepsilon_2}{2d}$$

Fig.2 Bending deformation of the shape sensor.

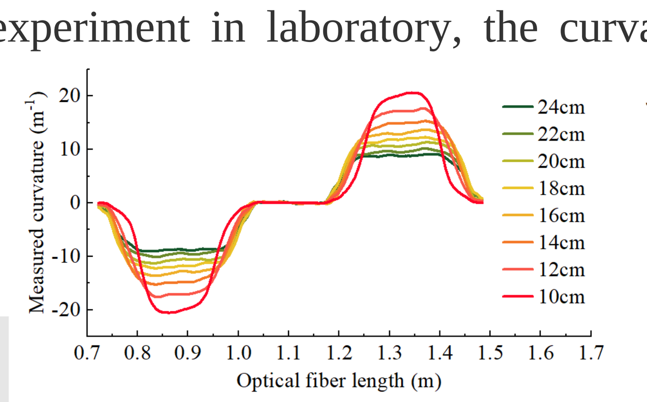


Fig.3 Curvature calibration test

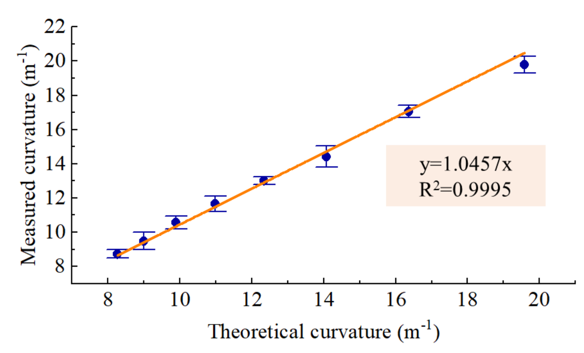


Fig.4 The curvature correction coefficient obtained by fitting.

Shape reconstruction theory

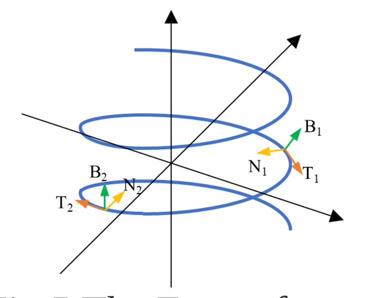


Fig.5 The Frenet frame.

- Frenet-serret equation in space curve theory was introduced.
- The mathematical relationship between vector and curvature.
- Describes the coordinates of points in a space curve.

$$\begin{bmatrix}T_{n+1}\\N_{n+1}\end{bmatrix} = \mathrm{Norm}\left\{\begin{bmatrix}1 & \kappa_n\cdot\Delta s\\ -\kappa_n\cdot\Delta s & 1\end{bmatrix}\cdot\begin{bmatrix}T_n\\N_n\end{bmatrix}\right\} \qquad P_{n+1}=P_n+T_n\cdot\Delta s$$

Indoor rutting test

- 70# base asphalt and AC-13 gradation were used to make rutting specimens.
- The sensor was arranged on the surface of the sample by slotting method.
- The data of distributed optical fiber sensor was collected by optical frequency domain reflectometer (OFDR) . The spatial resolution was 2.6 mm and the frequency was 250 Hz.

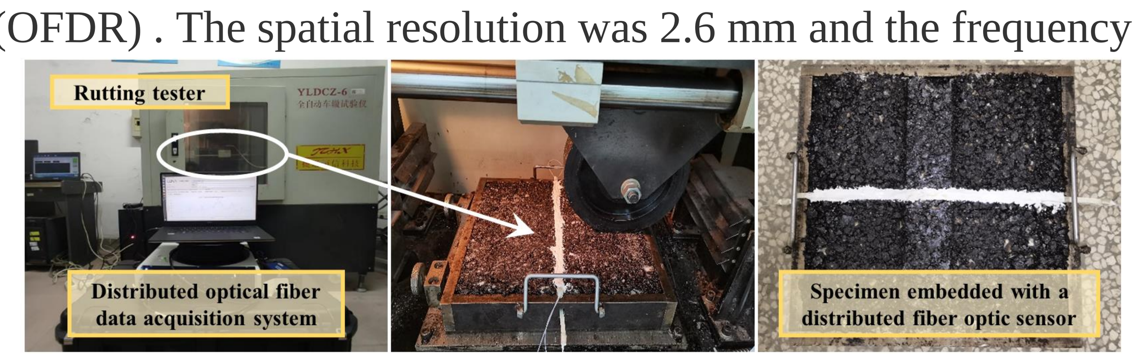


Fig.6 Rutting deformation monitoring system.

Results and Discussion

Monitoring Data pre-processing

- The time series data representing the cumulative strain were filtered and extracted.
- The difference between the above-mentioned strain time series and the initial strain before loading was calculated, and the basic data for shape reconstruction was obtained.

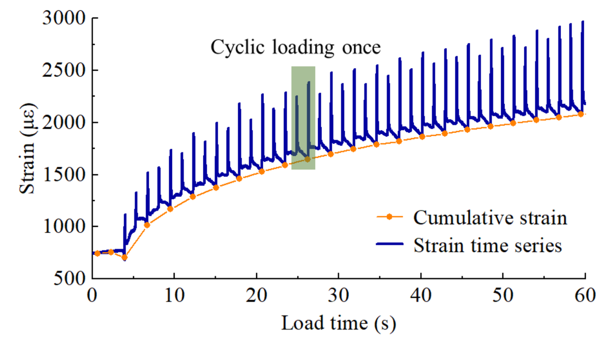


Fig.7 Time-history strain of the measuring point of the distributed optical fiber shape sensor.

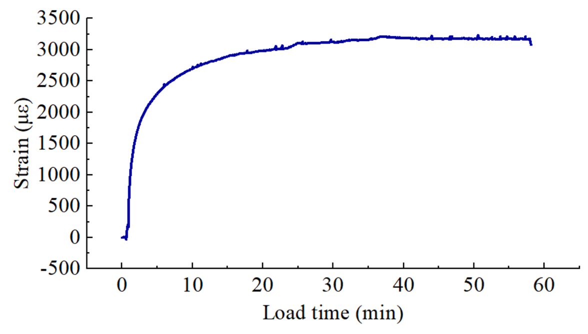


Fig.8 The time-history strain of the sensor during the whole loading process.

- The strain of the shape sensor neutral axis under compression and tension was extracted.
- The strain caused by the bending deformation was obtained by calculating the fold difference.
- According to the curvature-strain relation and the curvature correction coefficient, the curvature distribution was calculated.

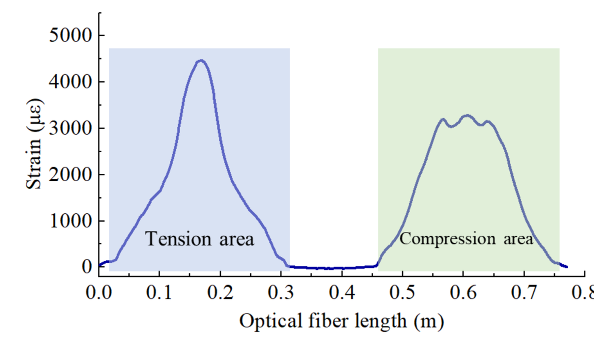


Fig.9 Measured along-fiber strain of distributed optical fiber shape sensor.

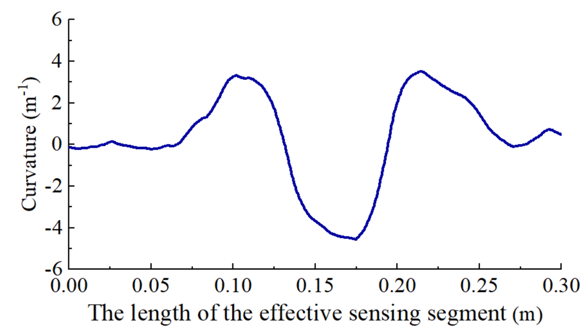


Fig.10 The measured curvature along the fiber of distributed optical fiber shape sensor.

Reconstruction and verification of rut deformation

- According to Frenet-Serret equation, starting point frame and measured curvature distribution, the coordinates of each point of distributed optical fiber shape sensor were calculated.

starting point frame: $\begin{bmatrix}T_1\\N_1\end{bmatrix}=\begin{bmatrix}1&0\\0&1\end{bmatrix}$ starting point coordinates: $P_1=[0,0]$

- The Bézier curve was created between the starting point and the end point to correct the iteration error of the discrete point coordinates and obtain the final reconstructed curve shape.
- The relationship between the rut depth reconstructed by distributed optical fiber shape sensor and the rut depth measured by displacement sensor was compared.
- The results show that the accuracy of the rutting depth obtained by the reconstruction algorithm was high, and the average relative error was 0.981% .

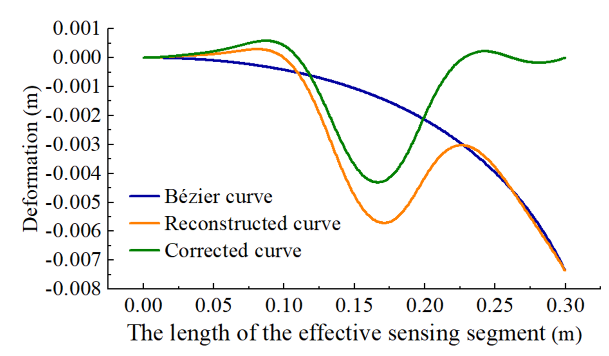


Fig.11 Shape reconstruction of rutting cross-section.

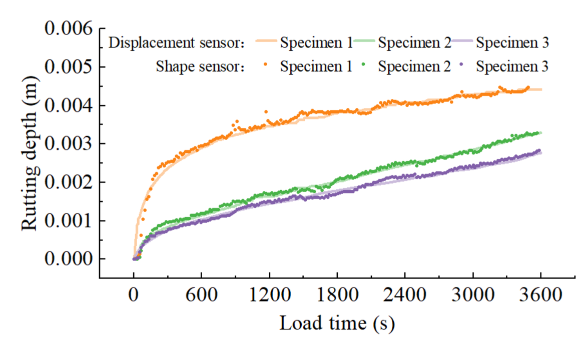


Fig.12 Verification of rut shape reconstruction.

Development Law of rut deformation

- The monitoring of rutting deformation by distributed optical fiber shape sensor can be divided into two stages: compaction stage and flow deformation stage, which correspond to the development stage of permanent deformation of asphalt pavement.

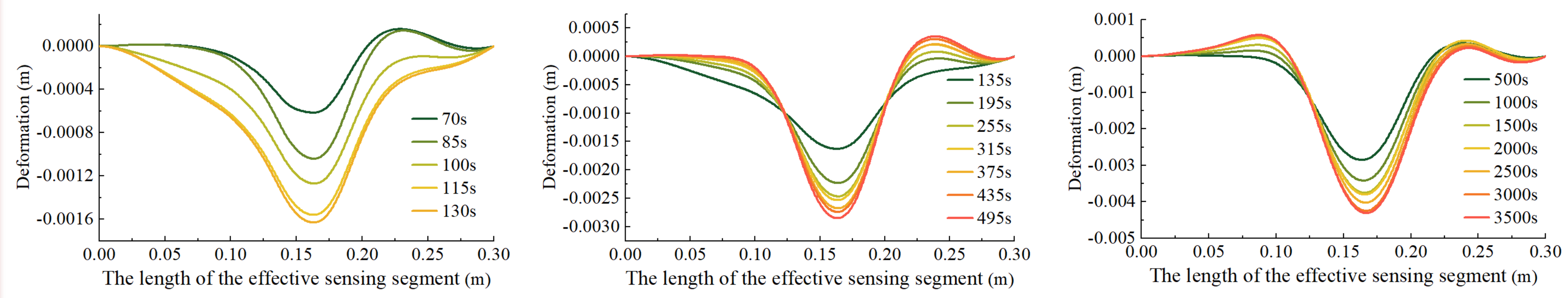


Fig.13 The deformation of distributed optical fiber shape sensor in three stage.

Conclusions

- A flexible distributed optical fiber shape sensor was designed, the relationship between strain and curvature was presented, and the curvature correction coefficient was determined by curvature calibration experiment.
- Based on the space curve theory, a distributed shape reconstruction algorithm for optical fiber was presented.
- The monitoring and reconstruction of the rut deformation were carried out through the indoor experiment, and the feasibility of the method was verified by comparing with the data of the rut depth measured by the displacement sensor.